THE INTRINSIC CARRIER DYNAMICS
OF InGaAs/AlGaAs SINGLE QUANTUM WELL, STRAINED-LAYER,
SEMICONDUCTOR LASERS

HIDEAKI PAGE

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GUILDFORD
SURREY
U.K.

Supervisor Prof. A.R. Adams

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I would like to dedicate this work to my parents and to Corinne.
The man who says it cannot be done should not interrupt the man who is trying to do it.
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CHAPTER 1

1. INTRODUCTION

1.1 EVOLUTION OF THE SEMICONDUCTOR LASER

The evolution of the semiconductor laser may be measured from the reductions of the lasing threshold current that follow successive improvements in laser design. The idea that net stimulated emission and eventually lasing can be brought about in semiconductor materials stem from 1958-1961, [1-3]. Basov et al [4] suggested the use of a forward biased pn junction as the basis of a laser. The qualitative understanding of the necessary conditions for population inversion in semiconductors were presented by Bernard and Duraffourg [5], who suggested GaAs and GaP as candidate materials for lasers. Early worked demonstrated the near 100% quantum efficiency from electroluminescence in GaAs at 77K, [6]. This was followed by observations of the slight reduction of the line width of the electroluminescence spectra of a GaAs pn junction at 77K and at current densities of $1.5\times10^3$ Acm$^{-3}$, by Nasledov et al, [7]. However the lack of a resonant cavity made it unclear whether lasing had occurred.

The demonstration of the first semiconductor laser was announced almost simultaneously by several groups. Hall, [8], formed a resonant cavity by polishing the ends of a GaAs crystal and measured coherent light emission based on the reduction in line width at 0.84$\mu$m and the behaviour of the far field radiation pattern. This work was followed by the measurement of coherent light emission from GaAsP by Holonyak and Bevacqua,[9], which was the first to use a III-V alloy for an injection laser.

These first semiconductor lasers were demonstrated only three years after the development of the first ruby laser by Maiman [10], and two years after the demonstration of the first gas laser by Javan et al [11]. Stimulated emission from semiconductors is more intense for a given degree of inversion than virtually any other
lasing material. However the resulting large rate of energy generation and heat dissipation limited the operation of these early lasers to very low temperatures.

The formation of a Fabry-Perot cavity by cleaving along parallel crystal planes to produce plane parallel facets the crystal were demonstrated by Bond et al [12]. This proved a considerable improvement over the previous technique of polishing the crystal to form facets.

### 1.1.1 HOMOJUNCTION LASER

Current injection in these early devices was usually achieved with a forward biased pn junction, fig(1a). At zero bias the diffusion current of electrons from the n-region to the p-region and holes from the p-region to the n-region is exactly countered by the drift current due to space charge regions of ionized acceptor and donor sites. Applying a forward bias to the junction enhances the diffusion current across the junction. The distribution of electrons diffusing from the n-doped region into the p-doped decreases exponentially as, \( \exp(-x/L_n) \), where \( L_n \) is the diffusion length of electrons, typically 1-3\( \mu \)m. A similar expression can be written for holes. At a given forward bias, there will be a non-equilibrium population of electrons and holes, distributed over an active region. At sufficient forward bias and at some point between the n and p regions this population will be great enough to generate the threshold gain needed for lasing. However the diffusion length of the injected carriers tends to be greater than the width of the active regions and the carriers can diffuse away from the active region and are unavailable for the process of gain. The material surrounding the active region can give rise to strong optical absorption as the bandgap of the material is equivalent to the lasing photon energy. As there is only a small variation in the refractive index across the pn junction and thus the optical field tends to spread into the lossy regions. The threshold current of these devices are very high, in excess of \( 26 \times 10^3 \text{ A cm}^{-2} \) [13].

These high threshold current densities limit the operation of simple pn junction lasers to low temperatures making these devices impractical for technological applications. Continuous wave (CW) operation at 205K of such devices was demonstrated by Dyment and D'Asaro [14]. Their work resorted to heavy heat sinking of the laser and the
use of a narrow stripe contact along the length of the laser. This acts to channel the current into a narrowly defined volume of the laser thus reducing the total volume that needs to be pumped and hence the threshold current. Such stripe configurations still form an important feature of many modern laser geometries.

1.1.2 HETEROSTRUCTURE LASERS

The idea of the use of a heterostructure to reduce the lasing threshold current was first proposed by Kroemer [15], but was not fully realised in lasers until later by Rupprecht[16,17] and Hayashi & Panish [18,19] who measured a threshold current of $8.6 \times 10^3 \text{ Acm}^{-2}$ an order of magnitude reduction compared to homojunction devices. Earlier work by Alferov [20,21] suffered from a poor material quality due to the lattice mismatch between GaAsP and GaAs inducing misfit dislocations in his devices which lead to large threshold currents. It is interesting to note that the lattice mismatch between different materials in a sufficiently thin layer has been used to great advantage as it incorporates strain within the active layer. This subject will be discussed later. Woodall et al [22] used AlGaAs/GaAs system grown by Liquid Phase Epitaxy (LPE). This system of materials is closely lattice matched and formed the basis of the early heterostructure lasers.

The difference in bandgap between two dissimilar semiconductor materials can be used to create an energy discontinuity in the conduction and valence band edges, fig(1b). This can be used to impede the diffusion of carriers and confine them in the active region. A simple heterostructure laser is a three layer device consisting of a narrow bandgap material, forming the active region, sandwiched between two larger bandgap materials forming barriers to impede the flow of injected carriers. The refractive index of the larger bandgap material, conveniently happens to be less than that of the narrow bandgap material. Therefore the refractive index step between the barrier and active region also acts as a waveguide which confines the optical field within the active region. Also there is no absorption in the wide bandgap layers surrounding the active region as the bangap of these layers is greater than the lasing photon energy.
Fig (la) Shows the operation of a forward biased pn homojunction laser. Electron and hole injection across the bandgap gives rise to a non-equilibrium carrier population around the vicinity of the junction. At a sufficient forward bias there will be a point where the carrier density will be sufficient to give rise to lasing. Carriers diffusing away from the junction and poor optical confinement around the junction limit the operation of these devices to liquid nitrogen temperature.

Fig (lb) Shows the operation of a double heterojunction laser. Carriers are confined in an active region due to the band edge discontinuity arising from the different bandgaps of the constituent layers. The step-like change in the refractive index between the layers also helps to confine the optical mode within the vicinity of the active region, so that more of the optical field interacts with the gain medium.
1.1.3 QUANTUM WELLS

Further reduction in the threshold current has followed improvements in material quality through growth techniques and elaborate geometries in laser design. However a fundamental shift in laser design has accompanied the use of quantum wells (QW) [23-25]. Improved growth techniques, namely Molecular Beam Epitaxy (MBE) and Metal Organic Vapour Pressure Epitaxy (MOVPE) have allowed the growth of high quality, very thin layers at atomic monolayer per minute rates. When the thickness of such a layer approaches that of the de Broglie wavelength of the carriers ($\lambda=\hbar/p \sim L_z \sim 100\text{nm}$) then the effects of quantum confinement become noticeable [26]. The motion of the carriers becomes constrained in the growth direction of the layer whereas they are free to move within the plane of the layer. Their motion changes from three dimensional in bulk material to two dimensional in QW material.

QW's offer the potential to lower the threshold current density and its temperature sensitivity, increase the differential quantum efficiency, reduce the lasing line width and increase the modulation bandwidth [27] of the semiconductor laser. The reduction in threshold current density is mainly due to the order of magnitude reduction in active volume rather than quantum size effects. However the step-like Density of States function (chapter 2) suggests that the change of gain with carrier density $dG/dn$ is higher than in the bulk case. An overview of QW's is given [28].

These thin layers also have the advantage that large strains, $\sim 1\%$, due to the lattice mismatch between the layer and barrier material may be supported without the formation of misfit dislocations. The lattice mismatch between different materials has limited the choice of materials in bulk heterostructure designs. A wide range of ternary and quaternary (chapter 5) III-V solid solution can now be used to vary the bandgap of the active region, producing lasers covering a wide range of operating wavelengths.

1.1.4 STRAIN

The effects of externally applied strain on semiconductor lasers has been demonstrated to reduce the threshold current density and produce polarized output during the early
days of lasers development [29-33]. A theoretical description was presented by Elesiev et al [34,35] and demonstration of the first strained layer QW laser was in 1982 [36]. However it was not until Yablanovitch and Kane [37] and Adams [38] that serious attention was focused on the subject.

Strain allows the possibility to modify the structure of the valence band, thereby reducing the density of states and enhancing the TE or TM gain. An overview of strain is given [39]. The modification of the valence band structure has also been demonstrated by Adams [40] to reduce inter valence band absorption (IVBA) and Auger recombination which act to increase the threshold current and its temperature sensitivity in 1.5 and 1.3µm devices. Strain will be discussed in more detail in chapter 2.

1.1.5 LASER GEOMETRIES

There are many different variations in laser structure based on the simple heterostructure design. In devices with thin active layers, such as a QW, the optical field extends over a much greater width than the active region. Extra layers may be added surrounding the QW barriers material to provide separate confinement for the optical field, in a separate confinement heterostructure (SCH) laser. Some of these methods are illustrated in fig(2).

The reduction in the threshold current density can be brought about in two major ways. First by reducing the volume of the active region that needs to be pumped to achieve lasing and second by confining the optical field around to the active region. Stripe geometry lasers demonstrate a simple method for confining the injection current to a narrowly defined active region. Such lasers are often termed gain guided lasers. Here the refractive index step between successive layers confines the optical field in the growth direction whereas the spatial extent of the optical field in the plane of the active layer is dictated by the distribution of the gain in the plane of the layer. The stripe may be formed by laying down oxide layers either side of the stripe contact. In proton or deuteron stripe lasers the material either side of the stripe is bombarded by proton or deuteron beams, destroying the crystal structure of the material and rendering it insulating. The injection current is then strongly channelled into the active region through the conducting, unperturbed layers.
A second method of forming a stripe is to grow a further n-doped layer on the p-type top contact. A stripe contact can be defined by diffusing Zn into n-type layer in the pattern of the stripe contact, converting it p-type until it contacts the underlying p-type layer. The material surrounding the stripe will be under reverse bias when the stripe is under forward bias, whilst the contact will be under forward bias, thus the injected current is channelled through the stripe into the active region.

In ridge waveguide lasers a p-type top contact forms a ridge that stands proud of the active region. The injected current is channelled into the active region through the ridge. The ridge also provides weak index guiding of the optical field in the plane of the layers. The ridge may be surrounded by material to provide strong index guiding of the optical field in plane of the layers. These devices are termed buried heterostructure (BH) lasers. Elaborate configurations of materials can again be used to form reversed biased pn junctions to strengthen the channelling of the current into the active regions. However the large number of interfaces facilitates the nucleation of defects and reduces the reliability of these devices.

Other notable designs are the distributed feedback (DFB) laser and the Vertical Cavity Surface Emitting Laser (VCSEL). In the DFB laser a layer with a periodically varying refractive index is placed near the active region where it can interact with the optical field. This forms a photonic crystal which can favourably select modes for amplification. All the devices described so far have are termed edge emitters as the light is emitted in the plane of the layers. VCSEL’s emit light in the growth direction of the layers. The layers are often fabricated in the forms of columns thus defining a very small active region. As the cavity length is very short highly reflecting (99.9%) multilayered Bragg stacks must be used to achieve lasing. These lasers have the advantage that they can be fabricated in large 2-D arrays on a single substrate.
Fig(2) Shows some different configurations of laser geometries all of which act to confine carriers within a well defined active region. Fig(2a) Shows a simple stripe top contact. Current is forced to flow through the metallic stripe, whilst being impeded by the insulating material surrounding the stripe. The bulk of the laser consists of the substrate. The active layers are located just under the stripe contact. Therefore only a narrow region of the active region is pumped. Fig(2b) the stripe proton or deuteron beams are used to destroy the crystal structure around the stripe contact, rendering the material insulating. Current is forced to flow through the remaining conducting channel. Fig(2c) A further n-type top contact is grown on top of the usual p-type top contact. Zn may be diffused into this new layer in the pattern of the stripe contact. This changes the n-type material to p-type, forming a conducting channel down to the p-type sub-layer. The material surrounding the stripe is reversed biased when the channel is forward biased. Fig(2d) Shows a ridge waveguide laser. The material surrounding the ridge has been etched away leaving a conducting ridge. Fig(2e) Shows a buried heterostructure device. The ridge in fig(2d) is surrounded by n-type doped material forming reverse biased barriers to confine the carriers within the conducting channel.
1.2 BACKGROUND WORK TO THIS THESIS

The development of the semiconductor laser can chiefly be seen from the point of view of improvements in design and growth fabrication techniques. However, aside from this, the performance of semiconductor lasers are fundamentally limited by the physical electron hole dynamics in the materials used in device. The focus of this work is to contribute to the understanding of the behaviour of semiconductor lasers in terms of these carrier processes, rather than the quest for improved device design. Carrier processes may initially be divided into radiative recombination processes, which contribute to gain, and nonradiative loss process, such as Auger recombination, which compete with radiative recombination. Optical absorption mechanisms such as Inter Valance Band Absorption (IVBA) may also compete with radiative recombination processes. Understanding how these processes vary over a wide range of material systems is a worthy goal. Work of this type has been done on long wavelength 1.5\mu m lasers [41] and on visible lasers operating at 633nm [42].

1.3 and 1.5\mu m lasers are commercially important for telecommunication systems. These wavelengths occur at the minima of the attenuation spectrum for silica based fibres, those which form the basis of existing telecommunication networks. Two major loss processes, Auger recombination and IVBA (sections 2.17 & 2.18) have been shown to be significant in these devices. IVBA is an optical absorption process, that reduces the photon density generated through stimulated emission. Extra carriers have to be injected to make the photon generation rate exceed the absorption rate to achieve lasing. This leads to greater threshold carrier densities and therefore greater threshold currents. IVBA also effects the external differential efficiency above threshold, the ratio of the increase in light intensity for a given increase in injection current. IVBA arises from the excitation of an electron in the spin split off band (SO) band to the heavy hole (HH) in the HH band. The energy difference between the HH and SO bands equivalent to the lasing photon energy is moved to large k values with increasing fundamental bandgap. The probability of finding a hole in the HH band at these large k values into which to promote an electron from the SO band is reduced. Thus IVBA is expected to decrease with increasing bandgap. Strain is expected to reduce the HH mass (section 2.12) thus increasing the curvature of the HH band. This also has the effect of increasing the k
vector at which IVBA occurs. A corresponding reduction of IVBA is also expected with strain. The application of externally applied hydrostatic pressure increases the direct bandgap at a rate $\sim 10 \text{meV/kbar}$. The variation of external efficiency as a function of hydrostatic pressure in bulk, unstrained QW and strained QW $1.5\mu\text{m}$ lasers has been measured [40]. The increase in efficiency with pressure for bulk and unstrained QW devices is consistent with the removal of IVBA. However the efficiency of both tensile and compressively strained QW devices is relatively pressure insensitive indicating that IVBA is insignificant in these lasers. The reduction of IVBA from unstrained to compressively strained $1.5\mu\text{m}$ lasers has been independently measured by Fush et al [43] and Joindot et al [44]. Thus tensile and compressive strain has been shown to reduce IVBA in $1.5\mu\text{m}$ lasers.

In Auger recombination, electron hole recombination occurs with the excitation of a third carrier to a higher energy state. As both energy and momentum conservation are necessary in the transition, the rate of Auger recombination is dependent on both bandgap and carrier effective mass. Increasing the direct bandgap and reducing the HH effective mass are both expected to reduce the rate of Auger recombination [38]. Being a three body process the Auger recombination rate is proportional to the cube of the injected carrier density. Therefore Auger effects are compounded by the presence of IVBA.

Band to band Auger recombination has been shown to be the dominant loss mechanism in bulk $1.5\mu\text{m}$ lasers, [45], whereas phonon assisted Auger may be dominant in QW devices [46,47]. The reduction of threshold current with externally applied hydrostatic pressure in these devices has demonstrated that Auger recombination is a dominant process in $1.3$ and $1.5\mu\text{m}$ lasers [41]. It is difficult to measure the total Auger rate in a given device however it has been estimated, [48], that Auger can account for $\sim 80\%$ of the threshold current in $1.5\mu\text{m}$ devices. Thijis et al [49] have addressed both the tensile and compressively strained material systems at the $1.5\mu\text{m}$ wavelength. Their measurements show a decrease of a factor of five in the threshold current for a strain, compressive or tensile, of $1.5\%$. This reduction is greater than expected for the reduction
in the radiative current alone and is indicative of the reduction in Auger recombination with strain. Similar conclusions have also been drawn independently by others [50].

At the bandgap of the materials used for visible lasers, GaInP, Auger processes and IVBA are expected to be entirely quenched. However the difference in bandgap between the materials forming the heterostructure are decreased with increasing bandgap. Thus the effectiveness of the material systems used to form an effective heterobarrier to confine carriers within the active region are reduced. The increase in threshold current density with pressure has been measured [51] in 633nm devices. The effect of pressure (section 2.13) is to reduce the energy separation between the X and L band edges in the cladding regions with respect to the Γ band edge in the active region. The heterobarrier seen by injected carriers is reduced with pressure therefore facilitating their ability to diffuse out of the active region. The resulting leakage current (section 6.3) is a dominant component to the threshold current of these devices.

Thus we see different loss mechanisms dominating the threshold current density at different ends of the electromagnetic spectrum. Auger and IVBA tend to decrease with increasing bandgap and poor carrier confinement tends to increase with increasing bandgap. We therefore speculate that there exist a range of wavelengths where these two processes are minimised and the threshold current becomes almost entirely radiative in nature. Such devices may be considered to be ideal. This is the basis of the work in this thesis. Here we aim to investigate a range of both tensile and compressively strained lasers operating from 749 to 980 nm, lasers intermediate between the visible and long wavelength regions.
CHAPTER 2

2. THEORY

2.1 LASING

Electroluminescence in a semiconductor arises from electron hole recombination across the direct bandgap, the difference between the conduction band (CB) and valence band (VB) band edges. Therefore the photon energy of the light emitted from a semiconductor is of the order of the bandgap energy. The intensity of the light emitted from the semiconductor is governed by the relative electron and hole populations in the CB and VB. A net excess of stimulated emission and therefore optical gain can be generated at a sufficiently high electron and hole concentration. A laser is formed by enclosing the gain medium within a Fabry-Perot cavity. Light generated in the gain medium is able to traverse back and forth between the facets of the cavity. This optical feedback leads to an oscillation condition when the gain in the cavity is sufficient to overcome the optical losses incurred by the light traversing the cavity. This oscillation condition marks the onset of lasing. Therefore a threshold carrier density is needed to produce a threshold gain to bring about lasing. The resulting electron hole recombination rate gives rise to a threshold current.

2.1.1 GAIN

For a given electron hole density there will be a given photon generation rate due to spontaneous emission. There will also be a given downward transition rate due to stimulated emission and an upward transition rate due to absorption in response to the photon flux passing through the material. Each downward transition generates a photon of light while each upward transition absorbs a photon. If the rate of downward transitions exceeds the rate of upward transitions then net optical gain is achieved. The optical gain is defined as the fractional increase in photons per unit length. Gain is simply the inverse of optical absorption. By filling states in the CB with electrons, and states in the VB with holes, the chances of an electron in the VB finding a vacant state in the CB into which it can be promoted through the absorption of a photon are reduced. Conversely the probability of an electron finding a vacant
state in the VB (hole) with which it can recombine are increased. Thus in general a non-equilibrium population of carriers is needed to achieve gain.

2.1.2 LASER OSCILLATION

Optical gain in a given material may be achieved when the material is pumped to a sufficient level of excitation such that the rate of stimulated emission exceeds the rate of stimulated absorption. Photons passing through the material will then be amplified through the net excess of stimulated emission. This, however, is not sufficient to bring about the onset of lasing, optical feedback is needed. Optical feedback can be added by placing the gain medium within a Fabry-Perot cavity. A portion of the light generated within the gain medium is always reflected back into the gain medium by the reflective facets of the cavity. The other portion of the light is transmitted through the facets to form the useful output beam of the laser.

Light may traverse back and forth between the two reflecting facets of the cavity. If the light intensity at one facet is unattenuated after making a round trip through the cavity, i.e. after the gain and facet loss have been taken into account, then it can be continually reflected back and forth ad infinitum. This is the lasing threshold condition, the point where our laser starts to oscillate.

Consider the intensity variation with length of the optical field propagating between the two reflective facets of the laser cavity. If the gain per unit length does not vary over the length of the laser the light intensity varies exponentially with distance [52].

\[ F_\pm = F_{0\pm} \exp\left[ \pm (g - \alpha)z \right] \]

Equation 2-1

\( F \) is the optical flux density, \( \pm \) refers to the forward and backward propagating waves, \( g \) is the gain per unit length and \( \alpha \) is the loss per unit length from processes not associated with the gain mechanism such as diffraction, scattering and free carrier absorption. At threshold the forward and backward propagating waves are self-replicating. The loss in optical intensity through reflection at the facets can be entirely
Fig(1) Illustrates the conditions under which lasing occurs in a Fabry-Perot cavity. Light traversing the cavity encompassing a region of net gain will undergo amplification until it reaches one of the facets. On reflection a fraction, $R$, the facet reflectivity, is reflected back into the gain medium, whilst the remainder is transmitted through the facet to form the laser beam. If the gain is sufficient to recoup the loss in intensity on reflection then the beam may cycle back and forth indefinitely. This is the lasing oscillation condition.

Fig(2a) Shows the evolution of the gain spectra and the variation of the peak gain with current. The low energy cut off in the gain spectra (point of zero gain) occurs at a photon energy of the order of the bandgap. The upper energy cut off occurs at transparency condition, where stimulated emission is balanced by absorption. The peak of the gain spectra can be seen to increase with current, fig(2b), and to move towards higher photon energies. For small values of gain the peak gain may be considered to increase linearly with current. In the absence of nonradiative recombination processes the threshold current is the current needed produce the threshold gain. However as the gain increases the gain/current characteristic starts to roll over. This is the region of gain saturation and is caused by band filling effects. A laser operation in gain saturated region would therefore be expected to be sensitive to changes in the threshold gain.
recouped by the gain in the cavity. In order to maintain the optical distribution in fig(1), the intensity A at facet 2 from the forward propagating wave must stem from the intensity D after reflection at facet 1. The intensity C at facet 1 must stem from the intensity B after reflection at facet 2. We may express the intensities B and D in terms of the reflectivity’s R and R2 of each facet.

\[ D = R_1 C \]  
Equation 2-2

\[ B = R_2 A \]  
Equation 2-3

Thus the forward and backward propagating waves become.

\[ C = R_2 A \exp[(g - \alpha)L] \]  
Equation 2-4

\[ A = R_1 C \exp[(g - \alpha)L] \]  
Equation 2-5

We may eliminate A and C in Equation 2-4 and Equation 2-5 to give.

\[ g_{th} = \alpha + \frac{1}{2L} \ln \left( \frac{1}{R_1R_2} \right) \]  
Equation 2-6

Equation 2-6 is of the form.

| Threshold gain= Optical Loss+ Mirror loss |

2.1.3 EINSTEIN RELATIONS
There are three distinct types of CB to VB transitions that take place with either the emission or absorption of a photon. An electron in the VB may be excited to a vacant state in the CB through the absorption of a photon of energy equal to the transition. Conversely, in spontaneous emission, an electron in the CB may recombine with a hole in the VB giving up its energy as a photon of light. Finally a downward transition may be initiated through the interaction with a photon of light that generates a second photon of identical energy, phase and polarization. This is stimulated emission, the
fundamental process that can generate gain in a laser. The relative rates at which these transitions occur is very much dependent on the proportion of electrons in the CB and holes in the VB and on the photon density. A non-equilibrium distribution of electrons and holes, i.e. injecting carriers into the CB and the VB respectively, will favour optical emission processes over optical absorption. Thus we may bring about electroluminescence by injecting a non-equilibrium density of electrons and holes in a semiconductor.

The intra-band scattering time of the order ~1ps is very much shorter than the interband scattering time ~1ns, [53]. The non-equilibrium carrier density in the conduction or VB can then be thought of being in thermal equilibrium with themselves. Therefore the distribution of electrons in the conduction or VB may each be described by their own Fermi-Dirac distributions, each with governed by a separate quasi-Fermi level relative to the conduction or VB edge. The probability, $f_1$, of finding an electron at an energy $E_1$ in the VB is now.

$$f_1 = \frac{1}{1 + \exp \left( \frac{(E_1 - F_1)}{kT} \right)}$$

Equation 2-7

Where $F_1$ is the quasi-Fermi level, $T$ the temperature and $k$ is Boltzmann’s constant. Likewise the probability of finding an electron at energy $E_2$ in the CB is given by:

$$f_2 = \frac{1}{1 + \exp \left( \frac{(E_2 - F_2)}{kT} \right)}$$

Equation 2-8

Here $F_2$ is the quasi Fermi level for electrons in the CB.

The intra-band transition probabilities may be understood by considering the transitions between two levels one in the CB and one in the VB. Thus an upward transition from state 1 in the valence band to state 2 in the CB will absorb a photon of
energy $E_{12}$. Conversely a downward transition from state 2 in the CB to state 1 in the valence band will emit a photon of energy $E_{21}$.

The rate of absorption is proportional to the probability of finding an electron in the valence band, $\rho_c f_1$, and the probability of finding a vacant state in the conduction band $\rho_e (1-f_2)$ and the photon density $P(E)$. $\rho_c$ and $\rho_e$ are the effective density of electron and hole states at states 1 and 2. These are difficult to define when only considering two energy levels. However they cancel out from the derivation. so strict definition is not necessary.

$$r_{12} = B_{12} \rho_e f_1 (1-f_2) \rho_c P(E_{12})$$

Equation 2-9

The constant of proportionality, $B_{12}$, is the Einstein coefficient for absorption. An equivalent expression can be found for the rate of stimulated emission, $r_{\text{stim}}$. This is proportional to the probability of finding an electron in the conduction band, $\rho_e f_2$, and the probability of finding a hole in the valence band, $\rho_c (1-f_1)$, and the photon density $P(E)$.

$$r_{21}(\text{stim}) = B_{21} \rho_c f_2 (1-f_1) \rho_e P(E_{21})$$

Equation 2-10

The constant of proportionality, $B_{21}$, is the transition probability. Finally the probability of spontaneous emission, $r_{\text{spon}}$, is proportional to the probability of finding an electron in the conduction band, $\rho_e f_2$, and a hole in the valence band, $\rho_c (1-f_1)$.

$$r_{21}(\text{spon}) = A_{21} \rho_e f_2 (1-f_1) \rho_c$$

Equation 2-11

The constant of proportionality is the spontaneous transition probability.
The relationship between $B_{12}$ and $B_{21}$ can be seen by considering the transition rate at thermal equilibrium. The total downward transition rate must be equal to the upward transition rate.

$$r_{12} = r_{21} \text{(stim)} + r_{21} \text{(spon)}$$

Equation 2-12

From this we may derive the photon density at thermal equilibrium considering that $F_1 = F_2$.

$$P(E_{21}) = \frac{A_{21}}{B_{12} \exp\left(\frac{E_{21}}{kT}\right) - B_{21}}$$

Equation 2-13

This must be equal to the blackbody photon density at this energy [54].

$$P(E_{21}) = \frac{8\pi m^3 E_{21}^2}{h^3 c^3 \left[\exp\left(\frac{E_{21}}{kT}\right) - 1\right]}$$

Equation 2-14

Comparing Equation 2-13 and Equation 2-14 we see that.

$$B_{12} = B_{21}$$

Equation 2-15

### 2.1.4 NECESSARY CONDITION FOR NET STIMULATED EMISSION

This can now be derived from our previous discussion of transition rates. In order for there to be more stimulated emission than absorption, $r_{21} \text{(stim)}$ must be greater than $r_{12}$. Therefore.
It has been shown, Equation 2-15, that $B_{21}$ is equal $B_{12}$. Therefore we may express the above inequality purely in terms of population probabilities. Substituting Equation 2-7 and Equation 2-8 for $f_1$ and $f_2$ yields.

\[
\exp\left(\frac{E_2 - E_1}{kT}\right) > \exp\left(\frac{E_2 - E_1}{kT}\right)
\]

Equation 2-17

From this it is evident that the quasi-Fermi level splitting, $F_2-F_1$, has to be greater than the photon emission energy, $E_2-E_1$, for the downward transition rate to exceed the upward absorption rate. This is the Bernard Duraffourg condition [5]. When the quasi-Fermi level splitting is equal the photon emission energy the material effectively becomes transparent, a photon entering the material will stand as much probability of absorption as regeneration. The carrier density at transparency is called the transparency carrier density.

### 2.1.5 IDEAL LASERS

It is useful to introduce the concept of an ideal laser in order to see the benefits of introducing quantum confinement and strain into the laser structure. As discussed in the Chapter 1 the reduction of the threshold current has driven much of the research in semiconductor lasers. Ideal lasing characteristics are approached as the threshold current is minimised and this is achieved by reducing the relative proportions of nonradiative and optical loss processes. In the absence of all other loss processes the transparency current density, the current required to maintain the transparency carrier density, represents the fundamental limit for the lowest threshold current attainable in a laser. The threshold current may be expressed in terms of its components parts.

\[
\text{Threshold current} = \text{Transparency current} + \text{Current due to loss processes}
\]
The current due to loss processes includes the current needed to provide the extra gain above transparency to overcome the mirror losses in the laser.

2.1.6 GAIN SPECTRA AND THRESHOLD CURRENT

The Bernard Duraffourg condition tells us that the quasi-Fermi level splitting has to be greater than the transition energy for there to be net positive gain. When a semiconductor is pumped into a non-equilibrium state, carriers with energy in excess of the quasi-Fermi level will not satisfy this condition. Fig(2a) shows the typical form of the gain spectra for a laser pumped into a non-equilibrium state. The gain is very much dependent on the transition energy between successive states making up the conduction and VB, a quasi-continuous series of two level states. The gain becomes negative (absorption) at energies greater than the quasi-Fermi level splitting. Here the population of carriers is insufficient to satisfy the conditions for net positive gain. At low energy, equal to the bandgap the gain becomes zero because there are no states in the forbidden bandgap.

As the laser is pumped harder the peak gain will eventually satisfy the lasing condition. In the absence of nonradiative processes the current density needed to maintain the carrier density to generate this threshold gain is the threshold current density. It therefore useful to know the relationship between peak gain and injection current. The total current going into radiative processes is proportional to the total spontaneous emission rate, Equation 2-25. Fig(2b) shows the typical form of the variation of peak gain with current. At low gain values the gain can be approximated to vary linearly with current. This can be expressed as [55].

\[ g = \beta (J_{rad} - J_n) \]

Equation 2-18

Where, \( \beta \) is the linear gain coefficient and \( J_n \) is the current at zero gain. This can be equated with the threshold gain condition in Equation 2-6 to give an expression for the threshold current density [56].
\[ J_{in} = \frac{J_0}{\eta} + \frac{1}{\eta \Gamma \beta} \left( \alpha + \frac{1}{L} \ln \left( \frac{1}{R} \right) \right) \]

Equation 2-19

Where, \( \eta \) is the quantum efficiency taking account of the number of carriers going into radiative transitions, and \( \Gamma \) is the optical confinement factor of the propagating mode, the fraction of the optical field that coincides with the gain medium.

2.1.7 GAIN SATURATION

The gain/current relation does not remain linear indefinitely. As the quasi-Fermi levels move into the bands with increasing pumping the occupation probability, given by the Fermi-Dirac functions Equation 2-7 and Equation 2-8, of carriers at the band edge rapidly approaches 1. Thus the increase in gain at a particular photon energy for a given increase in injected carrier density is steadily reduced. The gain/current characteristic roll over and the gain becomes saturated. Large optical losses can push a laser into a region of gain saturation and thereby increase its threshold current.

2.2 ENERGY BANDS IN SEMICONDUCTORS

In general there will be a continuous variation of the electron or hole energy with wavevector, \( k \), in the CB or VB. The derivation of this \( E \) vs. \( k \) relationship is complex but is often approximated to be parabolic [57].

\[ E_{c,v} = \frac{\hbar^2 k^2}{2m_{c,v}} \]

Equation 2-20

Where the subscript \( c \) or \( v \) refers to the electron CB or hole VB dispersion respectively and, \( \hbar \), is the reduced Planck's constant. The mass, \( m \), is the effective mass of the carrier.

Fig(3), shows a typical \( E \) vs. \( k \) diagram for a bulk, unstrained III-V semiconductor. At \( k=0 \) a minimum in the CB and a maximum in the VB can be seen. This is known as the \( \Gamma \) point. At large \( k \) values and depending on the crystallographic direction, two extra satellite minima, \( X(100) \) and \( L(111) \) are seen in the CB. The difference in
Fig(3) Shows a representation of the band structure of a typical semiconductor. Here the energy of the allowed electron and hole states is plotted against their wavevector, a measure of the particle's momentum, in a particular crystallographic direction. Several important features are observed. In the conduction band dispersion three distinct energy minima at $\Gamma$, L, and X, are observed for different $k$-values. The valence band dispersion consists of three distinct bands, the heavy hole (HH), light hole (LH) and spin split off (SO) bands. The bandgap of a semiconductor is equal to the energy difference between the VB maxima and each of the CB minima. If the $\Gamma$ minima is lowest in energy then the bandgap is direct. Alternatively the bandgap is indirect if the L or X minima are lowest conduction band minima. Direct or indirect minima play an important role in optical transitions.

Fig(4) Shows the effects of quantum confinement on the electron wave functions. Modern growth techniques allow the fabrication of thin layers of material ~100Å, a thickness of the order of the de Broglie wavelength of the electron. The difference in bandgaps between different semiconductor compounds presents a energy discontinuity in the conduction and valance band edges that can form a potential well. Carriers residing in the well experience the effects of quantum confinement and the movement in the growth direction is constrained. The allowed electron energy bands become quantised in the growth direction whilst remaining continuous for each quantised level in the plane of the layer.
energy between the lowest CB minimum and the VB maximum is equal to the fundamental bandgap of the semiconductor. If the fundamental bandgap stems from either the X or L satellite minima then the semiconductor is an indirect bandgap semiconductor, such as Si, GaP or AlAs. Otherwise, if the fundamental bandgap occurs between the \( \Gamma \) points of the CB and VB then the semiconductor has a direct bandgap, such as GaAs or InAs.

Optical transitions do not occur between the satellite L or X minima and the VB maximum because both energy and momentum (\( \pm k \)-vector) conservation must be considered in the transition. The momentum given to the photon in an optical transition is small in comparison to the difference in momentum between the electron in the satellite minimum and hole in the VB maximum. Therefore indirect bandgap semiconductors make poor electroluminescent devices.

2.2.1 QUANTUM CONFINEMENT

Modern growth techniques such as MOVPE and MBE have allowed the growth of high quality layers of material <0.1\( \mu \)m thick. If a narrow bandgap material is sandwiched between a material with a larger bandgap then a step-like discontinuity in the conduction and VB edges can be seen and a potential well is formed, fig(4). If the thickness of the layer material is of the order of the de Broglie wavelength of the electron or hole, then the momentum of the carriers in the z-direction take on discrete quantised values and a quantum well is formed. The carriers are constrained in the z-direction whilst being free to move in the plane of the potential well. The carrier motion becomes "two dimensional" in nature.

In the limiting case of an infinitely deep QW, the wave function of the carrier cannot penetrate the barrier. A node of the wavefunction in the well must coincide exactly with the barrier well interface. The wavelength in the z-direction is equal to \( 2L_z/\pi \) \( n \), where \( n \) is an integer and \( L_z \) is the width of the well. The energies of the confined states relative to the bottom of the well (\( E=0 \)) are then given by \([58]\).
\[ E_n = \frac{n^2 \hbar^2}{8mL^2} \]

where \( m \) is the effective mass of the confined carrier and \( \hbar \) is Planck's constant.

As the well width is increased towards infinity the energy difference between the confined states becomes smaller and approaches a continuum of states as in a bulk three dimensional carrier distribution.

2.2.2 DENSITY OF STATES (DOS)

The energy bands of a semiconductor are formed from quasi-continuous allowed energy states separated by energy gaps corresponding to regions of forbidden energy states. The density of allowed states, in a given band per unit volume, is of interest from the point of view of band filling by injected carriers. The larger the density of states in a given band the greater the carrier density can be in a given energy range. Thus a greater carrier density will be needed to reach a condition of population inversion and generally the greater the threshold current of the laser. It is also advantageous to lower the DOS away from the lasing transition. This can be achieved with the quantised energy states of a QW.

The distribution of electronic states can readily be seen to depend on the dimensions of the crystal, fig(5). In a bulk three dimensional sample, all the available \( k \) states, less than some value \( k \), are bounded by a sphere or radius \( k \). If one of the crystallographic dimensions is reduced to the order of the de Broglie wavelength of the electron in the crystal, \( \sim 0.1 \mu m \), then the distribution of electronic states becomes two dimensional, as in a quantum well. The available \( k \) states, less than some value \( k \), now lie in a circular plane of radius \( k \). The reduction of a second dimension to less than \( 0.1 \mu m \) will result in a linear one dimensional distribution of states or a quantum wire. If all three dimensions are reduced then the distribution of electronic states will take on the form of a classic "particle in a box" type problem, or a quantum dot.
The DOS can be shown to vary as the square root of carriers energy in a three dimensional system [59].

\[ n(E) = \frac{V}{8\pi^3} \left[ \frac{2mn}{\hbar^2} \right]^{\frac{1}{2}} \sqrt{E} \]

Equation 2-22

Where \( V \) is the volume of the semiconductor. In a two dimensional system such as a QW the DOS can be shown to be independent of energy [59].

\[ \rho(E) = \frac{Am}{2\pi\hbar^2} \]

Equation 2-23

Where \( m \) is carrier effective mass, \( \hbar \) is Planck’s constant and \( A \) is the area covered by the QW well.

The DOS in a two dimensional system forces a peak in the carrier density at the band edge, whereas the peak in the carrier density occurs away from the band edge in a three dimensional bulk sample.

### 2.2.3 DENSITY OF STATES, TRANSPARENCY AND QW’S

The density of states and quantum confinement have a profound effect in governing the magnitude of the transparency carrier density. Fig(6) shows the transparency carrier distributions in the CB and VB for three different situations: a) the bulk material with equal conduction and valence band densities of states b) QW material with equal conduction and valence band density of states and c) QW material with asymmetric conduction and valence band density of states, the situation encountered in most semiconductor compounds. In cases a) and b) we see that the quasi-Fermi levels coincide with the band edge at transparency in accordance with the Bernard-Durrafourg condition. The carrier population in a given band is governed by the position of the quasi-Fermi level relative to the band edge. Equation 2-7 and Equation 2-8. For a given effective mass and assuming a charge neutrality condition the transparency carrier densities are roughly similar in the bulk and QW cases.
Fig(5) Illustrates the density of states as a function of energy for a bulk 3-dimensional system and a quantum confined 2-dimensional system. The effect of reducing one of the dimensions to the order of the de Broglie wavelength is to constrain the motion of the carriers within the plane of the layer. This leads to the change from a continuous to a step-like DOS as shown. The 2-dimensional DOS is independent of energy for a given confined state.

Fig(6) Shows the effect of the DOS on the transparency condition in a semiconductor laser. Three different cases are considered, a) bulk material, b) a QW and c) a QW with asymmetric DOS. At transparency the quasi-Fermi level splitting is equal to the bandgap and can be seen to coincide with the band edges in case a) and b). However in case c) the asymmetry in the valence band density of states pushes the quasi-Fermi levels towards the band with the smaller DOS. Assuming the effective masses are similar in cases a) and b) then the injected carrier densities are roughly equal. However the order of magnitude decrease in the volume of the QW leads to an order of magnitude reduction in the transparency current needed to maintain the injected population. Assuming the conduction band DOS to be the same in all cases then the transparency carrier density is greatest in case c). The transparency carrier density and hence the threshold current may therefore be minimised by moving to a system with symmetrical DOS.
However the order of magnitude decrease in volume from bulk to QW means that the current density needed to maintain a given carrier population is expected to be an order of magnitude less in the QW [60].

The fig(6c) we see that the asymmetry in the DOS shifts the quasi-Fermi levels towards the band with the smaller density of states, given charge neutrality in the QW. Higher energy states will be filled in the band with lower DOS than in the band with higher DOS. Assuming that the conduction band DOS are the same in examples b) and c) then the CB carrier density at transparency is greater in case c) than case b), as the quasi-Fermi level is pushed deeper into the band. The overall transparency carrier density must be greater in case c) than b) as we have charge neutrality.

In summary the transparency carrier density is expected to be reduced by an order of magnitude by changing from a bulk to a QW regime. This is because of the order of magnitude reduction in active volume between the bulk and a QW. Furthermore the transparency current density can be minimised by having a symmetrical DOS in the B and VB. This situation may be approached through the application of compressive strain in a QW.

2.4 STRAIN

The properties of a semiconductor laser are in many ways governed by the VB structure. Strain incorporated in a thin layer grown on a substrate, such as a QW, provides a convenient method of engineering the VB structure hence improving the sing characteristics of a device. The lattice mismatch between a grown layer and substrate will result in that layer adopting the lattice constant of the substrate. Therefore it will undergo biaxial distortion in the plane of the layer and, through Poisson's ratio, the opposite uniaxial distortion in the growth direction of the layer. In thick enough layer the strain energy will be sufficient to nucleate misfit dislocations and the strain will tend to relax. These misfit dislocations act as nonradiative combination centres which will increase the threshold current of the laser [61]. However in a thin enough layer the energy stored in the strained lattice is insufficient to nucleate a misfit dislocation and the strain cannot relax. There is a critical strain
thickness product under which the layer may remain stable. The strain thickness product may be calculated from the method of Matthew’s and Blakeslee [62] or People and Bean [63], by considering a balance between strain energy and minimum energy to induce misfit dislocations. A typical rule of thumb for the strain thickness product is of the order of 150-200 Å% [64]. A further discussion of the critical thickness in InGaAs/AlGaAs and GaAsP/AlGaAs layers is given in chapter 5. Typical strained layers used in lasers tend to be of the same thickness as a QW.

Strain acts to break the symmetry of the cubic zinc blend lattice at the Γ point. The HH and LH valence band and the conduction band E vs. k dispersions result from the interaction of the electron s-like and hole p-like wave functions with the periodic potential of the crystallographic planes in the crystal. In an unstrained sample the periodicity of the crystallographic planes is the same in the growth direction as in the plane of the layer i.e. the crystal is approximately isotropic. Therefore the VB is degenerate at the Γ point, fig(7b). Strain makes the crystal anisotropic and lifts the degeneracy of the VB.

If the natural lattice constant of the layer is larger than that of the substrate then the layer is forced to adopt the smaller lattice constant of the substrate. The layer undergoes biaxial compression in the plane of the layer and uniaxial extension perpendicular to the plane of the layer. The layer is said to be in a state of compressive strain. Conversely if the natural lattice constant of the layer is smaller than that of the substrate then the layer is forced to adopt the greater lattice constant of the substrate. The layer undergoes biaxial extension in the plane of the layer and uniaxial compression perpendicular to the layer. The layer is said to be in a state of tensile strain.

2.2.4.1 COMPRESSIVE STRAIN (001)

The anisotropy of the crystal is reflected in the VB. In the compressive regime the highest energy VB becomes LH-like in the plane of the layer (x,y-direction) and HH-like in the growth direction (z-direction). The lowest energy valence band becomes HH-like in the plane of the layer and LH like in the growth direction, fig(7a). In a QW the confined energy is governed by the mass in the growth direction whilst the DOS is
governed by the effective mass in the plane of the layer. The degeneracy of the valence band is naturally split in a unstrained QW due to the difference in VB effective masses. The HH band is more deeply confined than the LH band. Compressive strain will act to exacerbate this splitting by increasing the energy of the HH(z) band with respect to the LH(z) band. Moreover the HH(z) deepest confined state is LH-like in the plane of the layer. Thus the DOS of the valence band can be reduced. Thus we may approach our ideal limit of matching the DOS of the CB and VB, section 2.2.3, and so reduce the transparency carrier density with increasing compressive strain.

2.2.4.2 TENSILE STRAIN (001)
In a tensile-strained layer the highest energy VB becomes HH-like in the plane of the layer and LH-like perpendicular to the layer. Conversely the lower energy VB is LH-like in the plane of the layer and HH-like in the growth direction. fig(7c). In a QW this has the effect of increasing the LH(z) confined state with respect to the HH(z) confined state. Initially the HH(z) band will still be more deeply confined than the LH(z) band due to it heavier effective mass. Eventually the strain induced shift in the HH(z) and LH(z) valence bands will be sufficient to re-establish degeneracy and the HH(z) and LH(z) bands will crossover. Further tensile strain will make the LH(z) state more deeply confined than the HH(z) state making the fundamental transition change from EcI-HH(z)1 to EcI-LH(z)1. The in-plane effective mass of the deepest confined state becomes HH-like. Therefore the DOS is now governed by the HH in-plane effective mass so there will be more asymmetry between the DOS of the CB and VB than is seen with compressive strain. However the DOS is still smaller than expected with degenerate a VB at the HH(z)/LH(z) crossover.

2.2.4.3 TE AND TM GAIN
Strain also has a noticeable effect on improving the gain of the laser. This can be seen by considering the spatial components of the valence band wave functions at the band edge. The VB Bloch functions may be expressed in terms of three basis function each having the same symmetry as p-orbitals. These can be written in terms of linear combinations x, y and z components. In the case of a layer grown on an 001 orientated
substrate the xy-direction is in the plane of the layer whilst the z-direction corresponds to the growth direction. These basis functions are given below [39].

\[
U_{HH} = \frac{1}{\sqrt{2}} \left( U_x + i U_y \right) \quad \Rightarrow \quad \bar{U}_{HH} = \frac{1}{\sqrt{2}} \left( \bar{U}_x - i \bar{U}_y \right)
\]

\[
U_{IH} = \frac{1}{\sqrt{6}} \left( U_x + i U_y - 2 U_z \right) \quad \Rightarrow \quad U_{IH} = \frac{1}{\sqrt{6}} \left( U_x + i U_y - 2 U_z \right)
\]

Equation 2-24

In fig(7d) the TE and TM polarizations are related to the x, y and z-axis for a broad area laser grown on an 001 orientated substrate. The polarization of a photon emitted through electron hole recombination, may be related directly to the spatial components of the VB Bloch functions, described above Equation 2-24.

In the case of an unstrained bulk laser or the tensile-strained QW laser at the HH(z)/LH(z) crossover, the degeneracy of the HH and LH bands at the zone centre means that the VB maximum has equal contributions from x, y and z-like states. A radiative transition has equal probability of originating from an x, y or z-like orbital. Thus the measured radiation will be randomly polarized. For any given laser cavity one polarization is useless. This also means that only a third of injected carriers will contribute to any given polarization.

The application of compressive strain shifts the HH(z) confined state up in energy relative to the LH(z). The fundamental transition is now E1-HH(z). From Equation 2-24, the HH band has no z-like character but equal x and y-like character. Half of all injected carriers contribute to the TE polarization, light polarized in the y-direction whilst the other half produce photons polarized in either the x-direction or the z-direction which do not contribute to lasing. fig(7d). TE gain is enhanced with respect to the unstrained case. Conversely the application of tensile strain shifts the LH(z) quantum confined state up in energy relative to the HH(z). The fundamental transition is now E1-LH(z). From Equation 2-24 the LH state has 2/3 z-like character for small strains, thus 2/3 of recombination events produce TM polarized photons. Those polarized in the z-direction. There is also a coupling between the LH and spin split off states under biaxial strain. This can be shown to enhance the z-like character still.
Fig(7) Shows the effect of biaxial strain on the band structure of a semiconductor grown on an 001 orientated substrate. The shifts in the HH and LH band edges depend on the crystallographic direction. The asymmetry in the valence band dispersion acts to lighten the effective mass in the plane of a QW, reducing the valence band DOS, making it more symmetrical with the conduction band DOS. This effect is stronger in the compressive regime than the tensile. However, the enhancement of the TM gain in the tensile regime is stronger than the enhancement of the TE gain in the compressive. In general, strain acts to reduce the radiative current needed for threshold.

Fig(8) Shows the effect of externally applied hydrostatic pressure on the band structure of a typical semiconductor. The direct bandgap increases with pressure at a rate of around 10 meV/kbar whilst the X and L bandgaps decrease at 2 meV/kbar and increase at 4 meV/kbar respectively. This modification in bandstructure with pressure provides a convenient method of simulating compositionally different semiconductor compounds.
further with increasing tensile strain [39]. The TM gain is enhanced in favour of TE gain. This is the advantage of tensile strain. Although the reduction in the valence band DOS is not as marked as in the compressive regime the enhancement of the TM has a greater effect in reducing the transparency carrier density than compressive strain.

2.2.5 HYDROSTATIC PRESSURE
Externally applied hydrostatic pressure causes a symmetrical three dimensional reduction in the lattice constant of the crystal. This three dimensional distortion increases the mixing between bonding p-like and antibonding s-like orbitals that are associated with the VB and CB states, respectively. Hence the energy of these states increases, the antibonding states increasing in energy faster than bonding states. This has the net effect of increasing the direct bandgap of the semiconductor, typically at a rate (pressure coefficient) of around 10meV/kbar [65]. The L and X satellite CB minima can also be induced to change. The L bandgap is seen to increase at 4-5 meV/kbar [65] whilst the X bandgap is seen to reduce at 2meV/kbar [65]. This is illustrated in fig(8). Thus the use of externally applied hydrostatic pressure is a convenient method for simulating compositionally different semiconductors by varying the bandgap of the material.

2.3 RECOMBINATION PROCESSES
Band to band recombination processes will govern the magnitude of the current flowing into the laser. These can be divided into radiative and nonradiative processes, those that give light and those that do not.

2.3.1 RADIATIVE RECOMBINATION
The useful current flowing into a laser can be considered as the total current that contributes to radiative recombination processes. This is often expressed as the total current going into spontaneous emission. The total spontaneous emission rate per unit volume is equal to the integral of the spontaneous emission rate per unit energy over all transition energies. Thus the radiative current density is written as [66].
\[ J_{\text{nat}} = qd \int R_{\text{spont}}(E) dE \]

Equation 2-25

Where \( q \) is the fundamental electronic charge, \( d \) is the thickness of the active region and \( R_{\text{spont}}(E) \) is the spontaneous emission rate per unit volume per unit energy. Under conditions of charge neutrality and in the Boltzmann regime the radiative current may be written as [66].

\[ J_{\text{nat}} = qVBn^2 \]

Equation 2-26

Where \( B \) is the radiative recombination coefficient, \( V \) the active volume and \( n \) is the carrier density. This reflects the two body nature of the radiative recombination process.

### 2.3.2 NONRADIA TIVE RECOMBINATION LOSS MECHANISMS

Injected electron hole pairs may recombine nonradiatively across the bandgap, that is without the emission of a photon. Such recombination events do not contribute to the emission spectrum that is amplified to lasing. The total rate of nonradiative recombination can be seen as a current in parallel to the useful radiative current. Nonradiative recombination across the bandgap contributes to the self heating of a semiconductor device as the bandgap energy is dissipated in the form of phonons or a highly energized third carrier as in an Auger event, which is followed by phonon emission. Nonradiative processes may also be highly temperature sensitive thus causing the threshold current to be temperature sensitive. Two major nonradiative recombination mechanisms are typically seen in semiconductor lasers Auger recombination [67] and Shockley Read [68] Hall [69] or monomolecular recombination.
2.3.3 SHOCKLEY, READ HALL RECOMBINATION

Electron hole recombination may take place via localised energy state or traps that exist in the forbidden energy gap. Because the transition probability depends on the energy difference between conduction and VB these intermediate states can substantially enhance the probability of recombination. The source of these trap states are numerous but are generally associated with crystallographic defects and contaminant atoms in the semiconductor. The energy of these states can be measured by Deep Level Transient spectroscopy (DLTS). For example AlGaAs system is well known to have numerous traps associated with oxygen reacting with the aluminum in the material. Such traps have been measured by [70] and their effect on increasing the threshold current on AlGaAs based laser demonstrated by [71].

The probability of recombination through traps can be seen through the net result series of capture and emission of carriers between trap states and the CB and VB. States near the middle of the bandgap are most likely to influence the recombination rate as the probability of an electron being re-emitted from the trap to the CB after capture is equal to the probability of the electron recombining with a hole by jumping from the trap to the VB.

The electron or hole lifetime, $\tau_{n,p}$, may be expressed in terms of the average thermal velocity of the carriers, $v_{th}$, the electron or hole capture cross section $\sigma_n$ or $\sigma_p$ and the density of traps $N_t$, [72].

$$\tau_{n,p} = \frac{1}{v_{th} \sigma_{n,p} N_t}$$

Equation 2-27

Thus the total recombination rate or monomolecular recombination current is proportional to the carrier density, $n$, divided by the carrier lifetime. Thus.

$$I_{nr} = \frac{qVN}{\tau}$$

Equation 2-28
Here q is the fundamental electronic charge and V is the active volume within which all recombination events occur.

2.3.4 SURFACE RECOMBINATION

The abrupt discontinuity in the crystal structure at a surface leaves a large number of dangling bonds. These act in a similar manner as above and cause a large number of localised interbandgap energy states through which nonradiative recombination can occur. The recombination rate may also be modelled as above. In practice the contributions from both Shockley Read Hall recombination and surface recombination can be combined in a single nonradiative lifetime.

2.3.5 AUGER RECOMBINATION

Electron hole recombination may occur with the energy of the transition being given to a third carrier rather than a photon. Because of the need to satisfy both energy and momentum conservation the transition probability is dependent on the shape of the VB structure. Many types of Auger processes can occur in semiconductor. however two types will be discussed here to illustrate the general behaviour of Auger recombination with bandgap. These are illustrated in fig(9). The nomenclature for Auger processes is as follows. C indicates the conduction band. H the heavy hole band and S the spin-split-off band. In the direct CHCC process the electron and HH can recombine to excite an electron higher into the CB. The change in momentum in recombination across the bandgap is reflected in the change in momentum of the excited electron. In the CHSH process, the energy and momentum in the recombination are transferred to excite an electron from the spin-split-off band to the HH band.

Auger recombination is a three carrier process thus in an undoped sample the Auger current is proportional to the cube of the carrier density. The total Auger current can be approximated by [73].
\[ J(T)_{\text{Auger}} \propto C(T)n^3 \]

Equation 2-29

Where \( C(T) \) is the Auger coefficient which may be written in the form [73].

\[ C(T) = C_0 \exp \left( \frac{-E_a}{kT} \right) \]

Equation 2-30

where, \( k \), is Boltzmann’s constant, \( T \), the temperature and \( E_a \), is the activation energy of the process. The activation energy can be shown to be related to energy vs. wavevector dispersion and reflects the need to conserve both energy and momentum in the transition. Assuming a parabolic band approximation Equation 2-20, and Boltzmann’s statistics, the activation energies of the various Auger processes can be written as.

\[ E_a(CHCC) = \frac{m_e E_g}{m_e + m_{HH}} + E_g \]

Equation 2-31

and

\[ E_a(CHSH) = \frac{m_{so}(E_g - \Delta_s)}{(2m_{HH} + m_e - m_{so})} + E_g \]

Equation 2-32

Where, \( m_e \), is the CB effective mass, \( m_{HH} \), is the HH mass, \( m_{so} \), is the spin split off band mass, \( E_g \), is the bandgap and \( \Delta_s \), is the spin orbit splitting. It is apparent from these equations that the activation energy can be increased by increasing the bandgap. The shortening of the lasing wavelength to 749-980nm, the lasing wavelength of the devices used in this thesis, should effectively quench the Auger rate in these devices, especially given the exponentially activated nature of the process. However it is stressed that Equation 2-31 and Equation 2-32 represent a simplification of the Auger activation energy. The strong nonparabolic nature of the bands in a semiconductor make calculation of the exact Auger rate difficult.
Fig (9) Shows two possible band to band Auger recombination processes that can occur in semiconductor compounds. In each case an electron may recombine with a hole giving up both energy and momentum to a third carrier. Auger processes are therefore nonradiative and act to reduce the quantum efficiency of optoelectronic devices. The need to conserve both energy and momentum in a transition means that Auger processes are sensitive to the E vs. k dispersion. Increasing the bandgap makes it harder to find a state into which to eject the third carrier, that will satisfy both energy and momentum conservation. Therefore Auger recombination is also expected to reduce with increasing bandgap.

Fig (10) Illustrates the IVBA process in a semiconductor. The energy difference between the SO band and the heavy hole HH band increases with the wavevector k, due to the lighter effective mass of the SO band. Therefore the possibility exists of exciting an electron with a photon emitted at the lasing wavelength from the SO to the HH band at some wavevector, k. IVBA represents a optical loss process that can curtail the performance of semiconductor lasers. However the probability of finding a hole in the HH decreases as the wavevector increases. Matching the effective masses of the HH and SO bands means that IVBA can only occur for carriers at large k values, thereby reducing the probability of absorption. The effective mass can be reduced with strain. This has proved an effective way of reducing the effects of IVBA in long wavelength lasers.
2.3.6 INTERVALENCE BAND ABSORPTION

Photons may be absorbed by promoting an electron in the spin split off band into the HH band. This occurs at a k-value such that the energy difference between the SO and HH bands is equal to the lasing photon energy. This is illustrated in fig(10a). The result is that more carriers have to be injected to make the photon generation rate exceed the absorption rate to achieve lasing. The energy difference between the HH and SO bands equivalent to the lasing photon energy is moved to large k values with increasing fundamental bandgap. The probability of finding a hole in the HH band at these large k values in which to promote an electron from the SO band is reduced. For parabolic bands the energy at which IVBA occur, \( E_{\text{IVBA}} \), can be written as:

\[
E_{\text{IVBA}} = \frac{m_w (E_x - \Delta_n)}{(m_{\text{HH}} - m_w)}
\]

Equation 2-33

Thus IVBA is expected to decrease with increasing bandgap or decreasing HH mass. IVBA would be impossible when the HH mass equals the spin split off mass. Strain is expected to reduce the HH mass thus increasing the curvature of the HH band. This has the effect of increasing the k vector at which IVBA occurs, fig(10b). A corresponding reduction of IVBA is also expected with strain. The variation of external efficiency as a function of hydrostatic pressure in bulk, unstrained QW and strained QW 1.5\( \mu \)m lasers has been measured [40]. The increase in efficiency with pressure for bulk and unstrained QW devices is consistent with the removal of IVBA. However the efficiency of both tensile and compressively strained QW devices is relatively pressure insensitive indicating that IVBA is insignificant in these lasers. The reduction of IVBA from unstrained to compressively strained 1.5\( \mu \)m lasers has been independently measured by Fush et al [43] and Joindot et al [44]. Thus tensile and compressive strain has been shown to reduce IVBA in 1.5\( \mu \)m lasers.

2.3.7 TOTAL RECOMBINATION CURRENT

The total current flowing in the semiconductor laser may be expressed in terms of the sum of the various recombination currents that occur in a particular device. Expecting
no more than a three body process the total injection current can be modelled as a cubic equation of carrier density [74].

\[ J = qV(An + Bn^2 + Cn^3) \]

Equation 2-34

From our previous discussions of recombination mechanisms we may associate each power term with a given recombination process. Thus \( An, \) Equation 2-28, is the contribution from Shockley Read Hall type processes, \( Bn^2, \) Equation 2-26, is the contribution from radiative processes and \( Cn^3, \) Equation 2-29 comes from Auger recombination. IVBA, though not a recombination process, will act to increase the overall carrier density required for lasing and therefore the total recombination current.
CHAPTER 3

3. HETEROJUNCTIONS AND DEVICE MODELLING

3.1 INTRODUCTION

The mechanics of the operation of semiconductor lasers may be understood from the point of view of the recombination dynamics of the electron and hole populations injected into the active regions of the laser. This was the viewpoint presented in the previous chapter. However, a knowledge of the carrier injection dynamics in a heterojunction device may also contribute to the understanding of the operation of the semiconductor laser. This subject is discussed in this chapter. The operation of a multilayered heterojunction device, comprising of barrier, cladding and quantum well regions, may be understood from the operation of the fundamental heterojunctions that occur at the interface between each layer in the device. Therefore the operation of a simple two step pn heterojunction is initially discussed.

As a voltage is applied to forward bias the junction the exact balance between the drift and diffusion currents flowing across the junction is changed. A net excess of diffusion current is then free to flow across the junction. These diffusion currents form the source of the injected carrier populations in the active region of the lasers. In the pn heterojunction the carrier injection can be shown to be dominated from the wider bandgap side of the material.

An evolutionary advance in the technology of the semiconductor laser was made with the use of a double heterostructure device, originally suggested by Kroemer et al [15]. Such lasers consist of a narrow bandgap layer sandwiched between two wider bandgap layers. The narrow bandgap active layer is usually lightly doped compared to the wider bandgap, p or n cladding layers. Thus, under forward bias, carrier injection is dominated by carriers flowing from the wider bandgap material into the narrower bandgap material. Therefore the non-equilibrium concentration of electrons and hole needed for lasing can build up in the narrow bandgap active layer. Carrier flow across
the active layer is impeded by the sharp discontinuity in the conduction and valence band edges seen at the interface between the layers, arising from the difference in their bandgaps. This discontinuity acts to confine the injected carrier population within a well defined active region and has been instrumental in the marked reduction in the threshold current density in this class of lasers.

The voltage applied across a double heterojunction device is divided by some unknown ratio between its two composite heterojunctions. Two approaches may be adopted in understanding the overall injection from each junction.

Simple assumptions about the Fermi level alignment in the cladding regions and the quasi-Fermi level splitting in the active region may be made. The quasi-Fermi level splitting can be assumed to be equal to the voltage appearing across the whole double heterostructure. This model, though simplistic allows the possibility of understanding the pumping of the laser and the carrier confinement by the heterobarriers (discussed chapter 6), through the measurement of the laser diodes current voltage characteristics. The detail of how to do this is elaborated on in chapter 4. Furthermore other authors [75] have used similar models to calculate the injected carrier densities under conditions of charge neutrality in the laser. With this knowledge the threshold conditions in the laser may be modelled.

A further more complex method assumes that carriers will flow throughout the structure until Poisson’s equation is satisfied. An overview of the numerical solution of Poisson’s equation to find the injected carrier density throughout the laser is presented. Such an approach was used by Menea [76] to model the strain, pressure and temperature dependence of the threshold current of some of the lasers studied in this thesis, as described in chapter 6.

3.2 HETEROJUNCTIONS UNDER FORWARD BIAS

A semiconductor laser diode is made up from a series of heterojunctions of varying layer thickness and doping density. The electrical characteristics of a pn heterojunction may be understood analytically [77]. As the junction is formed and under conditions of no externally applied electric field, the abrupt concentration discontinuity due to the
Fig(1) Illustrates the behaviour of a heterojunction under forward bias. At zero bias the discontinuity between the equilibrium carrier concentrations arising from the difference in doping between the n and p-side of the junction leads to diffusion currents which flow across the junction. The migration of these carriers leave unsatisfied donor and acceptor sites around the vicinity of the junction. The net space charge due to this depletion region creates a drift current that counters the diffusion of carriers across the junction. The depletion region will grow until no net current flows. Under forward bias the drift current is reduced with respect to the diffusion current. Thus a net current can flow across the junction. The source of this current can be seen in the build up of minority carriers at the edges of the depletion regions. The diffusion of these carriers away from the depletion region, into the doped regions can be used to model the current voltage characteristics of the junction, equation 3-3 & 3-4. In a heterojunction device the current flowing across the junction is dominated by the carriers injected from the wider bandgap material.
doping in the n and p regions gives rise to the diffusion of carriers from the n-side to the 
p-side and visa versa, fig(1). The migration of charge across the junction leaves charged 
 donor and acceptor sites either side of the junction. The space charge of this depletion 
region creates an electric field gradient that counters the diffusion of the free charge 
carriers. Thus the depletion region will grow until there is sufficient electric field to 
exactly counter the diffusion of free carriers. Hence no current will flow across the 
junction at zero bias. Under forward bias the potential energy of the n-side of the 
junction is raised with respect to the p-side. This reduces the extent of the space charge 
region thereby reducing the electric field that counters the diffusion of carriers. Carriers 
in the doped regions see a reduced electrostatic potential barrier and an enhanced 
diffusion gradient that allows them to flow across the junction. Carriers that have 
completely migrated across the depletion region against the electric field gradient will 
diffuse away into the neutral doped regions. The electrical characteristics of a pn 
junction may be described in terms of these electron and hole diffusion currents. A full 
derivation of the carrier flow across a pn junction is given in Sze [78]. Assuming 
Boltzmann-like carrier distributions, the minority carrier concentrations, \( n_p \) and \( p_n \) at the 
edge of the depletion region may be written in terms of the applied voltage \( V \).

\[
n_p = n_{po} \exp\left(\frac{-qV}{kT}\right) \tag{3-1}
\]

and

\[
p_n = p_{no} \exp\left(\frac{-qV}{kT}\right) \tag{3-2}
\]

Here \( n_{po} \) an \( p_{no} \) are the minority carrier concentrations at the edge of the depletion region 
at thermal equilibrium. Assuming that recombination processes in the depletion region 
are zero the current flowing across the junction may be expressed entirely in terms of the 
diffusion of these carriers away from the depletion region. The electron and hole 
diffusion currents can be written as.
\[ i_n = \frac{-qD_n n_{po}}{L_n} \exp\left(\frac{qV}{kT} - 1\right) \]

Equation 3-3

and

\[ i_p = \frac{qD_p p_{mo}}{L_p} \exp\left(\frac{qV}{kT} - 1\right) \]

Equation 3-4

Here \( D_n \) and \( D_p \) are the minority carrier diffusion coefficients for electrons and holes respectively and \( L_n \) and \( L_p \) are their diffusion lengths. The minority carrier concentrations at thermal equilibrium may be expressed in terms of the bandgap of the material, \( E_g \), and the CB and VB band density of states, \( N_c, N_v \) respectively.

\[ n_{po} = \sqrt{N_c N_v} \exp\left(\frac{E_g}{kT}\right) \]

Equation 3-5

The action of the heterojunction in carrier injection can be seen by taking the ratio of the electron and hole diffusion currents. Equation 3-3 and Equation 3-4 and the equilibrium carrier density Equation 3-5. This ratio is written as.

\[ \frac{i_n}{i_p} = \frac{D_n L_p N_0 N_{c1} N_{v1}}{D_p L_n P_0 N_{c2} N_{v2}} \exp\left(\frac{E_{g2} - E_{g1}}{kT}\right) \]

Equation 3-6

Where \( N_c \) and \( N_v \) refer to the density of states on either side of the junction. fig(1). \( N_0 \) and \( P_0 \) are the doping densities in the n and p regions respectively and \( E_{g1} \) and \( E_{g2} \) are the bandgaps of the materials that comprise the heterojunction. At room temperature \( 1/kT=39eV^{-1} \), the exponential term of Equation 3-6 dominates even for small differences in bandgap. This means that the diffusion current is dominated by majority carrier injection from the wider bandgap side into the narrower bandgap side.
3.3 DOUBLE HETEROSTRUCTURE DIODE
A simple double heterostucture diode forms the basis of the majority of modern semiconductor laser structures. This is formed when a narrow bandgap lightly doped or intrinsic active region is placed between two wider bandgap more heavily doped layers. Under forward bias the majority carriers are injected from the wider bandgap layers into the narrow bandgap active region, giving rise to a non-equilibrium electron and hole carrier concentration in the active region that pushes the diode towards lasing. In a DH device the bandgap discontinuity between the narrow bandgap active region and the wide bandgap cladding regions acts as a potential barrier to inhibit the diffusion of carriers away from the active region. If the width of the active region is made much smaller than the carrier diffusion length then the carrier concentration can be expected to vary very little across the width of the active region. In the lasers used in this study the width of the barrier and QW layers enclosed in the SCH is around 0.2μm. This can be compared with a typical diffusion length of around ~1μm [79-81]. As n(x) falls as exp(-x/L_n) the carrier concentration would be estimated to fall to ~82% of its original value after diffusing this length.

3.4 FERMI-LEVEL ALIGNMENT IN THE LASER
The variation of the Fermi level across the double heterostructure diode is illustrated in fig(2). As a voltage is applied across the diode the electrostatic potential of the electrons at the ohmic contact of the n-doped layer may be raised with respect to the electrons at the ohmic contact in the p-doped layer. Thus the difference in potential energy between the Fermi levels at the n and p-contacts is equivalent to the applied voltage. The large number of free charge carriers from the doping concentrations means that the potential difference cannot be maintained over the doped regions. Therefore the electric field is approximately zero in the doped regions and the bulk of one doped region are raised in potential with respect to the bulk of the other doped region, rather than just the contacts.
Fig(2) Shows a schematic representation of a double heterostructure (DH) diode under forward bias. As injection is dominated from carriers from the wider bandgap material, the non-equilibrium population of carriers required for lasing can build up in the narrower bandgap active region. The non-equilibrium populations of electrons and holes is described by two separate quasi-Fermi levels. The position of the Fermi levels in the doped regions may be assumed to be fixed with respect to the band edges due to the large concentration of ionized dopants. The width of the narrower bandgap active region, 0.1-0.2 μm, is typically less than the injected carrier diffusion length, 1 μm. To a first approximation the injected carrier density may be assumed to be invariant across this region. The quasi-Fermi levels describing their respective populations may then be regarded as flat across this region. The splitting of the quasi-Fermi levels is therefore reflected in the junction voltage of the device. The flow of injected carriers across the active region is impeded by the discontinuity in the band edges arising from the differences in the bandgaps between the layers. Such a heterobarrier is instrumental in improving the performance of these devices. A fraction of the injected population can leak over the heterobarrier. The simple alignment scheme for the quasi-Fermi levels allows the estimation of the unconfined carrier populations. This subject is explored in more detail in chapter 6.
The large number of free carriers in the doped region also means that the Fermi-level describing the majority carrier concentrations are effectively fixed with respect to the band edges. The difference between the Fermi levels in the doped regions is then equal to the applied voltage.

A discontinuity in the Fermi-level moving from the n to the p doped regions around the vicinity of the junction is expected. This discontinuity may be described by a pair of quasi-Fermi levels mirroring the non-equilibrium carrier populations flowing across the heterojunctions into the active regions. A continuous variation in the electric field and carrier concentration for carriers injected across the depletion regions into the active regions is expected. The quasi-Fermi level describing the injected population at the heterojunction interface is therefore expected to align with the Fermi level in the doped regions. As described above section 3.3, the injected carrier population is assumed invariant across the active region. The quasi-Fermi levels may also be assumed to be invariant or flat across the active region. Therefore the energy difference or splitting of the quasi-Fermi levels should reflect the voltage applied across the junction.

The Bernard-Durrafourg condition states that a net excess of stimulated emission is generated when the quasi-Fermi levels are greater than the fundamental bandgap. Lasing should then occur when the applied voltage is a little greater than the electrostatic potential difference of the conduction and valence band, the bandgap energy expressed in volts. This is demonstrated below, chapter 4.

A fraction of the carriers injected into the active region will have an energy in excess of the heterobarrier confining the injected population within the active region. These carriers can leak into the opposite doped region. Once these carrier enter the opposite doped regions they become minority carriers. As minority carriers their chances of recombination are greatly increased, therefore their population rapidly diminishes to equilibrium levels. Thus the quasi-Fermi level describing this minority carrier population will eventually join the Fermi level describing the equilibrium population in the doped region. The position of the quasi-Fermi level with respect to the band edge.
describing the leakage population at the heterobarrier interface, can be used to estimate an activation energy for the leakage process. This subject is expanded on in chapter 6.

The applied voltage appears across the whole device but it is not clear exactly how this voltage is distributed across the device. This problem is compounded by introducing more layers such as in a QW laser. This presents a problem in modelling lasers as it is often desirable to calculate the non-equilibrium injected carrier concentration when considering gain, radiative and nonradiative currents.

Assuming the Fermi level alignment described above the injected carrier concentration may be calculated. One approach is to assume that charge neutrality exists across the laser structure. In a three layer SCH quantum well laser we may equate the sum of the injected electron cladding, barrier and well densities with the hole cladding, barrier and well densities. This approach has been adopted by Balig et al [75] and is expressed as follows.

\[ n_{\text{well}} + n_{\text{barrier}} + n_{\text{cladding}} = p_{\text{well}} + p_{\text{barrier}} + p_{\text{cladding}} \]

Equation 3-7

Under certain constraints contributions from the outer layering regions become negligible. For example for a sufficiently deep QW the barrier and cladding injected carrier populations become insignificant.

3.5 POISSON’S EQUATION AND THE LASER STRUCTURE

Under forward bias the free carriers drift and diffuse through the laser structure until the charge distribution satisfies Poisson’s equation. The voltage applied to the contacts will vary in a continuous way across the structure giving rise to a unique carrier distribution. An analytical solution is impossible in all but the simplest cases. However it is possible to set a series of finite difference equation under which Poisson’s equation may be solved numerically. In a laser structure under forward bias the electric field distribution can be reduced essentially to a one dimensional problem. Poisson’s equation is written as.
Where $V(x)$ is the electrostatic potential as a function of distance $x$, $\rho(x)$ is the charge density and $\varepsilon$ is the dielectric permittivity which, in this case, is taken a being uniform throughout the laser. The second differential can be expressed as a finite difference given Poisson's equation in a discretised form.

$$\frac{d^2 V(x)}{dx^2} = \frac{-\rho(x)}{\varepsilon}$$  

Equation 3-8

The domain over which the solution is found, the laser structure, is divided into $N-1$ intervals corresponding to $N$ grid points. Of these two are boundary points which can be taken to be the potential at the contacts of the laser and $N-2$ are internal points where the solution is unknown. In order to solve the problem it is necessary to have $N-2$ equations besides the boundary conditions. Therefore Equation 3-9 must be written for each grid point in the domain of the solution. For a simple example consider a solution domain covered by five grid points. The first point $V(1)=V_1$ and last point $V(5)=V_N$ are taking to be boundary points. Equation 3-9 can be written as.

$$V(1) = V_1$$
$$V(1) - 2V(2) + V(3) = \frac{-\Delta x^2}{\varepsilon} \rho(2)$$
$$V(2) - 2V(3) + V(4) = \frac{-\Delta x^2}{\varepsilon} \rho(3)$$
$$V(3) - 2V(4) + V(5) = \frac{-\Delta x^2}{\varepsilon} \rho(4)$$
$$V(5) = V_N$$

Equation 3-10

Given the potentials, solutions to these discretised equations yield the charge density and potential at each point throughout the structure. The net charge density in a semiconductor is dependent on the relative ionized donor acceptor and free electron and hole densities at each point in the structure.
\[ p(x) = q(p(x) - n(x) + N_{\text{p}}(x) - N_{\text{n}}(x)) \]

Equation 3-11

Where \( n(x) \) and \( p(x) \) are the free electron and hole densities and \( N_{\text{p}}^{-} \) and \( N_{\text{n}}^{-} \) are the ionized dopant densities. For simplicity all the dopants may be considered to be ionized at room temperature. Therefore the ionized dopant density is equal to the dopant density. However the free charge densities also depend on the potential via the Fermi occupation function. Assuming Boltzmann-like carrier distribution and parabolic bands the free carrier densities are given by.

\[ n(x) = N_{\text{c}} \exp \left( \frac{F_{\text{c}} - E_{\text{c}}}{kT} \right) \]

Equation 3-12

\[ p(x) = N_{\text{v}} \exp \left( \frac{E_{\text{v}} - F_{\text{v}}}{kT} \right) \]

Equation 3-13

Where \( F_{\text{c}} \) and \( F_{\text{v}} \) are the quasi-Fermi levels for electrons and holes respectively. \( E_{\text{c}} \) and \( E_{\text{v}} \) are the conduction and valence band edges and \( N_{\text{c}} \) and \( N_{\text{v}} \) are the density of states in the conduction and valence bands. Equation 3-12 and Equation 3-13 can be substituted into Equation 3-11 which in turn can be substituted into Equation 3-9. This yields a set of nonlinear finite difference equations with three unknown variables. These are of the general form.

\[ V(i-1) - 2V(i) + V(i+1) = -\frac{q\Delta x^2}{\varepsilon} \left( a_{\text{n}}(i) + N_{\text{c}}(i) e^{\alpha_{\text{n}}^i} - N_{\text{v}}(i) e^{\alpha_{\text{p}}^i} \right) \]

Equation 3-14

Where \( a_{\text{n}}(i) \) is the net ionized dopant density and \( a_{\text{p}}(i) \) and \( a_{\text{n}}(i) \) describe the position of the hole and electron quasi-Fermi levels from the band edges, \( [E_{\text{c}} - F_{\text{c}}/kT](i) \) and \( [E_{\text{v}} - F_{\text{v}}/kT](i) \) respectively. In general solutions of sets of equations such as these is complex...
and has to be performed self-consistently parameters reflecting the carrier dynamics such as the carrier lifetime, mobility and diffusion length. Such a solution is beyond the scope of this thesis. However such a technique was used by Meney [76] in modelling the devices in chapter 6, based on the technique of Lundstrom and Schuelke [82, 83]. Solution of sets of nonlinear equations such as these may be found using a quasi-Newton method [84], a variant of the Newton-Ralphson method for finding roots of polynomial equations.

3.6 SUMMARY
In this chapter an explanation of the operation of a semiconductor laser has been given from the point of view of the operation of the current voltage characteristics of the np junction. The behaviour of a multilayered device can be understood from the behaviour of its composite heterojunctions. It was shown that current injection across a heterojunction under forward bias is dominated by carriers from the wider bandgap material into the narrower bandgap material. The current voltage characteristics of the junction can be expressed by a simplified formula that shows good empirical agreement. This can be used to show the dominance of recombination or diffusion currents in the operation of the heterojunction.

Two heterojunctions can be used to construct a double heterojunction device, perhaps the most fundamental laser diode structure. Here a narrow bandgap active region is sandwiched between two wider bandgap layers. Under forward bias opposite charged carriers are arranged to be injected from the wide bandgap material into the narrow bandgap material. Thus the non-equilibrium carrier concentration required for population inversion and lasing can build up in the narrow bandgap active region. The discontinuity in the band edges setup by the differences in the bandgaps between the layers, creates a heterobARRIER that impedes the flow of the injected carriers across the active region. The injected population is therefore confined within a well defined active region.

The Fermi-levels in the doped regions may be thought of as being fixed with respect to the band edges due to the large number of free carriers arising from the ionized
dopant populations. The non-equilibrium population of carriers in the active regions cannot be described by a single Fermi level. However the intraband scattering time of the order of around ~1 ps is very much shorter than the interband scattering time of around ~1 ns. Therefore each of the respective non-equilibrium populations can be considered as being in thermal equilibrium with themselves and be described by their own quasi-Fermi level. The width of the active region of a DH device, 0.1 μm, is typically less than the diffusion length of the injected carriers, 1 μm. To a first approximation the injected carrier density can be considered to be invariant across the active region. Therefore quasi-Fermi levels describing their respective populations can also be considered as invariant across the active regions. This approximation greatly simplifies the energy alignment of the composite layers of the device under forward bias. The splitting of the quasi-Fermi levels can be reflected in the junction voltage of the diode, chapter 4. The alignment of the quasi-Fermi levels can be used to estimate the activation energy needed to thermally excite injected carriers over the heterobarrier and out of the active region. This is explored in more detail in chapter 6.

This simple model of the double heterostructure under forward bias may be exploited more quantitatively. The division of the forward voltage of the diode between its composite heterojunctions is not immediately apparent. The alignment of the quasi-Fermi levels with respect to the band edges in the active region is necessary to calculate the injected carrier population. One method that can been adopted is to assume charge neutrality over the cladding, and active regions, by equating the sum of the electron and hole densities over these regions. This scheme may also be adopted for a quantum well separate confinement heterostructure device.

A further, more sophisticated method, in modelling the laser diode is to solve Poisson's equation over the entire laser structure under forward bias. Such an equation cannot be solved analytically but is susceptible to resolution through a finite difference technique. The underlying principles of this numerical solution to Poission's equation has been illustrated.
CHAPTER 4
EXPERIMENTAL

4. INTRODUCTION

The most fundamental characteristic that can be measured to gauge the performance of a laser is its threshold current. This is the current that marks the onset of the lasing oscillation condition and is sensitive to the electron hole recombination processes occurring in the laser. A brief description of the lasers light/current (LI) characteristics and associated emission spectra will be given, along with the data acquisition rig used to measure these LI characteristics.

All the devices used in this thesis were measured under pulsed conditions rather than continuous wave (CW), in order to minimise self-heating effects which may act to increase the threshold above the value expected at ambient temperature. The pulse response of the data acquisition rig was characterised. This allowed a distinction to be made between the intrinsic response of the laser to pulsed signals and the distortion of the signals due to the experimental apparatus. Furthermore the increase in the threshold current with time averaged power was also measured. Thus a maximum operating duty cycle was established below which device self-heating effects were negligible. Particular problems were found with noise and electrical oscillations that occurred in synchronous with the firing of the drive pulse to the laser. A general strategy for shielding electrical equipment, absolutely necessary to produce measurable signals, was developed and adopted throughout the experimental apparatus.

The ambient temperature of the laser was controlled by mounting the laser on top of a Peltier heat pump. The temperature was measured with a semiconductor temperature sensor mounted in between the laser and the heat pump. The temperature at the point where the laser was held and the semiconductor temperature sensor were compared as they were separated by a short thermal path. Good agreement was found between the two measurements after a settling time of around 15 to 20 min.
A method for measuring the current voltage (IV) characteristics of the laser diode was developed. A unity gain buffer amplifier, Appendix 1, had to be used in order to suppress electrical ringing in the measurement system. The junction voltage has been shown in chapter 3 to give a measure of the quasi-Fermi level separation in the laser. Furthermore, the Bernard-Duraffourg condition [5] indicates that the quasi-Fermi level splitting is of the order of the bandgap at threshold. This was demonstrated to be the case in the 0.82% tensile strained laser, after the effects of parasitic series resistance had been removed from the raw IV characteristic. Moreover, the IV characteristics of red, yellow, and blue LED's were shown to progressively shift towards higher voltages as the emission wavelength was shortened.

4.1 LI-CHARACTERISTICS

The threshold current of a laser may be found by measuring the light intensity emitted from the facets of the laser as a function of the injected current. A typical LI characteristic is shown in fig(1). The rapid linear increase in the light intensity with current is indicative of the onset of lasing. This linear behaviour may be extrapolated back to zero light intensity to define the threshold current. The external differential quantum efficiency of the laser is given by the slope of the LI characteristics above threshold. Lasing is marked by a distinct change in the emitted facet spectrum. The spectrum below threshold is broad band in nature and is related to the spontaneous emission spectrum, Inset a) fig(1). The facet spectrum is termed Amplified Spontaneous Emission (ASE) spectrum because the light emitted from the facet has propagated along the gain medium and consequently undergone amplification. At sufficiently small currents, when the gain is small, the ASE spectra approximates to the pure spontaneous emission spectrum. Closer inspection of the ASE spectra would reveal the presence of closely spaced longitudinal Fabry-Perot modes. As the laser is pumped towards lasing the modes that coincide with the peak of the gain spectra are preferentially amplified. It is normal for several of these cavity modes to be excited into lasing giving a multimode output, inset b) fig(1). At threshold the stimulated emission rate into these modes dominates all other recombination processes occurring in the laser.
Fig(1) Shows the typical light current (LI) characteristics of a laser. The rapid linear increase in the light intensity is indicative of the onset of lasing. This linear increase may be extrapolated back to zero light intensity to define a threshold current. The facet emission spectra below threshold is broad band in nature. Once threshold is reached cavity modes coinciding with the wavelength of the peak of the gain spectra are preferentially amplified.

Fig(2) Shows the schematic representation of the measurement rig. Pulsed power was supplied to the laser from a signal generator via a pulse amplifier to extend the dynamic range of the power supplied to the device. A 47Ω resistor was mounted in series with the laser to impedance match the end connection to the 50Ω coaxial cable. The current flowing in the series circuit to the laser was measured by an inductive loop current probe. The optical signal from the laser was collected by a photodetector system consisting of a photodiode and a pulse amplifier. This system gave a linear voltage output with light intensity. The optical and current signals were measured on a digital oscilloscope interfaced with a computer. The same computer could be used to increment the amplitude of the power pulses from the signal generator thus automating the collection of an LI characteristic. The photodetector could be replaced with a unity gain buffer amplifier to provide a measurement of the junction voltage.
All the injected carriers above lasing go into the lasing transitions. Thus the light intensity above threshold is seen to increase linearly with current. The carrier density can be expected to be pinned or clamped above threshold. This pinning behaviour has been seen \cite{85,86} by the observation of the pinning in the intensity of true spontaneous emission spectrum emitted in a direction perpendicular to the lasing axis at or above lasing. Light emitted in this direction traverses a negligibly small section of the gain medium and so is not expected to be amplified.

### 4.2 LI MEASUREMENTS

Fig. (2) shows a schematic representation of the basic apparatus for acquiring LI measurements and the lasing threshold current. This rig consists of a pulse generator to supply power to the laser, a current probe to measure the current flowing into the laser and a photodetector to measure the light output from the laser. A pulse generator was used to supply power to the laser in order to minimise self heating effects in the device being measured. Self-heating effects can act to increase the threshold current above the ambient temperature value. As the devices used were unmounted chips, thermal contact between the laser and the base of the laser clip (section 4.2.2) was likely to be poor. A fuller account of self-heating effects will be presented in chapter 8. The pulse generator, Hewlett Packard 8112A, was ideal for generating voltage pulses into a 50Ω load. The effective series resistance of the laser chip was estimated at 8Ω from typical threshold V data. Thus a standard carbon 47Ω resistor was placed in series with the laser diode in order to match the load resistance to that of the signal generator. Adequate LI data could be taken without this matching resistance however the pulse shape derived from the current probe and photodetector did show slight ringing. A linear leading edge of 70ns and trailing edge of 200ns could also be set on the pulse generator to reduce the effects of ringing on the signals from the current probe and photodetector.

#### 4.2.1 PULSED MEASUREMENTS

If the lasers used in this thesis were operated under pulsed conditions instead of CW mode. The chips were not bonded down to a heat sink but operated in a clip arrangement, section 4.2.1 and consequently were in poor thermal contact with the surroundings. Therefore it was necessary to minimise self-heating effects and in the
worse case scenario prevent the chips from burning out. Typical pulsed widths used ranged from 1-3 μs at a repetition period of 50ms or greater, section 4.5.

All the signals measured from the lasers were in the form of electrical pulses. Any electrical pulse can be characterised by its rise and droop time, fig(3). The rise time of the pulse is defined as the time it takes for the signal to increase from 10% to 90% of its maximum value, whilst the droop time is defined as the time it takes for a signal to fall from 90% to 10% of its maximum value in response to a step input. The rise and droop time of a signal are a function of the frequency response of the measurement system. Any system can be described in terms of its high and low frequency responses. Thus the high frequency response will limit the rise time whilst the low frequency response will govern the droop time.

Modulation of the optical, arising from thermal effects, was measured in all these devices over the duration of the pulse width. The natural rise and droop times of all the detectors used, photodetector, section 4.2.4, the current probe, section 4.2.3 and IV measurement rig, section 4.4, were measured in order to show that the thermal modulation of the optical pulse due was a consequence of the properties of the laser under test, rather than an artefact of the measurement system.

4.2.2 THE LASER CLIP

All the devices used in the study were unmounted chips. The small dimensions of each device 500x225x100μm presents a practical problem in making electrical contacts to each device. The was overcome by using the laser clip illustrated in fig(4). Here the laser chip can be manually pushed under the spring loaded finger. The finger and the base form electrical contacts to the device and are insulated from each other via the spacer which is made from printed circuit board material. The whole arrangement may be easily manipulated and incorporated into various systems such as a cryostat or pressure system. The clip also has the advantage that the connection made to the laser are temporary as opposed to gold wire bonding.
Fig(3) Shows the definition of the rise and droop times of a typical pulsed signal. The rise time, following the electrical definition, is considered to be the time for the signal to increase from 10% to 90% of its maximum value. The droop time is defined as the time taken to fall from 90% to 10% of the maximum. These effects originate from the limited band width and low frequency cut off characteristics of the amplifier systems used in the measurement apparatus. The measured fall off of the optical signal was very much faster than the measured droop time of the photodetector. Thus implying that the change was caused by an effect intrinsic to the laser such as self-heating, rather than an artefact of the measurement system.

Fig(4) Shows the clip used to hold the individual laser chips in place. A spring loaded finger, electrically isolated from the base plate served to hold the laser in place with minimal force and the act as a top contact. The clip was mounted with respect to a Peltier heat pump shown below.
4.2.3 CURRENT PROBE
The current was measured with an inductive loop current probe. This had the advantage of not loading the series circuit, as it was electrically isolated from the drive circuit. The amplitude of the voltage pulse from the current probe was proportional to the current flowing in the series circuit and could be measured on a digital oscilloscope. The current probe was calibrated against a 10, 20Ω carbon resistors, giving the current in amps as 2.5 times the measured voltage in volts, into a 50Ω load at the oscilloscope. Good linearity was observed down to ~1mA, despite the fact that large leading and trailing edge spikes were observed on the current probe pulse at these low currents. The amplitude of the flat top of the current probe pulse was always measured. The current probe was easily able to follow the leading edge set on the pulse generator down to rise times around 200ns. The droop time of the current probe, measured as 400 ms, was found to be greatly in excess of the typical pulse widths used of around 3ms, thus the output pulse could be considered flat over the duration of the powering pulse.

4.2.4 THE PHOTODETECTOR
The photodetector consisted of a Si photodiode connected to an ac coupled pulse amplifier. The amplitude of the voltage pulse produced from the photodetector was proportional to the photocurrent generated in the photodiode. This in turn was proportional to the light intensity falling on the active surface of the diode. Two considerations were made in the design of the photodetector. These were the trade off between detector rise time and signal to noise ratio. A short rise time of a few hundred nanoseconds was specified for the photodetector as interest was expressed at the start of the project in resolving the evolution of the light output from the laser over the period of the drive pulse, ~3μs. The signal to noise ratio may be increased by increasing the active area of the photodiode thereby increasing the total amount of light that could be captured by the photodiode. However this has the effect of increasing the intrinsic capacitance associated with the pn junction. The effective time constant of the photodiode circuit is therefore increased, reducing the rise time of the diode. The fundamental limit on photodetector rise time is
given by the rise time of the photodiode. The 50mm$^2$ photodiode was quoted, from the manufacturers data, as having a rise time of 200ns more than adequate to resolve the evolution of the optical signal from the laser over the microsecond time scale of the drive pulse to the laser. An ac. coupled amplifier with a rise time of the order the photodetector rise time was designed [87] in order not to limit this further [88]. Subsequent measurements showed that the average power output from the lasers and the gain of the photodetector often required that the optical signal from the laser had to be attenuated using neutral density filters to prevent saturation of the photodetector output at or before lasing. However the large gain proved advantageous when measuring the low intensity output from an optical fibre. A slower detector rise time may be used to some advantage at the expense of losing the time information from the optical signal of the laser. This has the effect of incorporating a low pass filter on the front end of the detection system which will act to filter out any high frequency components of the detected signal associated with noise. In these devices self-heating effects were measured from the modulation of the optical intensity with time. The rate of change of temperature was measured as $\sim 7K/\mu s$, chapter 8. A faster detector still, with a rise time of 0.5ns [89], was also used to measure self-heating effects over a period of 810ns. The results of this system gave the same self-heating as the slower 200ns. photodetector. The small size of the fast 0.5ns detector limited the signal strength that could be acquired.

A Si photodiode was chosen because the window of spectral sensitivity coincided with the output wavelengths of the lasers used in this study, 749 to 980nm. A similar Ge based photodetector was tried but failed to give a measurable response even for the longer wavelength devices that approach the window of spectral sensitivity of Ge based photodiodes.

4.2.5 TEMPERATURE CONTROL
This was achieved for temperatures from room temperature up to 80C using a 2.5W Peltier heat pump mounted directly under the laser clip holder. fig(5). This whole arrangement was mounted on a heat sink. Good thermal contact was maintained between the surfaces of the Peltier heat pump and the metal of the laser clip mount through the liberal use of zinc based heat sink compound. The Peltier heat pump was
powered by a special low output impedance source as the heat pump presents very little series resistance. Temperature measurement was achieved by using an LM35 semiconductor temperature sensor was mounted in an orifice under the seat of the laser clip. The LM35 is laser trimmed to give a output of 10mV/C ±0.1C [90], thus a direct reading of the temperature could be achieved using a digital volt meter. As the temperature sensor was mounted in between the laser chip and the Peltier heat pump, temperature gradients between the position of the laser and the temperature sensor were investigated. This was achieved by mounting the welded end of a copper constantine k-type thermocouple under the finger of the laser clip. This was then buried in heat sink compound to provide good thermal contact. The differences in temperature between the LM35 sensor and the thermocouple did not exceed 0.1C over a temperature range of 60C. A settling time of around 15 to 20 minutes also found from these measurements. The temperature stability became increasingly poor at high temperatures, 70-80C, corresponding to Peltier currents of 5A. This could be markedly improved by reducing the resistance of the wires supplying the heat pump by connecting several wires in parallel. Some attempt was made to calibrate the temperature against Peltier current. However this was found to vary with laboratory temperature and so was used only as a rough guide. The sluggish nature of the thermal response of the system meant that the temperature could easily be stabilised ±0.2C by manually adjusting the Peltier current

The temperature range could be extended, 77 to 400K, by the use of an OXFORD instruments cryostat. The basic measurement system described here could easily be interfaced with the measurement system described here. Temperature measurement was provided with a precalibrated rhodium temperature sensor. Excellent agreement between the LI temperature characteristics was found over the common temperature windows of the two temperature control systems used. The Peltier system was preferred whenever possible as it was simpler to operate.

4.2.6 NOISE SHIELDING AND PICKUP
Cascading several items of equipment together, such as oscilloscopes, power supplies, signal generators etc., resulted in excessive electrical ringing and noise, which was sufficient to swamp the desired signals that were being measured. Several precautions
were taken to counter this noise and pickup. It was found that much of the ringing could be reduced by simply ensuring that the power connection fanned out from a common multiblock connector. This may act to break any earth loops unintentionally formed in setting up the system. Connecting separate items of equipment to different wall mounted sockets often lead to undesirable electrical ringing.

The photodetector was found to be particularly sensitive to pickup. Large amplitude ringing coinciding with the firing of the pulse generator could be observed, even when the aperture to the photodiode was blocked to shut off the light signal. This implied that the problem was electrical in nature. The problem was overcome by floating the circuitry of the photodetector, including the ground of the BNC coaxial connectors, with respect to the casing. A separate earth return was provided by shielding the coaxial signal return cable in braided sheath. Continuity of the shielding was maintained to the casing holding the amplifier circuitry. The shielding and the earth return were grounded remote from the photodetector at the connection to the oscilloscope. Thus any pick up induced in the photodetector circuitry would appear on both the signal and ground lines as they were floating with respect to the shield, fig(6). Only the difference between the two, the true signal, would be amplified. This precaution reduced this ringing to an almost negligible amount.

4.2.7 AUTOMATED MEASUREMENTS
The signal generator settings and the data acquisition from the oscilloscope were all controlled through a computer using standard general purpose interface bus (GPIB). The signal generator was set to incrementally increase the amplitude of the voltage pulse supplied to the laser thus increasing the current. The resulting current, photodetector or voltage signals were then measured thus acquiring a full LI or IV characteristic. The amplitude of the output signals were measured using algorithms built into the digital oscilloscope. This gave considerable flexibility in the type of data that could be taken. The current probe and junction voltage signals were taken using an amplitude measuring function because of the flat top of these signals. However the optical signal was seen to fall linearly after the leading edge above threshold. The oscilloscope was then set to measure the maximum of the light signal just after the leading edge.
Fig(5) Shows the apparatus used to mount the laser clip. The clip is held in close proximity over a Peltier heat pump used to provide environmental temperature control in the range 20-80°C. An LM35 semiconductor temperature sensor is inserted into a hole drilled in this base plate, such that it is positioned in between the laser and the heat pump, as close as practically possible to the laser. A thermocouple placed under the finger of the laser clip and buried in zinc loaded heat sink compound showed no more than 0.1°C difference from the semiconductor sensor, after a settling time of 15-20 minutes. The base plate on which the clip was seated also serves as a bottom electrical contact. A recess in this plate also served to align the position of the clip.

Fig(6) Shows a schematic representation of the electrical circuit used to isolate the photodetector system from the electrical pick that occurred in synchronous with the generation of the power pulse to the laser. The coaxial cable used to carry the desired signal was encased in a braided metal sleeve. Continuity of this shield was maintained by connecting the sleeve to the outer metal casing containing the photodetector pulse amplifier. The internal electronics was left floating with respect to the shield. The shield was only grounded remotely from the photodetector at the connection to the oscilloscope. Thus in principle any electrical pick up would occur on both the signal and signal return lines with respect to the shield, whilst the difference between them, the desired signal, would be maintained. This system proved effective in countering electrical pick up in the photodetector system and the unity buffer amplifier used in the IV rig. This also proved effective in hardening the system to noise derived from unintentional earth loops that plague many modular measurement system.
Furthermore two cursors could be set to probe the amplitude at different times on a
given trace. This function was used to measure the rate of fall of the optical pulse during
self-heating. The computer could also be made to read the pulse shape stored in the
digital oscilloscope.

4.3 PRESSURE MEASUREMENTS
The lasers could be measured under conditions of hydrostatic pressure from 0-15kbar.
The resulting shifts in the direct and indirect bandgaps of the semiconductor described
in chapter 2. could be used to simulate compositionally different semiconductor
compounds. A laser clip was mounted on the end of a piston that was immersed in a
50:50 amyl alcohol/Castor oil mix as a pressure medium. A hydraulic press was used
to drive the piston into the container holding the pressure medium. The resulting
compression of the pressure medium transferred the pressure hydrostatically to the
laser chip [91]. The science and technology of containing such explosively high
pressures will not be discussed here but can be found elsewhere [92]. The light output
from the lasers was coupled into a optical fibre mounted in a bore in the piston. The
same bore was used to carry the electrical connections to the device.

The pressure of the medium was measured using a manganin coil sensor. The
resistance of the wire varies in a known way with pressure. The sheer mass of the rig
could be used to assume a reasonable degree of temperature stability of the
experiment in the temperature controlled environment of the laboratory. Little drift in
the threshold current could be measured if it were held at a fixed pressure.

4.4 IV MEASUREMENTS
The junction voltage of the laser diode was measured to give an estimate of the quasi-
Fermi level splitting inside the laser, chapter 3. The IV data was measured using a four
point probe measurement. The current was supplied as before via the signal generator
and separate connections (voltage sens.), which carried no current, were made to
measure the voltage to avoid series resistances. These connections were made as close
as practically possible to the laser chip given its mounting arrangements. It was
originally thought that the input impedance of the oscilloscope. 1MΩ @ 30pF. was
sufficient so as not to present a significant load across the laser chip. Therefore the voltage sens. connections were made directly to the oscilloscope. However this caused a large amount of ringing that could not be overcome with numerical averaging from the digital oscilloscope. The voltage sens. connections made in this way certainly closed the earth loop between the signal generator and the oscilloscope (The current was measured with an inductive loop current probe so no physical connection). This problem was overcome by using a unity gain, high input impedance buffer amplifier, appendix 1. The amplifier circuitry was kept floating from its casing and provided with a separate earth return in the same manner as the photodetector. Although ringing was eliminated the output pulse shape from the amplifier became increasingly distorted as the length of coaxial cable between the laser and the amplifier was increased. It was found that good square pulses were measured if the length of this cable was kept below ~30cm. Good linearity of the amplifier was found using a series of test pulses from the signal generator.

A parasitic series resistance, $R_s$, was assumed in all IV measurements of laser diodes. This may be estimated by assuming that the voltage should pin at threshold (i.e. a differential resistance of zero) so that the IV characteristics above threshold would tend to become linear with a slope equivalent to the series resistance [93]. This could be found by performing a linear regression on the data above threshold and was found to be of the order ~1-2Ω. Assuming this value was constant over the entire IV run the contribution of the series resistance to the IV curve could be removed. This is illustrated in fig(7), for the 0.82% tensile-strained laser. The voltage appears to become pinned at threshold after the effects of series resistance have been removed from the initial data. The pinned voltage is expected to be of the order of the transition energy at the lasing wavelength because the Bernard-Durrafourg condition tells us that the quasi-Fermi level splitting, equal to the junction voltage, is equal to the bandgap at transparency. The quasi-Fermi level splitting at transparency is not equal to but less than that at threshold. However for a laser with low internal optical loss processes the quasi-Fermi level splitting at threshold is expected to be close to that at transparency. In this device the lasing wavelength of 761 nm is equivalent to a photon energy of 1.629 eV which is equal to the measured pinned voltage of 1.635 V within experimental error.
**IV 0.82% Tensile Strained Laser @ 20.0°C**

![Graph showing IV characteristics](image)

Fig(7) Shows the typical IV characteristic measured from the 0.82% tensile strained laser. A four terminal measurement was used to eliminate parasitic resistance effects from the connecting wires. In practice a unity gain, high input impedance, buffer amplifier was needed to decouple any loading effects that appeared in shunt with the diode being measured. This also proved effective in eliminating noise and ringing possibly derived from an earth loop that was made in bringing the voltage signal back to the oscilloscope. The effect of further ohmic drops due to contact resistance, appearing in series with the laser may be eliminated from the IV characteristics themselves. This assumes that the IV characteristics become linear at a sufficiently high voltage with a slope equivalent to this series resistance. In practice a resistance of a few ohms was typically measured. Removing the effect of this resistance from the IV characteristics shows that the junction voltage tends to pin around threshold. The pinning voltage may be assumed to be of the order of the transition energy at the lasing wavelength from the Bernard-Duraffourg condition. In this case the lasing wavelength of 761 nm gives a transition energy of 1.629 V close to the measured voltage of 1.635 V.
Fig(8) Demonstrates IV measurements on a red, yellow and blue LED. The shift in the characteristic towards shorter wavelength is expected as the junction voltage is expected to follow the bandgap of the active material. The slope of the characteristics also becomes smaller towards shorter wavelengths. This may demonstrate the increasing effective contact resistance with bandgap as it becomes harder to find effective dopants to form an ohmic contact.
IV data was also taken for a red, yellow and blue LED, fig(8). The junction voltage is expected to be of the order of the bandgap of the diode being measured. This can be seen in the general shift to higher voltages of the IV characteristics as the wavelength is shortened towards the blue end of the spectrum. The slope of the IV measurement falls towards the blue end of the spectrum. This may be attributed to an increase parasitic series resistance, possibly due to the effective increase in contact resistance. This may arise from the weaker action of dopants, in wide bandgap semiconductors, forming an ohmic contact. The upper measurable limit of the unity gain buffer amplifier can be seen in the IV curve for the blue LED which is limited to 5V.

4.5 SELF-HEATING EFFECTS

As a given fraction of the power supplied to the laser goes into heat generating processes the operating temperature of the laser chip may be expect to rise during operation especially if the device is in poor thermal contact with its surroundings. This was assumed for all the lasers in this thesis as they were mounted in the laser clip. The result of this is that the measured threshold current is likely to be slightly greater than that expected at the background temperature measured by the temperature sensor. This self-heating may be countered by operating the laser under pulsed conditions as this will reduce the time averaged power supplied to the device. The power supplied to the device is a function of the duty cycle of the pulsed power source. Therefore the question arises as to what duty cycle is required to make self-heating effects negligible. This was investigated by using the laser diode itself as a temperature sensor and measuring the variation of threshold current with duty cycle. The temperature of the laser chip would be expected to rise exponentially during the on-period of the pulse and fall exponentially during the off period. After a large number of power cycles the chip will reach thermal equilibrium where the temperature rises from and falls to a background temperature somewhat above ambient. This may be seen in more detail in chapter 8. Decreasing the off-time or increasing the on-time will increase this background temperature. Fig(9) shows the variation of threshold current with duty cycle. Here the on-time was kept constant at 1μs to provide a flat top for the current pulse whereas the period was set to 1ms, 200, 100, 20, 10 μs respectively. There is very little change in threshold current with off-periods of 1ms and 200, 100 μs whereas the threshold current is seen to increase after 20, 10 μs. Thus with the longer period the laser has time to cool down to
Variation of LI Characteristic with Duty Cycle

Fig(9) Shows the increase in the threshold current of the 0.68% tensile-strained laser with increasing duty cycle at a fixed ambient operating temperature. The “on time” of 1μs was kept constant whilst the period between the drive pulses, the repetition period, was shortened. The increase in the threshold current demonstrates the action of self-heating in the devices. Self-heating effects tend to become negligible for sufficiently long “off-times”. The repetition periods used throughout the experiments in this thesis were of the order of 50ms, i.e. very much greater than the limit presented here. Self-heating effects due to the time averaged power supplied to the device may therefore be considered negligible. Further self-heating effects over the duration of the on-time may also be considered negligible as the optical signal was derived one rise time after the start of the optical signal. The time evolution is dealt with in further detail in chapter 8 of this thesis.
the ambient temperature. In practice periods of 50ms or greater were used to absolutely ensure that the background temperature was kept at ambient in all the lasers used in this study. Furthermore measuring the maximum in light signal immediately after the leading edge of the pulse ensured that the heating time was kept to a minimum. The current and voltage signals supplied to the laser were seen to be constant and therefore immune to the thermal modulation effects seen in the optical signal. Therefore the power supplied to the chip, the current voltage product, was constant during the on-period.

4.6 SUMMARY
The measurement apparatus described here was constructed around the need to measure the LI and IV characteristics of the laser under two controlled environmental parameters of temperature and pressure. However self-heating effects can act to raise the threshold current above the value expected at ambient temperature. This was overcome by measuring the devices under pulsed conditions, minimising the time averaged power supplied to the laser. The response of the measurement system to pulsed signals was therefore characterised. Thus a distinction could be made between the intrinsic pulse response of the laser and the distortion of the pulsed signal by the apparatus. Furthermore a maximum operating duty cycle was established below which self-heating effects were negligible. A standard operating duty cycle, far below this limit was adopted throughout all these measurements. The response time of the detector system was fast enough to follow the time evolution of the pulsed signal from the laser over a period of a few microseconds. This was used to measure efficiency of the device from the self-heating in chapter 8. However the speed of the detector system made the measurements susceptible to electrical noise and ringing which are usually integrated out in a slower system. An effective shielding method was developed and adopted throughout the apparatus and was found absolutely necessary to produce measurable signals.

In chapter 3 the junction voltage was shown to follow the quasi-Fermi level splitting in the device. The Bernard-Duraffourg condition [5] indicates that the quasi-Fermi level splitting in the laser should be of the order of the bandgap at threshold. This was shown to be the case in the 0.82% tensile-strained laser, after the effects of parasitic series
resistance had be removed from the raw IV characteristics. The IV characteristics of a red, yellow and blue LED were also found to move to higher voltage as the wavelength was shortened.
CHAPTER 5

THE DEVICES

5. INTRODUCTION

The lasers used in this thesis form a systematically varying set of devices with which it is possible to explore the variation of the threshold current and its underlying processes over a wavelength range in the near infrared between 980 and 749nm. The variation of the band structure across this systematically varying set of samples is explored in this chapter.

All the devices used in this study were nominally identical in composition and structure apart from the composition of the single quantum well which varied systematically from device to device. The active regions and SCH layers were grown on an 001 orientated GaAs substrate. The SCH region was made from an Al$_{0.5}$Ga$_{0.5}$As/Al$_{0.3}$Ga$_{0.7}$As combination of alloys which are closely lattice matched to the substrate and therefore considered unstrained. The GaAsP and InGaAs material systems were used to form the basis of the active region of these devices as their alloy compositions could be tailored to cover this wavelength range. The addition of indium to a GaAs QW acts to increase the lasing wavelength and incorporate compressive strain into the active layer. Conversely the addition of phosphorus to a GaAs QW acts to shorten the lasing wavelength and incorporate tensile strain into the active layer.

The material compositions and strains were provided from the growers [94]. This data, together with the bandgaps, band offset ratios, was used for calculation of the optical transition energy and the layer strains in the QW's, using model solid theory of van de Walle and Krijin [95,96]. The method used to calculate of the energy of the confined states in finite depth quantum well is also demonstrated. The calculated optical transition energy was found to be in close agreement with that measured at the
lasing wavelength. The calculated strain in the QW was also found to be close to that measured through X-ray diffraction techniques [94], giving confidence in the material data supplied from the growers.

The bandgaps of the materials in the compressively strained regime were found to be described, in the literature, by two different bowing parameters (bowing parameters are defined in section 5.2). Both of these bowing parameters were tested on a randomly selected set of published data found on studies photoluminescence on InGaAs/AlGaAs quantum wells. Examples were found where optical transition energies in the QW were described by each bowing parameters. No preference was found for either value. The ratio of the bowing parameters, 1.6, is greater than expected from variation due to experimental error. This implies some physical difference between the samples. It is tentatively suggested that alloy ordering effects during the growth of these samples may be responsible for the difference in these devices. The larger bowing parameter used for these lasers suggest that some alloy ordering [97, 98] may have occurred in these devices.

Strain can be supported in a given layer if the critical strain thickness product of that layer is not exceeded as described in chapter 2. Previous experimental studies [99] suggest a value for the critical thickness for GaAsP/GaAs which is not exceeded by the tensile GaAsP lasers used in this thesis. Furthermore the maximum compressively strained InGaAs lasers used in this thesis fall inside the strain thickness product calculated using the method of Matthews and Blakeslee [62]. Therefore the lasers used in this thesis are likely to be unrelaxed and free of these misfit dislocations.

All the lasers used in this thesis had $A_20, \lambda/2$ facet coatings. Theory shows that the reflectivity of these coatings is dependent on the refractive indices of the laser material, the coating and the external medium, the thickness of the layer and the wavelength of the radiation reflected at the facet. If the thickness of the layer is made equal to $\lambda/2$, measured at the lasing wavelength, then the reflectivity of the layer becomes independent of the refractive index of the layer material. The reflectivity reduces to that of a facet without a coating. This simplifies the analysis of the change
of facet reflectivity as the laser is immersed in a liquid as has been done in chapter 7. The role of the facet coatings is to protect the surface of the facet from degradation rather than to enhance the reflectivity of the facet.

5.1 MODEL SOLID THEORY

This is a method in which the bulk band edge energy levels can be calculated as a function of strain and composition and was used in sections 5.5 & 5.6 in calculating the strain and optical transition energies from the material data supplied by Carl van der Poel [94]. This method places the CB and VB band edge energies on an absolute energy scale. Therefore the band offset ratio between different materials forming a heterojunction may be calculated. It should be noted that this absolute energy scale only has physical significance when comparing band edge energies in model solid calculations. The method, presented by Van de Walle[95] and Krijin [.96], starts by relating the calculated energy of the CB and VB band edges to a common reference level. This reference level was chosen to be the average electrostatic potential in a semi-infinite model solid, $E_{v,av}$. Tables of values of $E_{v,av}$ and all the relevant parameters for model solid calculations for different binary compounds are given in Krijin. The band edge energies for ternary or quaternary compounds can be found by interpolation between the values calculated for the constituent binary compounds, using the appropriate bowing parameter, section 5.2. The energy of the VB band edge, as presented by Krijin, is expressed as follows.

$$E_v = E_{v,av} + \frac{\Delta_0}{3} + \Delta E(hy)_{v,av} + \Delta E(sh)_{HH,LH,SO}$$

Equation 5-1

The effects of strain are resolved into two components, a hydrostatic shift $\Delta E(hy)$ and a shear shift $\Delta E(sh)$. In the absence of strain the valence band edge is expressed relative to the average valence band energy $E_{v,av} = (E_v(HH)+E_v(LH)+\Delta_0)/3$. The hydrostatic shift results from a volumetric change of the unit cell of the crystal as it undergoes biaxial distortion due to strain. Because Poisson’s ratio is less than unity the resulting uniaxial
distortion perpendicular to the plane of the layer means that the overall volume of the unit cell is changed. This is equivalent to the volumetric change in the unit cell due to externally applied hydrostatic pressure presented in chapter 2. The total shift is proportional to the change in fractional volume multiplied by a deformation potential. The deformation potential is calculated from model solid theory and takes into account the mixing between the valence band basis functions. The shear shift is different for each HH, LH and SO bands due to the different mixing between the x, y and z components of the p-like VB orbitals. The shear energy shift is dependent on the crystallographic orientation of the substrate, 001 or 111. This can be calculated from a distortion of the lattice due to the shear and a shear deformation potential.

The energy of the direct CB edge, in the absence of strain, is simply the VB edge energy plus the experimentally derived bandgap.

\[ E_e = E_{e\text{av}} + \frac{\Delta g}{3} + E_g + \Delta E_e (hy) \]

Equation 5-2

The s-like symmetry of the conduction band states at \( \Gamma \) mean that there is only a hydrostatic shift in band edge energy with strain.

### 5.2 BOWING PARAMETERS

The shifts in the band edge energies presented above are calculated for material parameters derived for binary III-V compounds. The bandgap and spin orbit splitting of a solid solution of these binaries generally does not fall linearly between its constituents but follows a nonlinear behaviour that can be described by a second order polynomial. Thus for ternary compounds of the form \( AB_xC_{1-x} \), a given parameter, \( T \), e.g. the bandgap or the spin orbit splitting etc. May be written as a function of composition as follows.

\[ T_{ABC}(x) = xT_{AB} + (1-x)T_{AC} + x(1-x)S_{ABC} \]

Equation 5-3
The coefficient $S$ is the bowing parameter of the ternary compound which is usually derived experimentally.

5.3 CALCULATION OF QUANTUM CONFINED STATES

Solutions of confined states in the QW of these lasers were also used in sections 5.5 and 5.6 to calculate transition energies at the lasing wavelength. Exact analytical solution of the energy states in an infinitely deep QW may be obtained via equation 2-21, as the wavefunction must go to zero at the edges of the well. In a QW of finite depth this is not the case and an exact analytical solution cannot be written. The solution to Shrödinger's equation for the wavefunction at the well/barrier boundary changes from oscillatory, $A\cos(kx)+B\sin(kx)$, to exponentially decaying, $C\exp(Kx)+D\exp(-Kx)$, as the energy of the particle is less than the potential energy of the barrier. The even and odd solutions respectively of the wavefunction in the well can be shown to satisfy the transcendental equations [102].

\[ k \tan\left(\frac{kL}{2}\right) = K \]

Equation 5-4

\[ -k \cot\left(\frac{kL}{2}\right) = K \]

Equation 5-5

and

\[ k^2 + K^2 = \frac{2mV_0}{\hbar^2} \]

Equation 5-6

Where, $m$, is the effective mass of the particle in the well, $L$, is the width of the well, $V_0$, is the depth of the well and $\hbar$ is the reduced Planck's constant. Here $k$ and $K$ are defined by.
\[ k^2 = \frac{2mE}{\hbar^2} \]  

Equation 5-7

\[ K^2 = \frac{2m}{\hbar^2} \left( V_0 - E \right) \]  

Equation 5-8

Thus from a solution to k we may derive the confined energy E. For even solutions eliminating K and E in and expressing Equation 5-1 gives.

\[ \tan(\theta) = \frac{\sqrt{\left( \frac{2mV_0}{\hbar^2} \right) - \left( \frac{2\theta}{L} \right)}}{2\theta/L} \]  

Equation 5-9

Where \( \theta = kL/2 \). The solutions to this may be seen graphically fig(1). The solutions occur at the intersections of \( \tan(\theta) \) with the function on the RHS. of Equation 5-9. These solutions must occur in the range where \( \tan(\theta) \) is positive or \( n\pi < \theta < (n+1/2)\pi \). The total number of solutions that are contained in the well fall in the range of theta values for which the RHS of Equation 5-9 is positive. A similar result can be obtained for odd solutions. The intersection between the LHS and RHS of Equation 5-9 was determined by using a numerical bisection method.

5.4 THE LASER STRUCTURES

All the lasers used in this study were nominally identical in structure and composition apart from the composition of the single QW. The compositions of the SCH and layer widths of the cladding, barriers and QW were the same in each device. This allows us to
Fig(1) Illustrates the graphical solution to find the confined states in a finite quantum well. In practice the solution was found using a numerical bisection method. For simplicity the well was considered to be square with a depth defined by the band offset ratio between the barriers and the well layers.
correlate the variation of threshold current from laser to laser with the incremental variation of the QW material composition.

The lasers were 50μm oxide stripes, 500μm long with λ/2 Al₂O₃ coated facets. Each device had a nominally identical SCH grown on an 001 orientated GaAs substrate by MOVPE in a PLANET reactor, [96], by Carl van der Poel, Philips Eindoven, [94]. The overall laser structure is illustrated in fig(2).

The different strains and lasing wavelengths of the devices are given below.

<table>
<thead>
<tr>
<th>Strain (%) -ve tensile, +ve compressive</th>
<th>Lasing Wavelength (nm)</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.00</td>
<td>749</td>
<td>0.290, phosphorous</td>
</tr>
<tr>
<td>-0.82</td>
<td>769</td>
<td>0.238, phosphorous</td>
</tr>
<tr>
<td>-0.68</td>
<td>767</td>
<td>0.197, phosphorous</td>
</tr>
<tr>
<td>-0.51</td>
<td>784</td>
<td>0.148, phosphorous</td>
</tr>
<tr>
<td>-0.30</td>
<td>802</td>
<td>0.087, phosphorous</td>
</tr>
<tr>
<td>-0.13</td>
<td>822</td>
<td>0.038, phosphorous</td>
</tr>
<tr>
<td>0.00</td>
<td>847</td>
<td>0.00, phosphorous or indium</td>
</tr>
<tr>
<td>0.22</td>
<td>866</td>
<td>0.032, indium</td>
</tr>
<tr>
<td>0.41</td>
<td>890</td>
<td>0.059, indium</td>
</tr>
<tr>
<td>0.69</td>
<td>915</td>
<td>0.099, indium</td>
</tr>
<tr>
<td>0.90</td>
<td>946</td>
<td>0.130, indium</td>
</tr>
<tr>
<td>1.18</td>
<td>974</td>
<td>0.170, indium</td>
</tr>
</tbody>
</table>

The compositions refer to the fraction of either phosphorus or indium added to the unstrained GaAs QW. Only the maximum compositions 29% phosphorus and 17% indium were supplied by the growers whilst all the strains were measured by X-ray diffraction [94]. Therefore the intermediate compositions were linearly interpolated from the maximum compositions using Vergard’s law [104].

The cladding and barrier regions of the SCH were formed from differing alloys of AlGaAs. Fig(3) shows the variation of bandgap of AlₓGa₁₋ₓAs with Al composition x. From this we may see that the 1140Å Al₀.₃Ga₀.₇As barrier layers fall below the direct/indirect bandgap Γ-X cross over at x=0.4. Conversely the 1.4μm, Al₀.₅Ga₀.₅As, cladding layers fall above this point and are indirect with X being the lowest lying band
Fig(2a) Shows the widths and thicknesses, compositions and doping densities of the constituent layers of the lasers used in this thesis. Fig(2b) Shows the bandgaps, band offset ratios and positions of the satellite minima of each of the constituent layers. The bandgap of the Al$_{0.3}$Ga$_{0.7}$As barrier layer is direct whilst the bandgap Al$_{0.5}$Ga$_{0.5}$As cladding layer is indirect. The position of the X-minimum will be shown to be important in the operating characteristics of these lasers, chapter 6.
Fig(3) Shows the variation of the bandgap of unstrained AlGaAs as a function of composition. The bandgap changes from a direct to an indirect type at a 40% aluminium concentration, with the X-minimum falling below the Γ-minimum. In the lasers used in this study the Al0.3Ga0.7As barriers are direct whilst the Al0.5Ga0.5As cladding layers are indirect.

Fig(4) Shows the variation of the bandgap and lattice constant as various binary semiconductors are alloyed together. In these lasers AlGaAs layers are used in the barriers and cladding regions. These layers remain closely lattice matched to the GaAs substrate and therefore unstrained over the entire composition range between GaAs and AlAs. However the bandgap may be varied with composition to form an effective heterobarrier. The addition of phosphorus or Indium to a GaAs quantum well changes the bandgap and varies the lattice constant with respect to the substrate. This allows the lasing wavelength to be shifted with composition whilst incorporating the beneficial effects of compressive or tensile strain into the active layer.
edge. As Al₉Ga₁₋₉As is closely lattice matched to GaAs (the substrate material) these layers may be considered unstrained. Fig(3) illustrates the limit at which the Al₉Ga₁₋₉As cladding can form an effective heterobarrier with which to confine carriers in the active region. This subject is expanded on in chapter 6.

The N-type cladding layer is doped to 5x10¹⁷ cm⁻³ with Si and the P-type cladding layer is doped to 1x10¹⁸ cm⁻³ with Zn. The barrier and well regions are nominally undoped.

The simplicity of these laser structures is advantageous from the point of view of this research. Sophisticated device structures which act to confine carriers within a well defined active region, such as those described in the introduction section 1.1.5, may add extra complications in analysing experimental results. In the absence of any extra contributory factors we may consider that we are looking at the lasing properties of the material only rather than any improvements that stem from the laser architecture. However, though the current densities needed to pump these lasers to threshold may be comparable to other devices, the magnitude of the threshold current may be larger than other designs as these lasers do not have sophisticated structures for current and optical mode confinement.

5.5 TENSILE STRAIN

Between 0 and 29% phosphorus was incrementally added to an unstrained GaAs QW. The resulting increase in bandgap acted to shorten the lasing wavelength from 847 to 749 nm. The lattice constant of the GaAsP is smaller than that of the GaAs substrate and therefore forced to grow under biaxial tension in the plane of the QW, as the layer adopts the larger lattice constant of the substrate. This distortion leads to a reduction, through Poisson's ratio, in the lattice constant in the growth direction. The increase in bandgap and the reduction of the lattice constant with phosphorus concentration is shown fig(4).

To a first approximation the bandgap discontinuity between the barrier and QW material was considered to form a square potential well, the depth of which is defined by the band offset ratio between the two materials. This was calculated using model solid
Fig(5) Shows the calculated variation of the quantum well $E_1$-HH(z) and $E_1$-LH(z) transition energies as a function of tensile strain for a 90Å GaAs$_{1-y}$P$_y$ / Al$_{0.3}$Ga$_{0.7}$As $x$:0.00-0.29 single quantum well. The addition of phosphorus to GaAs acts to reduce the lattice constant with respect to the GaAs substrate, thereby incorporating tensile strain into the active layer. Tensile strain acts to reduce the HH(z) confined state with respect to the LH(z). This first pushes the valence band quantum well into degeneracy at around 0.2% tensile strain and then forces the HH(z) state below the LH(z) state. The calculated transition energy closely follows the transition energy measured from the lasing wavelength.
theory section 5.1 The optical transition energy was then calculated from the bandgap of the QW material plus the offsets of the CB and VB quantum confined states, using the method in section 5.3. The effective masses were derived from strain compensated Luttinger parameters, linearly interpolating between the two binary materials GaAs and GaP forming the QW calculated in a model developed by Meney [105]. The calculated variation of the E1-HH(z)1 and E1-LH(z)1 transition energies as a function of strain are shown for the 90Å GaAs$_{1-x}$/Al$_{0.3}$Ga$_{0.7}$As quantum well, fig(5).

The calculated transition energies are in close agreement with the measured photon energy at the lasing wavelength. This is expected as the carrier population is greatest at the band edge in a QW due to the step like DOS. Thus the band edge population reaches population inversion first via the Bernard Duraffourg condition [5]. The shift in the E1-HH(z)1 and E1-LH(z)1 transition energies follow the shifts in the VB states under tensile strain described in section 2.2.4.2. In the unstrained GaAs QW the E1-HH(z)1 transition energy is smaller than the E1-LH(z)1 transition due to the deeper quantum confinement of the HH(z) states. The transition energies approach each other with increasing strain and become equal at 0.2% tensile strain. Further increase in tensile strain results in the E1-LH(z)1 transition being less than the E1-HH(z)1 transition energy as tensile strain reduces the HH band with respect to the LH. The photon energy at the lasing wavelength appears to follow the smallest transition energy.

5.6 COMpressive STRain

Between 0 and 17% indium was incrementally added to a GaAs QW. This can be seen to increase the lasing wavelength from 847 to 974nm, mainly through the reduction of the fundamental bandgap. This also incorporates compressive strain into the QW. The increase in lattice constant and the decrease in bandgap with indium concentration is shown in fig(4). Compressive strain acts to increase the energy of the LH band with respect to the HH band thus augmenting the difference between the HH(z) and LH(z) quantum confined states. Fig(6) shows the calculated transition energies for the In$_{1-x}$Ga$_{x}$As/Al$_{0.3}$Ga$_{0.7}$As quantum well that form the basis of these lasers. This time there appears to be a discrepancy between the calculated transition energies and the measured
Fig(6) Shows the calculated transition energy as a function of compressive strain for a 90Å $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ $x:0-0.17$ single quantum well. The addition of indium to GaAs reduces the fundamental bandgap and increases the lattice constant. This acts to reduce the fundamental transition and incorporate compressive strain in the layer. Compressive strain acts to shift the HH(z) with respect to the LH(z) state in the opposite sense to tensile strain. The HH(z) and LH(z) states are pushed away from each other with the E1-LH(z) being the fundamental well transition. Two bandgap bowing parameters, 0.38eV and 0.61eV, are commonly found in the literature for the InGaAs material system. For these lasers better agreement between the measured optical transition energy at the lasing wavelength and the calculated transition energy can be found by using a bowing parameter of 0.61eV rather than 0.38eV.
photon energies at the lasing wavelength if the bowing parameter for In\(_x\)Ga\(_{1-x}\)As used by Krijn of 0.38eV is used. However better agreement can be found if the bowing parameter used by Carl van der Poel of 0.61eV is used. The significance of the difference in these bowing parameters is unclear. The low temperature photoluminescence measured by Kirby et al [106] in In\(_{0.12}\)Ga\(_{0.88}\)As/GaAs QW is better described by the Krijn bowing parameter 0.38eV rather than 0.61eV. This is also true of the range In\(_{0.2}\)Ga\(_{0.8}\)As/ Al\(_x\)Ga\(_{1-x}\)As of structures given by Hosea and Lancefield [107] and GaAs/InGaAs structures grown by Marzin et al [18]. On going work of this department by Rowlands [109] on In\(_x\)Ga\(_{1-x}\)As/InP which address tensile-strained rather than the previously compressively strained In\(_x\)Ga\(_{1-x}\)As is also described by the 0.38eV bowing parameter. The bulk bandgap of In\(_x\)Ga\(_{1-x}\)As measured by various technique and analysed by Schulze et al [97] is better fitted with the 0.61eV bowing parameter. This is also true of the data presented in Landholt & Bornstein [110]. It is interesting to speculate on the origin of this discrepancy. The ratio of these bowing parameters is 1.6, greater than expected from the experimental error. This implies that there is some physical difference between the samples presented here even though they are based on the same material system. Both Schulze et al and Berolo et al [97,98] state that the introduction of a disordering term to their virtual crystal calculations of the bandgaps in In\(_x\)Ga\(_{1-x}\)As was necessary to fit the data. If this discrepancy were due to some physical effect rather than parameterization then some correlation between this and the anomalously high threshold currents measured in these compressive devices may be expected. Further work to resolve this issue would be necessary.

5.7 MATERIAL QUALITY

Poor material quality tends to have an adverse effect on the operating performance of semiconductor lasers. Crystallographic defect sites, misfit dislocations and contaminants can all act as centres for nonradiative recombination, which will reduce the quantum efficiency of an electroluminescent device. In these lasers in particular the Al in the AlGaAs cladding and barrier layers is well known to be subject to oxidation during growth [70,71], which tends to generate inter band gap electron traps[70] which favour nonradiative Shockley, Read, Hall recombination processes [68,69].
Here we attempt to assess the growth quality of the material by calculating the well strain, and transition energies from the basic material parameters. The strain in the QW was measured [94], by x-ray diffraction. It should be possible to calculate these strains using the compositional data supplied for each laser. Through Vergard's law, [104], strain is expected to be linearly related to composition. The In mole fraction was varied between 0 and 17% whilst the phosphorus mole fraction was varied between 0 and 29% during the growth of the well. The calculated QW strain agrees well with the values measured by X-ray diffraction, suggesting that the layers are at least compositionally correct. Furthermore it has already been shown that the calculated QW transition energy is close to the measured photon energy at the lasing wavelength, if the appropriate bowing parameter is used. Variation in the QW width would tend to shift the lasing transition away from the calculated values for our 90Å QW. However no significant variation in lasing wavelength or threshold current was observed over batches of 10 of each strain that were fabricated.

5.8 STRAIN RELAXATION

When the energy stored through strain exceeds that needed to nucleate misfit dislocations the strain relaxes forming defects. These defects have been shown to increase the threshold current of a semiconductor laser [71]. If the strain does not exceed this value then the layer will remain stable and not relax. The strain energy stored in the layer increases with layer thickness. Therefore a critical strain thickness product may be defined which should not be exceeded in order to maintain good strained material, fig(7). The strain thickness product may be calculated by the method of Matthews and Blakeslee [62] or by People and Bean [63] and is typically of the order of 150-200Å% but a very large uncertainty. The critical thicknesses of the GaAs/GaAsP and GaAs/InGaAs material systems have been studied experimentally. Fox and Jesser [99] have measured a strain thickness product of 559Å% using transmission electron microscopy (TEM). Their value exceeds the expected value of 78Å% using a Matthews and Blakeslee force-balance calculation but this discrepancy may be due to incorporating extra frictional forces into the force-balance model.
Energy to Form Dislocations

Energy stored in strain

Layer Thickness

Fig(7) Illustrates the conditions under which strain relaxation in the quantum well can occur. For a given strain the energy stored in the strained lattice increases linearly with layer thickness. As the critical thickness is reached when this energy will equal that needed to form misfit dislocations. Above this critical thickness strain will relax in the form of misfit dislocations. These misfit dislocation act as nonradiative recombination centres, which will reduce the quantum efficiency of an optoelectronic device.
Fig(8a) shows the critical thickness of GaAs₁₋ₓPₓ grown on a GaAs substrate calculated by the method of Matthews and Blakeslee and People and Bean. The stars show the samples measured by Soga et al [100] by TEM. Their results indicate the onset of lattice relaxation as the People and Bean limit is crossed. Strain thickness products larger than the Matthews and Blakeslee calculation have been measured for the same material system by Fox and Jesser [99]. The data from Soga et al also suggests that the strain thickness product of the most phosphorus rich tensile strain samples in this thesis, x=29% in a 90Å quantum well, is not exceed. However the Matthews and Blakeslee limit is exceeded. Fig(8b) shows the strain thickness product for InGa₁₋ₓAs grown on GaAs from Wang and Groves [141]. The strain thickness product of the most Indium rich compressively strained sample used in this thesis, x=17% in a 90Å quantum well, is not exceed. Therefore InGaAs quantum wells in this thesis can be assumed to be unrelaxed.
Fig(9) Illustrates the reflection of the optical field at one of the $\lambda/2 \ Al_2O_3$ coated facets. The reflectivity of a given facet is dependent on the refractive index of the laser medium, the layer, the external environment and the thickness of the layer. At a thickness of $\lambda/2$, the reflectivity becomes independent of the refractive index of the layer material. The use of such a coating in these lasers is to provide a protective capping layer between the external environment and the laser material rather than to enhance the facet reflectivity.
This larger strain thickness value is also supported by TEM measurements of Soga et al [100], shown in fig(8a). The thickness of the TEM fringe increased as their samples, shown as stars, crossed a critical thickness equivalent to 4000Å%, in good agreement with People and Bean but again greater than the Matthews and Blakeslee calculation. This was interpreted in terms of lattice relaxation at the GaAsP/GaAs interface. This experimental data suggests the strain thickness product of GaAsP layers on GaAs is better described by the People and Bean calculation. This maximum strain thickness product in the tensile strained lasers used in this work is 90Å%, i.e. well below the critical levels shown by all but People and Bean. However, as will be shown below, our device characteristics may be explained by a model with negligible dislocations for all samples. The temperature and pressure dependence of the threshold current measured in chapter 6 could not be explained in terms of strain relaxation of the QW.

Fig(8b) shows the Matthews and Blakeslee curve for InGaAs on GaAs calculated by Wang and Groves [141]. This time the maximum compressive strain of our samples (1.18% for a 90Å QW – 100 Å%) falls inside the Matthews and Blakeslee limit (~250Å%) suggesting that these lasers are also unrelaxed.

5.9 FACET COATINGS

The use of thin layers of material to increase the reflectivity of the facet and reduce the mirror losses in the laser is common. Analysis of the reflectivity of such a layer in terms of its composition and thickness has been presented by numerous Authors, [111]. The reflectivity of a layer, for normal incidence, is given by.

\[
R = \frac{(n_1 - n'_2)n'_1 \cos \delta + i(n_1 n'_2 - n'_1^2) \sin \delta}{(n_1 + n'_2)n'_1 \cos \delta + i(n_1 n'_2 + n'_1^2) \sin \delta}
\]

Equation 5-10

Here, \(n_1\) is the refractive index of the substrate, \(n'_1\) is the refractive index of the layer, \(n'_2\) is the refractive index of the external environment, and \(\delta\) is the phase lag of the optical wave after propagating across the thickness of the film. If the thickness of the film is made equal to half the wavelength then, \(\delta=\pi\), and the reflectivity of the film reduces to.
At this thickness the reflectivity of the film becomes independent of the refractive index of the film. This is the case in these lasers and hence the $\lambda/2 \text{Al}_2\text{O}_3$, coatings serve only as protective capping layers rather than acting to increase the facet reflectivity of the lasers.

5.10 SUMMARY

In this chapter the overall structure of these lasers has been described. These devices are all single quantum well GaAsP/AlGaAs or InGaAs/AlGaAs lasers grown on an 001 orientated GaAs substrates. Each laser has a 50\(\mu\)m oxide stripe contact and $\lambda/2$ Al$_2$O$_3$ coated facets. Attention has focused on the variation of the bandstructure from laser to laser as all these devices differ only by an incremental variation in the composition of the quantum well, whilst the composition and structure of the barrier, cladding and substrate are nominally identical. Thus any measured variation in performance from device to device, such as the threshold current, may be correlated with this incremental variation in composition and bandstructure.

The GaAsP and InGaAs material systems provide a convenient way of tuning the lasing wavelength in the near infrared region 0.980-0.749\(\mu\)m, whilst incorporating the beneficial effects of strain into the active layer of the devices. Thus the addition of phosphorus to a GaAs QW acts to shorten the lasing wavelength, incorporating tensile strain into the QW, whilst the addition of indium increases the lasing wavelength and incorporates compressive strain into the QW.

Calculations of the strain and fundamental QW transition energy in the GaAsP material system closely agree with the layer strain measured through x-ray diffraction.
and the measured transition energy at the lasing wavelength respectively. The calculations show that the Confined HH and LH states in the QW become degenerate at a tensile strain of ~0.2%. The large valence band density of states that results from degeneracy may be correlated with the observed maximum of threshold current, below (chapter 6), at 0.2% tensile strain.

The strain can be predicted to the same degree of accuracy in the compressively strained InGaAs material system. However the transition energy at the lasing wavelength is better predicted using a bandgap bowing parameter of 0.61eV[94] rather than 0.38eV [96]. Similar calculations on number of example quantum well systems, [106-109], has shown that the choice of bowing parameter is dependent on the system under examination. The ratio of these two parameters, 1.6, is greater than expected from the experimental error, implying a physical difference between the samples measured even though they are based on the same material system. A possible candidate could be alloy ordering effects in the InGaAs layer that have been seen to shift the fundamental bandgap [97,98].

A fall in quantum efficiency of a laser may arise from strain relaxation effects if the critical strain thickness product of the quantum well material of the active layer is exceeded. Any rise in threshold current towards high strains may be associated with these strain relaxation effects. The strain thickness product and calculated for InGaAs [141]. The results suggest that the maximum strain achieved in both the tensile and compressive regimes for these 90Å quantum wells comfortably below the calculated strain thickness product in either case. Therefore it can be assumed that these devices are free of the detrimental effects of strain relaxed layers.

It has also been shown that the λ/2 Al₂O₃ facet coatings serve only as protective capping layers rather than enhancing the facet reflectivity. This arises because the reflectivity of a single layer reflective coating becomes independent of the refractive index of the layer material, Al₂O₃, at a thickness of λ/2. The facet reflectivity becomes a function of the refractive index step between the laser and the external atmosphere identical to that expected from a laser without facet coatings. Thus a change in the
external medium in which the laser is operated may be modelled in terms of the change in the refractive index of that medium alone. This simplifies the modelling of the behaviour of these lasers in the liquid pressure medium, assuming that the shift in the lasing wavelength with pressure is small percentage of the starting wavelength.
CHAPTER 6

INFLUENCE OF CARRIER LEAKAGE ON THRESHOLD CURRENT OF TENSILE-STRAINED GaAsP/AlGaAs

6. INTRODUCTION

The GaAs/AlGaAs material system is closely latticed matched and has been widely used for the production of lasers diodes. The formation of a GaAsP quantum well active region by the addition of phosphorous to GaAs provides a convenient method for moving to shorter operating wavelengths. This also has the effect of incorporating tensile strain which can be beneficial in increasing the radiative efficiency and reducing the threshold current [112].

In this chapter the series of tensile-strained GaAsP/AlGaAs single-quantum-well lasers are studied. It is again stressed that these devices differ from one another only by an incremental change in phosphorous composition in the QW. Since the dimensions and compositions of the substrate, barrier and cladding regions remain identical, a direct correlation of the observed variation of threshold current with just the band structure of the QW may be made.

As phosphorous is added to the initially unstrained GaAs QW, the threshold current is seen to first increase between 0 and 0.2% tensile strain and then fall from 0.2 to 0.51% tensile strain. This is associated with the effects with tensile strain increasing the energy of the LH(z) band with respect to the HH(z), ultimately reversing the splitting of the valence band degeneracy imposed through pure quantum confinement in the unstrained well. The maximum in the threshold current, observed at ~0.2% tensile strain, coincides with the strain calculated at which the degeneracy of the valence band is re-established (Section 5.5). This is consistent with the expectation
that the degenerate valence band structure would maximise threshold carrier density and so maximise the threshold current. Beyond 0.51% tensile strain (14.8\% phosphorous concentration) the threshold current begins to increase again. Tensile strain by itself would be expected to continue splitting of the valence bands and augment the TM gain characteristics, thereby reducing the threshold current still further. The temperature dependence of the threshold current is also seen to increase in the lasers in this strain range. A further increase in threshold current in these devices can be induced by the application of externally applied hydrostatic pressure. Such an increase with temperature and pressure in InGaAlP visible lasers has been interpreted previously [113] as evidence that the threshold current of these lasers is becoming dominated by a leakage current of electrons escaping via the X-minimum into the p-doped cladding region of these devices. It will be seen that a similar conclusion can be drawn for the lasers studied here. This view is supported by the observation of the reversible loss of lasing at a pressure 6kbar, the pressure where Γ-X crossover occurs and the Al\(_{0.5}\)Ga\(_{0.5}\)As barrier region becomes indirect.

6.1 VARIATION OF THRESHOLD CURRENT WITH STRAIN

In the previous chapter it was shown that the effect of incorporating phosphorus into a GaAs quantum well was to increase tensile strain and shorten the lasing wavelength. Fig(1) shows the variation of threshold current with tensile strain as phosphorus is incorporated into the QW. The maximum in the threshold current at 0.2% tensile strain coincides with the calculated strain at which the QW becomes degenerate at the HH(z)/LH(z) crossover (Section 5.5). This crossover point has been demonstrated through measurements of the TE and TM photoluminescence in nominally identical QW structures [94]. This is the point at which the valence band DOS is most different from that of the conduction band. Thus the transparency carrier density is likely to be at a maximum leading to a maximum in the threshold current (Section 2.11). Reducing the strain from 0.2 to 0% the deepest confined valence band state becomes HH(z)-like. The in-plane dispersion makes the DOS LH(x,y)-like thus the DOS approaches that of the conduction band and the transparency carrier density is reduced. Also (Section 2.12) an
Fig(1) Shows the isotherms of threshold current as a function of strain. The threshold current tends toward a maximum at the HH/LH crossover at 0.2% strain. The increase in threshold current and the divergence of the isotherms at strains in excess of 0.51% are indicative of the onset of an extra strain and temperature dependent nonradiative component to the threshold current.
enhancement of the TE gain and the suppression of the TM gain can be expected which also contributes to the reduction in the threshold current. A smaller reduction in the valence band DOS is expected as the strain is increased beyond 0.2% as the deepest confined state is now LH(z) making the DOS governed by the HH(x,y) effective mass. However the enhancement of the TM gain as the tensile strain is increased is stronger than the enhancement of the TE gain as the tensile strain is reduced passed the point of valance band degeneracy. Thus an initial reduction in the threshold current is seen as tensile strain is increased.

The threshold current is seen to increase rapidly as the strain is increased further than 0.51%. This is not explicable in terms of the modification of the valence band due to the effects of tensile strain. Also, the isotherms of threshold current are seen to diverge past this strain. This is indicative of the presence of some extra, more temperature sensitive, non-radiative component to the threshold current. It is identification of this non-radiative current that is the objective of the work presented here and unless otherwise stated it should be assumed that we are referring to devices with tensile strains equal or greater than 0.51%.

6.2 VARIATION OF THRESHOLD CURRENT WITH TEMPERATURE

The variation of threshold current with temperature has been measured from 77-360K for the 0.68%, 0.82% and 1.00% tensile strained lasers and the results are presented in fig(2). At temperatures, ~77-250K, a gentle linear increase of the threshold current with temperature is observed. Beyond 250K a superlinear increase in threshold current with temperature is seen, indicative of the onset of an extra, thermally activated contribution to the threshold current. A similar behaviour has already been seen previously [114,115].

The initial linear temperature dependence of the threshold current is explicable by the expected temperature dependence of an ideal QW laser. In the absence of other non-radiative recombination mechanisms all injected carriers will recombine radiatively in
Fig(2) shows the temperature dependence of the three most tensile-strained lasers. The threshold current tends towards a linear variation with temperature below ~250K as expected from theory. This trend may be used to find the excess current indicative of an extra thermally activated, nonradiative component to the threshold current.
Fig(3) An Arrenhius plot of the excess current, fig(2), shows the linear behaviour indicative of an exponentially activated process. The activation energy derived from the slope of the curve is \(-300\)meV. We estimate that this corresponds to the position of the electron quasi-Fermi level from the cladding band edge. This suggests that poor carrier confinement within the laser heterostructure may be responsible for the observed strain and temperature dependence of the threshold current.
the QW. Equation (2.6-2) shows that the radiative component of the threshold current can vary as the square of the carrier density. The temperature dependence has two components. The coefficient of radiative recombination decreases as $l/T$ [116] in a ideal QW, whereas the carrier density will increase in proportion to the density of states which is in turn proportional to the temperature in a QW. Therefore the temperature dependence of the radiative component of the threshold current may be expressed as.

$$I(rad) \propto T$$

Equation 6-1

With this good agreement between experiment and theory we may assume that the radiative current continues to increase linearly at higher temperatures, as indicated by the extrapolations shown in fig(2), and address the cause of the extra excess threshold current.

This excess current is displayed on an Arrhenius plot in fig(3). The linear behaviour is characteristic of an exponentially activated process of the form.

$$I(excess) = \exp(-\Delta E/kT).$$

Within experimental accuracy the slopes for the 1.00%, 0.82% and 0.68% tensile strained lasers are equal and correspond to an activation energy 300meV.

### 6.3 LEAKAGE CURRENT

The concept of a leakage current will be presented below before any attempt is made to justify that the previous results may be described in terms of such a leakage current. An understanding of the basic process of carrier leakage over the heterobarrier will place the following measurements in context.

Under a given forward bias a certain fraction of the injected carrier density will have energy in excess of the barrier/cladding heterobarrier discontinuity. These carriers have the possibility of leaking into the doped cladding region, where as minority carriers.
they recombine and are lost from the lasing process. The flux of carriers appears as an extra non-radiative component to the threshold current. The leakage current is limited by the rate at which the unconfined carriers can drift and diffuse into the cladding region. In the limiting case where the drift component is zero the leakage current, $J_{\text{leak}}$, may be expressed as [117].

$$J_{\text{leak}} = \frac{qD_{n,p}N_{c,v}}{l_{n,p} \tanh \left( \frac{w}{l_{n,p}} \right)} \exp \left( \frac{-\Delta E}{kT} \right)$$

Equation 6-2

Where, $q$, is the fundamental electronic charge. $D_{n,p}$, is the diffusion coefficient for electron or holes, $l_{n,p}$, is the diffusion length of the minority carriers in the cladding regions, $w$, is the width of the doped cladding region, $N_{c,v}$, is the conduction or valance band density of states in the cladding region. $\Delta E$, is the activation energy of the process. $k$, Boltzmann's constant and $T$ the temperature. It is assumed that the carrier concentration falls to zero at the end of the cladding region.

The exponential Boltzmann's tail term gives the unconfined carrier density above the barrier/cladding band offset. Thus the activation energy will be equal to the separation of the quasi-Fermi level from the cladding band edge. Under forward bias, the flat band condition is approached and the diffusion limited case is assumed in our structures.

The variation of the threshold current with both temperature and strain may be understood in term of the leakage currents. The addition of phosphorus to GaAs not only incorporates tensile strain into the QW, but increases the lasing transition energy, as the bandgap of GaAsP is greater than that of GaAs. In these lasers the bandgap of the QW material, which varies from laser to laser, approaches that of the barrier, which is identical in each laser. The QW become shallower with strain. The quasi-Fermi level separation at transparency will follow the increase in transition energy with strain. Thus the quasi-Fermi levels will also tend to approach the band edges in the material surrounding the QW leading to a population of carriers outside the QW. The activation
energy of the leakage process will reduce with strain and therefore the fraction of carriers with energy in excess of the heterobarrier discontinuity will increase through Equation 6-2. Therefore, even though the radiative component of the threshold current is expected to fall with strain, the leakage component of the threshold current will be expected to increase. The opposite action of these two components may well explain the initial fall then rise in the observed threshold current.

The temperature dependence of the threshold current may also be explained in terms of this leakage current. The thermal activation of carriers over the heterobarrier will also increase the leakage current. At a sufficiently low temperature a negligibly small fraction of the injected carrier population will have energy in excess of the heterobarrier. Thus the leakage current can be considered as zero. The temperature dependence of the threshold current will be described by the temperature dependence of the radiative component of the threshold current only. This corresponds to the linear region of the threshold current temperature characteristics, fig(2). The rapid increase in threshold current with temperature can be described by an exponentially activated process, such as that described by Equation 6-2. Thus the measured activation energy, ~300meV, should correspond to the activation energy in Equation 6-2, the position of the minority carrier Fermi level measured from the cladding band edge.

6.3.1 ESTIMATION OF THE ACTIVATION ENERGY

The activation energy for the leakage process may be estimated from a knowledge of the quasi-Fermi level positions in the laser structure under forward bias. As discussed previously in chapter 3, the splitting of the quasi-Fermi levels in the intrinsic active regions can be found from the threshold voltage. The threshold voltage is expected to be of the order of the lasing photon energy through the Bernard-Duraffourg transparency conditions. This is reflected in the IV curve for the 0.82% tensile-strained laser is shown in fig(7), chapter 4. After eliminating the effects of parasitic series resistance the threshold voltage tends to pin at 1.635V. The lasing photon energy at the wavelength of this device is 1.629 eV. Thus the quasi-Fermi level splitting at threshold is in line with
expectation. Assuming the quasi-Fermi levels are flat across the active regions (equivalent to the injected carrier density being invariant over this distance) it is possible to estimate the position of the quasi-Fermi level from the cladding band edge in either the n or p-type regions. This will give a measure of the population of carriers unconfined by the heterobarrier. The position of the electron quasi-Fermi level from the p-type cladding band edge can be estimated as follows.

\[ \Delta E_e = E_g^X - qV_{th} - (F_v - E_v) \]

Equation 6-3

A similar expression may be written for the position of the hole quasi-Fermi level from the n-type valance band edge.

\[ \Delta E_v = E_g^X - qV_{th} - (E_c - F_v) \]

Equation 6-4

Where, \( E_g^X \), is the bandgap to the X minimum in the indirect cladding of these devices and \( qV_{th} \) is the threshold voltage in electron volts, equivalent to the quasi-Fermi level splitting in the active region of the laser. \( (F_v - E_v) \) is the position of the Fermi level relative to the valance band edge, in the p-type cladding region. At room temperature the Fermi-level may be considered to be pinned the valence band edge due to the large number of ionized acceptors. A similar situation occurs in the n-type region where the Fermi level is pinned, \( (E_c - F_v) \), from the conduction band edge due to the large number of ionized donors.

For simplicity all the dopants were considered to be ionized. The position of the pinned Fermi-level could then be calculated from these fully ionized populations. Due to the large number of dopants the exponential Boltzmann’s approximation to the Fermi-Dirac integral was considered to be invalid. The numerical approximation to the Fermi-Dirac integral of Bednarczyk [118] was then used. A numerical bisection method was applied using this approximation to solve for the Fermi level position for the given ionized dopant concentration.
Using the bandgap bowing parameters presented in Krijin [96] for the X-minimum in Al$_x$Ga$_{1-x}$As, the activation energy of the electron and hole leakage processes were 305 and 260 meV respectively. These values are in reasonable agreement with the values of the activation energy found in the Arrhenius plot, fig(3) and are in line with values expected from our leakage hypothesis.

6.4 VARIATION OF THRESHOLD CURRENT WITH PRESSURE

Further insight into the behaviour of the threshold current in these devices can be seen through the external application of hydrostatic pressure. The direct bandgap at the $\Gamma$ point in a III-V semiconductor increases with pressure at a rate of ~10 meV/kbar, whilst the indirect bandgap of to the X minimum decreases with pressure at a rate of ~2 meV/kbar. This means that the indirect bandgaps of the cladding region will decrease relative to the direct bandgap of the barrier region. This will reduce the height of the potential energy step to the cladding region which confines electrons and holes. Therefore an increase of the threshold current with pressure would be expected in these lasers if poor carrier confinement is responsible for their observed strain and temperature characteristics. [Auger processes tend to become increasingly quenched as the direct bandgap increases. A corresponding reduction in threshold current would be expected to be observed if Auger recombination were dominating the threshold current.]

The radiative component of the threshold current will also have some pressure dependence. This may be estimated, as has been done previously[119] from the rate of increase of the direct bandgap with pressure.

Fig(4a) and fig(4b), show the increase in lasing transition energy derived from the measured lasing wavelength with pressure, for the 0.82% and 0.68% tensile-strained lasers respectively. The linear increase at a rate of 9.76 meV/kar and 9.95 meV/kbar is in accordance with our expected rate of increase in direct bandgap with pressure. Fig(5a) and fig(5b), shows the increase in threshold current from ambient pressure, for the same lasers. We can compare this with the increase in radiative current with pressure.
Fig(4) Shows the photon energy at the lasing wavelength as a function of pressure. We correlate the increase in photon energy mainly to the increase of the direct bandgap of the GaAsP QW with pressure. We deduce a pressure coefficient of the direct bandgap of GaAsP of 9.8 meV/kbar.
Fig(5) Shows the increase in threshold current, normalised at atmospheric pressure, from atmospheric pressure for the 0.82% tensile- strained device. The rate of increase of threshold current with pressure is much greater than expected from just the radiative current alone. The increase in pressure induces a decrease of the X(cladding)/(barrier) heterobarrier. The resulting increase in threshold current is consistent with the conjecture that a leakage current of carriers spilling into the doped cladding regions makes a major contribution to the threshold current of these lasers.
derived [119], and shown the solid line fig(7a). The observed rate of increase in threshold current with pressure is clearly much greater than that of the radiative component of the threshold current. The strong increase in the threshold current with pressure shows clearly that Auger recombination, which decreases with increasing pressure [40], is not a significant loss mechanism in these lasers. However, such an increase can be explained in terms of carrier leakage as described above section 6.3.

**6.5 COMPUTER MODEL**

Detailed computer modelling of these devices was undertaken by Meney [76] in conjunction with the experimental work presented in this chapter. The observed changes in the threshold current with strain, temperature and pressure were simulated in these devices using a technique similar to Lundstrom & Shuelke [82,83], using the underlying principle of solving Poisson’s equation across the entire laser structure as presented in chapter 3.

The loss mechanisms incorporated into the model were leakage and monomolecular processes. These were modelled in a simplified form in order to facilitate the understanding of the carrier dynamics in the device. For example, Shockley Read Hall [68,69] and interface recombination were lumped together and described in terms of a fixed non-radiative recombination lifetime of 15ns for the carriers anywhere in the Γ states in the laser. Carriers populating the satellite minima were assumed to have a lifetime twice as long as those populating the Γ states to simplify the effect phonon interactions. This represents a considerable simplification of the problems involved in calculations of non-radiative recombination rates.

The diffusion limited leakage current was then calculated from Equation 6-2 from the knowledge of the carrier density above the barrier/cladding heterobarrier offset generated by the model. The diffusion parameters are found empirically to be those which give the best fit to the experimental data. The justification for this is that the observed variation of threshold current with strain temperature and pressure is expected to be described by the same process, leakage into the cladding regions and that the structure of the three lasers studied here varies, nominally, only in the composition of the QW.
6.6 FITS TO THE EXPERIMENTAL DATA

Fig(6), shows the fit to the variation of threshold current with strain. As expected the leakage current is seen to increase with tensile strain and dominate the threshold current, whilst strain acts to reduce the radiative component, $J_{\text{rad}}$, of the threshold current. The increase in the non-radiative current, $J_{\text{leak}}$, with strain arises from the increase in the total carrier population in the laser divided by the fixed non-radiative lifetime. The shortening lasing wavelength with strain means that the quasi-Fermi levels approach the band edges in the barrier/cladding regions at threshold and gives rise to the leakage current, $J_{\text{leak}}$. The same transport parameters were used to calculate the diffusion limited leakage current, from Equation 6-2, in each laser as the leakage current occurs in a nominally identical region of the laser structure.

Fig(7), shows the increase in threshold current with temperature for the 1.00% tensile laser. Again, the threshold current, above 250K, is seen to be increasingly dominated by the leakage current. Below 250K, the leakage current tends to be frozen out and we revert to the radiative regime. Good fits to the same data for the 0.82% and 0.68% tensile lasers were also achieved. Again we stress that the same transport parameters were used to calculate the diffusion limited leakage current. The linear behaviour of $J_{\text{rad}}$ and the exponential $J_{\text{leak}}$ justify our analysis of the experimental data in fig(2&3).

Fig(8), shows the calculated increase in threshold current with pressure for the 0.68% tensile laser. The calculations were done before the measurements were made and so represent a prediction. A series of curves of different threshold gains, 25, 35 and 45cm$^{-1}$ were generated. The closest match with the measured data occurred for a gain of 45cm$^{-1}$. Extrapolating the calculations to fit the data produced a gain of 47±2 cm$^{-1}$. This value is close the value of 50cm$^{-1}$ proposed by Carl van der Poel [94]. The leakage and radiative components of the threshold current for this fit are also shown, fig(8). The calculated increase in threshold current with pressure for the 0.82% tensile laser is clearly better explained by the increase in leakage current rather than the radiative current.
The model consistently predicts that the electron leakage current is very much greater than the hole leakage current. This is contrary to initial expectations as, with a symmetrical SCH and flat electron and hole quasi-Fermi levels across the laser, the heterobarrier perceived by electrons and holes should be similar. Also, the majority of unconfined electrons reside in the X and L minima of the indirect cladding. The mobility of these carriers are expected to be similar to that of unconfined holes due to their similar effective masses. However similar models [120], have shown that the hole quasi-Fermi level is not flat across the SCH. In this reference a rapid change in the hole population either side of the QW is mirrored in a lowering of the quasi-Fermi level with respect to the valence band edge. This may be interpreted in terms of efficient trapping of holes by the QW, leading to poor transmission of holes across the QW. The lowering of the hole quasi-Fermi level with respect to the valance band edge in the cladding region will act to increase the activation energy of the leakage process. The hole component of the leakage current will therefore be smaller under these conditions.

The increase in threshold current with pressure has been re-modeled for the 0.68% tensile laser, fig(9). This time, however, we have first removed the X-minimum from the barrier/well regions and retained the L-minimum and visa-versa. The previous good fit to the data was maintained with the absence of the L-minimum and keeping only the X-minimum, but lost with the removal of the X-minimum whilst retaining the L-minimum. This suggests that electron carrier transport through the X-minimum governs the leakage process. The valence band, as perceived by holes, was unaffected by these operations. This view was further supported by the observation of the reversible loss of lasing at 6kbar. in our 15kbar rig, in both samples tested. This pressure corresponds to the point at which the Al0.5Ga0.5As barrier region becomes indirect at the Γ-X conduction band crossover. fig(10).
Fig(6) Shows the calculated threshold current density as a function of strain in comparison to the measured values. Also shown are the radiative, nonradiative and leakage components of the threshold current. The electron mobility and diffusion length in the X-minima of the p-type cladding used to calculate the leakage current are shown. A fixed nonradiative lifetime of 15nsec were used for carriers anywhere in the minima and 30nsec for the X minima were used for simplicity. The threshold gain varied between 41 to 55cm⁻¹ as a function of strain. The increase in leakage current density with strain follows the observed increase in threshold current density with strain.
Fig(7) Shows the calculated threshold current density as a function of temperature for the 1.00% tensile laser. Again the radiative, nonradiative and leakage components of the threshold current density are shown. These were calculated from the same parameters as before, fig(6). The rapid increase in the threshold current density is clearly mirrored in the increase in leakage current density with temperature.
Fig(8) Shows the calculated increase in threshold current density and with pressure, in comparison with measured values for the 0.68% tensile-strained laser. The same parameters were used as in fig(6&7). The threshold current densities were calculated by treating the pressure invariant threshold gain as a fitting parameter which was found to be 47cm$^{-1}$. The leakage component of the threshold current increases more rapidly and then eventually dominates the radiative and nonradiative components of the threshold current combined.
Threshold Current Density vs. Pressure

$g_{th} = 45 \text{cm}^{-1}$ 0.68\% Tensile Laser@23C

Fig(9) Shows the previous data, fig(8), remodelled at a pressure invariant gain of 45 cm$^{-1}$. First the X-minima was removed and the L-minima retained in the well/barrier region and then visa versa. It is clear that the presence of the X-minima in the well/barrier region is needed to describe the data while the L-minima has a negligible effect.
Fig(10) Shows the calculated HH and LH bandgaps of the Al$_{0.3}$Ga$_{0.7}$As barrier region as a function of pressure. We correlate the reversible loss of lasing at 6kbar in both the 0.68% and 0.82% lasers with the barrier regions going indirect at the Γ-X crossover. This is further evidence that the presence of the X-minima in the barriers region plays an important role in the carrier leakage process.
6.7 SUMMARY AND CONCLUSIONS

In this chapter a study of a range of tensile-strained GaAsP/AlGaAs lasers operating between 847-749nm has been presented. Measurements of the variation of threshold current with strain, temperature and pressure have been presented as good empirical evidence for the same dominating process, a leakage current of unconfined carriers flowing into the cladding regions. This conclusion has been further supported by a computer model which has consistently generated good fits to all the observed data, using the same transport parameters for the leakage current. These parameters were expected to be invariant from device to device.

The computer model has consistently demonstrated that the leakage current was dominated by electrons flowing into the X-minimum of the indirect cladding. Re-modelling the data with first the X-minimum and then the L-minimum absent from the barrier/well region showed that the presence of the X-minimum and not the L-minimum was necessary to maintain a fit to the data. It is therefore concluded that the electron current flowing through the X-minimum of the device governs the magnitude of the leakage current. A consistent, reversible loss of lasing for two different devices at 6kbar has also been observed. This pressure corresponds to the point where the barrier regions become indirect at the Γ-X crossover.

Previous work has concentrated on explaining the leakage process in terms of the thermal activation of carriers over the heterobarrries at the barrier/cladding interface. The work presented here extends this view and shows that carrier flow across the SCH region also plays an important role in governing the magnitude of the threshold current. This shows that other considerations have to be made in optimising the design of the SCH region to minimise the deleterious effects of leakage currents. A compromise between maximising the heterobarrier height and maximising the Γ-X splitting in the barrier has to be made as one falls at the expense of the other. This sets a fundamental limit of the effectiveness of the AlGaAs material system to form an effective heterobarrier to confine the injected carrier population within the active region of the laser.
CHAPTER 7

COMPRESSIVE LASERS

7. INTRODUCTION

The results gained from the study of the tensile strained GaAsP lasers may be applied to the study the compressive InGaAs devices. This is because laser varies only by an incremental change in the QW composition, thus any change in the threshold current can be correlated to this change in composition. It has been demonstrated in, chapter 6, that shortening the lasing wavelength by introducing phosphorus into a GaAs quantum well induces a leakage current of unconfined carriers diffusing into the cladding regions. This arises from the increased carrier concentration that resides outside the QW as the QW become shallower relative to the AlGaAs separate confinement heterostructure. Thus the shorter wavelength GaAsP devices will suffer more from these leakage currents. The addition of Indium to a GaAs quantum well has the opposite effect to the addition of phosphorus as it makes the QW deeper relative to AlGaAs separate confinement heterostructure. Therefore the leakage current, already low in the low strained tensile devices, would be expected to be reduced still further or even become negligible in these compressive lasers. As discussed in chapter 1, other non-radiative recombination loss processes, shown to be important in long wavelength lasers, are not thought to be important in these devices. Auger recombination processes are also expected to be quenched at the bandgap equivalent to the lasing wavelength of these compressive lasers. Therefore these devices are expected to approach ideality, as our two wavelength dependent loss processes, Auger and leakage, should be minimised.

In this chapter this hypothesis is tested in a range of InGaAs single quantum well lasers. The threshold current of these devices was calculated on the basis of this ideal behaviour. However the calculated variation of the threshold current with strain did not follow the observed strain and temperature dependence of the threshold current in these lasers. In the absence of Auger and leakage processes, the magnitude of the calculated threshold current and its temperature dependence was significantly less than the
observed characteristics. Monomolecular non-radiative processes were also considered. Crystallographic defects can act as centres of non-radiative recombination which would compete with any radiative processes occurring in the laser. The aluminium in the SCH is susceptible to oxidation during growth producing a well known non-radiative defect centre. These could occur in poorly fabricated devices. Such defects would be expected to occur randomly across a batch of samples. However the consistent strain and temperature dependence across a large batch of samples was not in line with the expected random nature of these defects. Thus, if defects were to account for the observed threshold current and its temperature dependence, then their presence should be correlated with either the composition or the bandgap of the QW as this is the only difference between these devices. Another possible mechanism is strain relaxation of the strained QW layer. If relaxation were to occur, it would occur towards higher compressive strain, and could explain the observed turn up in the threshold current strain characteristics at high compressive strain. However the data presented in chapter 5 shows that the critical thickness of the InGaAs QW was not exceeded. Therefore the QW material could be assumed to be in an unrelaxed state.

The experimental evidence presented in this chapter indicates that large carrier densities associated with gain saturation effects may be the root cause of the poor behaviour of these lasers. This conclusion is based on several phenomena.

The measured threshold voltage was significantly greater, at most 344mV, than expected in these devices. The difference between the measured and expected values became greater with compressive strain. This implies, chapter 3, that the quasi-Fermi level splitting at threshold was also becoming much greater than expected. Therefore these lasers were having to be pumped harder in order to reach lasing and pumped harder still as the strain was increased.

The greater than expected voltage was consistent with the observation of optical emission from a higher lying subband in the valence QW in the most compressively strained laser. This suggests that a significant number of carriers reside in these states. If strain is to show its beneficial effects then the population of this higher energy subband
needs to be negligible. The polarization character and measured transition energy suggest that the higher energy spectral emission originates from the El-LH(z) transition, whilst the lasing emission is principally derived from the El-HH(z) transition. Pumping the laser (i.e. increasing the quasi-Fermi level splitting) to reach a higher than normal threshold gain in a gain saturated device would account for the presence of holes in this higher lying subband. Interestingly a clear TM polarized sub-peak was observed at the dominant TE transition energy that gave rise to a mixed polarization of the lasing emission. Band edge transition would be expected to give rise to a relatively pure TE mode for this compressively strained device. However transitions occurring away from the band edge may contain a contribution from the opposite polarization character. Transitions occurring away from the band edge would be seen at large carrier densities associated with gain saturated operation.

If these devices were operating in a gain saturated region then a small shift in the threshold gain would result in a large change in the threshold current. Such shifts may be observed by inducing increased mirror losses in the laser. This was achieved reversibly by immersing the device in a 50:50 liquid n-Pentane/isoPentane mixture. The increase in the mirror losses due to the reduction of the facet reflectivity arising from the higher refractive index of the liquid was calculated. The observed increase in threshold current was much greater than that calculated. Such a shift in the threshold current was not observed in the tensile-strained lasers when they were operated in a 50:50 amyl alcohol/castor oil, a mixture of even higher refractive index, during pressure experiments.

Gain saturation does not appear to be the whole story. In chapter 2 the current flowing into the laser was expressed in terms of the injected carrier density or an \( n \)-dependence. The \( n \)-dependence of the current may be assumed to be related to the dominant recombination process occurring in the device and can be measured from the intensity of the spontaneous emission integrated over all wavelengths. In an ideal device the current flowing into the laser may be accounted for purely in terms of radiative recombination processes. Under such a bimolecular recombination regime the current flowing into the device is proportional to the square of the injected carrier density. The measured
integrated spontaneous emission intensity showed an increase from a bimolecular to a trimolecular recombination process as the temperature of the laser was increased. This indicated the presence of an extra thermally activated component to the threshold current.

This change from an $n^2$ to an $n^3$ recombination regime may be explicable by two different mechanisms. No conclusive experiment was performed to confirm or refute each hypothesis.

The first, perhaps weaker, explanation is that the trimolecular recombination is explicable by Auger recombination as the three body nature of the process gives rise to the $n^3$ dependence of the current. The presence of Auger recombination can explain the observed temperature dependence of the threshold current of lasers operating at 1.3 and 1.5$\mu$m wavelengths. The presence of Auger recombination was not fully demonstrated by the experiment as the recombination regime would be expected to become fixed at $n^3$ at a sufficiently high temperature. A further increase in temperature may have revealed that the recombination regime may have eventually become fixed at a cubic process. The temperature range accessible to the experiment was limited by the apparatus. Theoretically it may be unreasonable to consider the presence of Auger recombination in these devices as Auger is quenched with increasing bandgap. Auger, shown to be important at 1.3 and 1.5$\mu$m wavelengths, may be insignificant in these 847 to 980 nm lasers. However, in a gain saturated device as the $n^3$ dependence of the Auger and large carrier densities would amplify the small probability of the occurrence of an Auger event.

The alternative explanation is that thermally activated leakage currents could give rise to the shift from a bimolecular to a apparent higher order $n$-dependence. The unconfined carrier density in the cladding regions is coupled to the carrier density in the QW. The greater the number of carriers in the well the greater the unconfined cladding population. In a leakage dominated device the current is proportional to the unconfined carrier density, equation 6-2. These unconfined carriers may be expressed as some function of the well density, which is proportional to the square root of the integrated spontaneous
intensity. The relationship between the current and the integrated spontaneous emission (well carrier density) may be expanded as a Taylor series. The higher order terms may also give rise to the observed \( n \)-dependence. The relationship between the current and the integrated spontaneous emission is expected to move beyond a cubic to a higher order \( n \)-dependence. Again the limitations of the experimental apparatus prevented the full demonstration of this. However the leakage hypothesis is also supported by the observation of the anomalously high threshold voltages in these devices, voltages that arise from gain saturated behaviour. The measured threshold voltage is of a similar magnitude to that measured in the tensile-strained lasers. This implies that the activation energy of the leakage process, chapter 6, is also similar.

Both of these conjectures, Auger or leakage, can only be expected to occur in these devices at excessively large carrier densities, those experienced in a gain saturated device. Their presence in these lasers is more a consequence of gain saturation rather than its cause. The question of why gain saturation occurs in these devices has not been answered through the results presented in this chapter. However, the enhancement of TE gain in the compressive regime is not as strong as the enhancement of TM gain in the tensile regime. Also the small optical confinement factor in these single quantum well devices means that more gain is required for lasing. Therefore these compressive lasers may be more susceptible to gain saturation effects than the tensile lasers. Optical absorption rather than non-radiative recombination may be the culprit in driving these devices into a gain saturated regime.

7.1 OBSERVED THRESHOLD CURRENT AS A FUNCTION OF STRAIN

Fig(1) shows how the threshold current varies as a function of compressive strain. A region from 0% to 0.69% compressive strain is observed where the threshold current seem relatively independent of strain. The spacing of the isotherms of threshold current appears to be very similar in this region. At strains greater than 0.69% the threshold current is seen to increase with strain whilst the isotherms of threshold current are seen to diverge.
Fig(1) Shows the variation of threshold current density with compressive strain. The threshold current density appears to be relatively independent of strain between 0 and 0.69% compressive strain. The spacing of the isotherms of threshold current density in this region also seem relatively independent of strain in this region showing that the temperature dependence of the threshold current density in this region is similar. The increase in threshold current density and the divergence of the isotherms at higher compressive strains suggest the presence of some extra strain and temperature dependence of the threshold current density. The solid lines represent the threshold current density for an ideal lossless laser with an estimated threshold gain of 50 cm⁻¹. The difference between the theoretical curves and the measured data clearly show the action of some extra strain or material dependent factor in the behaviour of these devices.
Compressive strain is expected continually reduce the threshold current, through the reduction of the valance band density of states. Chapter 2. Strain can be expected to reduce the threshold current up to the point where misfit dislocations occur as the layer exceeds its critical strain thickness product of around 150 to 200Å/%, chapter 5. Further increases in strain then act to increase the threshold current. Therefore observed strain independent region of the threshold current strain characteristics in fig(1) is not expected. Furthermore it was shown in chapter 5 that the strain thickness product was not exceeded in these devices so the increase in the threshold current beyond 0.9% compressive strain is not associated with the effects of strain relaxation in the QW. Moreover the characteristics are reproducible across a batch of ten samples. This makes the random nature of material defects associated with poor fabricated devices unlikely candidates for the observed characteristics.

7.1.1 CALCULATED RADIATIVE CURRENT AT THRESHOLD

As shown previously, chapter 2, lasing occurs when there is sufficient gain to overcome all our optical losses (mirror loss and absorption). The threshold current of an ideal laser may be calculated from the gain current relationship if the threshold gain is known. This would be the expected threshold current in the absence of all other non-radiative loss mechanisms or leakage currents.

A the gain current relationship was calculated using a model developed by Silver [121]. the essential details of which are described below. A three band k.p model was used to calculate the conduction and valence band dispersions in these lasers. From this the transition matrix element was calculated and hence the material gain. Previous work of Meney & Jones [122] has shown that a minimum of eight bands are necessary to give accurate calculations of the gain in 1.5μm InGaAsP lasers. Here we expect that a three band model differs little from a 6 band model due to a factor 2 for spin degeneracy. Also at larger bandgaps mixing effects from higher lying band are expected to be reduced especially if we are restricted to small k values. Thus a three band model applied to 1μm devices is expected to generate reasonably accurate gain values.
These lasers were modelled by enforcing charge neutrality between the QW and the barrier material, in a similar manner as described in chapter 3. In order to calculate the relative carrier distributions in the laser. From this the relationship between peak gain and either current density or well carrier density may be derived.

In these single QW devices the majority of the confined optical mode resides outside the active gain region, defined by the dimensions of the QW. The effective gain is the material gain reduced by the optical confinement factor, the fraction of the optical field within the gain region. For a fixed QW width, the optical confinement factor will reduce with increasing wavelength or in this case increasing compressive strain. The variation of the optical confinement factor with strain was calculated using the approximate method of [123,124].

Fig(2) shows the calculated peak gain, reduced by the optical confinement factor, as a function of current for the unstrained GaAs laser at 250, 300, 330 and 365K. The gain current relationship can be seen to roll over due to gain saturation effects as the lowest subband is filled with carriers. A further increase in current makes the gain increase again as the next subband is filled.

A threshold gain of 50cm⁻¹, a value close to that used in the tensile lasers, was chosen. This value of threshold gain also falls close to the end of the linear gain region and so marks the transition between linear and gain saturated behaviour. The solid lines in fig(1) show the calculated threshold current density as a function of strain for a fixed gain 50cm⁻¹. The curves clearly underestimate the actual threshold current across the entire range of strain. Furthermore the isotherms of radiative current do not diverge as rapidly as those measured indicating that the temperature dependence of the threshold current has not been accounted for.
Fig(2) shows the calculated peak gain current density characteristics for the 1.18% compressively strained laser, taking into account the optical confinement factor, $\Gamma$. Similar calculations were performed for the 0%, 0.41% and 0.90% compressively strained laser at the same temperatures. The threshold gain was estimated as 50 cm$^{-1}$, a value close to that of the previously studied tensile-strained lasers, to calculate the theoretical curves in fig(1). This places the threshold current density close to the end of the linear gain region. An increasingly larger current is needed to produce higher threshold gain. This is the region of gain saturation, the region where the highly populated subbands start to fill up, leaving a smaller number of available states through which injected carriers can contribute to gain. At higher carrier densities still the effect of carriers populating higher lying subbands is seen. The fact that the threshold current density temperature and strain characteristics are so underestimated at this threshold gain suggest that these lasers are operating in a region of gain saturation.
Estimated Threshold Gain vs. Strain
Compressive Lasers

![Graph showing estimated threshold gain vs. strain for different temperatures (250K, 300K, 330K, 365K)].

Figure 3 shows the threshold gain estimated from the threshold current strain characteristics, $g_\text{ig(1)}$ and the calculated gain current density curves, $g_\text{ig(2)}$. This assumes that there are no non-radiative processes contributing to the threshold current density and therefore probably presents an overestimate. Only at the lowest temperatures does the gain approach the value of $50 \text{ cm}^{-1}$, the value originally estimated for these lasers.
To estimate the threshold gain in these lasers the measured threshold currents have been used to back calculate the gain, using Eq(2). The results are displayed in Eq(3). At low temperatures the threshold gain is slightly in excess of the estimated gain of 50 cm$^{-1}$. However increasingly larger gains are required to adequately describe the data as the strain and temperature are increased. The highest threshold gain $\sim 200$ cm$^{-1}$ at 365K falls well within the calculated gain region of the next available subband. The magnitude of the threshold gain may be unfeasibly large for this material system which suggests the action of some other contribution to the threshold current. This is further supported by the lack of a significant shift in lasing wavelength with temperature, expected from lasing from the high subband.

7.2 GAIN SATURATION

7.2.1 EVIDENCE FOR GAIN SATURATION: IV MEASUREMENTS

As has been demonstrated in chapter 3, the junction voltage may be used to estimate the splitting of the quasi-Fermi levels in the laser. This combined with the Bernard-Duraffourg conditions means that the threshold voltage should be of the order of the transition energy at the lasing wavelength. This has been demonstrated in chapter 4, in the tensile-strained lasers. The IV characteristics of the 1.18% compressive laser is shown in fig(4). The threshold voltage after eliminating the effects of series resistance, is found to be 1.609V. The transition energy, at the lasing wavelength of 980nm, is 1.265eV. This difference places the quasi-Fermi level splitting some 344 meV greater than expected from the Bernard-Duraffourg condition. This is consistent with the observed emission from higher lying energy bands below, section 7.2.2, and suggests that the lasers has to be pumped much further than expected above transparency to reach lasing.

Fig(5) shows the threshold voltage as a function of compressive strain at 20C. Also shown is the transition energy at the lasing wavelength, assumed to be equivalent to the threshold voltage, through the Bernard-Duraffourg condition. The measured threshold voltage diverges from the expected value as more strain is incorporated into the QW.
Fig(4) shows the IV characteristic of the 1.18% compressively strained laser at 22C. The filled squares show the raw data with the effects of parasitic series resistance. At high enough currents the voltage drop across the series resistance become comparable to the junction voltage of the laser diode. The characteristics tend to a linear, Ohms law, relationship. the gradient of this linear region can be used to estimate and then eliminate the effects of this series resistance. The estimated pure junction voltage is shown by the open circles. It maybe assumed that the junction voltage is equal to the quasi-Fermi level splitting in the laser. The pinning of the junction voltage above threshold is expected as the recombination rate through stimulated emission at threshold tends to clamp the injected carrier population. The expected quasi-Fermi level splitting should be of the order of the transition energy in the QW through the Bernard Duraffourg condition. the voltage measured here is some 344meV greater than expected. This is consistent with the threshold carrier density being greater than expected such as would be found in a gain saturated laser.
Fig(5) shows the measured threshold voltage as a function of compressive strain. This can be compared to the expected threshold voltage derived from the transition energy at the lasing wavelength, through the Bernard Duraffourg condition (solid line). The difference between these two curve suggest that the quasi-Fermi level separation is becoming much greater than expected. This implies that the lasers have to be pumped much harder with increasing strain, as expected from a gain saturated device.
This is contrary to the behaviour that is expected from the Bernard-Duraffourg condition where the threshold voltage, equivalent to the quasi-Fermi level splitting at threshold, should follow the transition energy at the lasing wavelength. This implies that some strain dependent process is acting to increase the quasi-Fermi level splitting at threshold, thereby increasing the threshold carrier density.

The threshold voltage, 1.609V, in the 1.18% compressively strained lasers is of the same order of magnitude as that in the 0.82% tensile-strained laser, 1.641V. This implies, chapter 6, that the activation energy of the leakage process is 337meV. This activation energy is similar to that measured in the tensile-strained device suggesting that leakage currents may still be significant in these devices. However any leakage currents would be a secondary consequence of the increased splitting of the quasi-Fermi levels and not the root cause of the anomalous behaviour of these devices.

7.2.2 EVIDENCE FOR GAIN SATURATION: FACET AND SPONTANEOUS EMISSION SPECTRA

Fig(6) shows the spectra emitted from the facet of the 1.18% compressively strained laser. Two peaks are clearly observed. Lasing modes are seen to grow from the more intense longer wavelength at threshold. The energy splitting of the two peaks 61meV is very close to the calculated splitting, 63meV, of the HH(z)/LH(z) quantum confined states, suggesting that the origin of these two peaks are the E1-HH(z) and E1-LH(z) transitions. Other possible transitions in the structure were considered. The barrier transition, barrier well transition and those due to higher lying quantum confined states were all found to be greater in energy than those observed.

The incomplete joining of the spectra was due to an artefact in the triple spectrometer. The high resolution triple spectrometer was originally designed resolve fine lines in Raman spectra and not the relatively broad emission from a electroluminescent device. The emission spectra therefore had to be built up from a number of scans at different centre wavelengths. Though the amplitude information may be corrupted the essential spectra features are unchanged. The integrity of the spectral information can be seen in the emission spectrum taken from another spectrometer. This can be seen, fig(7), in a
scan of the emission spectra from a window milled in the substrate of the laser, acquired with an optical spectrum analyser (OSA) specifically designed for measurements of lasers and LED's. The same spectral peaks are seen as in the previous, triple spectrometer data showing that the observed spectra are genuine and not an artefact of the spectrometer. The triple spectrometer was used because polaroid filters, used in the investigation below, could be simply mounted before the entrance slit. The optical fibre input of the OSA made the use of externally mounted polaroid filters unfeasible.

To further demonstrate that the peaks originated from the E1-HH(z) and E1-LH(z) transitions, the spectra were viewed through two polaroid filters that were placed before the entrance slit to the spectrometer. The E1-HH(z) transition was expected to be TE polarized whilst the E1-LH(z) transition was expected to be TM polarized, chapter 2. The more intense, longer wavelength peak was seen when both of the polaroids are turned for maximum TE transmission whereas the higher energy peak is obscured. Conversely when both of the polaroids are turned to maximum TM transmission the less intense, higher energy peak is seen to appear and the more intense longer wavelength peak is obscured. A high energy TE tail can be seen to contribute to the less intense, high energy peak. However some apparent TM contribution to the longer wavelength peak is also seen.

The possibility of the more intense TE emission breaking through due to the less than unity extinction ratio of the polaroids giving rise to an apparent TM feature in the dominant TE peak was considered. This was tested by viewing the spectra through crossed polaroids. The first polaroid was turned so that it gave maximum TM transmission. Any residual TE emission that was transmitted through this polaroid could then be easily transmitted through the second that was turned for maximum TE transmission. The apparent TM contribution to the longer wavelength peak was completely lost when viewed through these crossed polaroids strongly suggesting that the longer wavelength peak did indeed have a TM contribution. This can be seen in fig(8). Moreover as the current was increased towards threshold lasing modes were seen to emanate from this TM peak when both polarizers were set for maximum TM transmission. As the lasing emission is more intense still than the background spectra
TE light breaking through the polaroids is even more likely. However the lasing mode is seen to be extinguished when viewed through crossed polaroids. Therefore the lasing emission had a mixed TE/TM character.

If the laser were pumped heavily into gain saturation region, then a significant population of carriers would reside in states away from the band edge. The polarization character of these states cannot be explained in terms of the pure HH or LH character of these states. Mixing between the x, y and z-components of the valance band Bloch functions could give rise to the mixed polarization character observed here. The benefits of strain are usually described in terms of the states at the Γ-point. This has been shown, chapter 2, to give rise to an enhancement of the TE gain over the TM gain. However, if mixing were to occur between these states then the expected enhancement of the TE and suppression of the TM gain characteristics would not be as marked. In a laser already susceptible to gain saturation effects, the full enhancement of gain through strain would be lost. Mixing between the valance states away from the Γ-point would tend to augment any gain saturation effects.

The most fundamental result that can be derived from an examination of these spectra is that the energy splitting and the polarisation are both expected from the $E_1$-HH(z) and $E_1$-LH(z) transitions. In this most compressively strained laser the energy splitting between these two states is at a maximum. Applying the Bernard-Durrafourg condition to this device raises the question of why the higher lying transition is seen at all. The presence of the higher energy emission is indicative of carriers populating higher lying states. This would ultimately lead to an increase in the threshold current.

7.2.3 EVIDENCE FOR GAIN SATURATION: INDUCED MIRROR LOSSES

The reflectivity of the facet may readily be varied by immersing the laser in a liquid medium. The refractive index of liquids is generally greater than that of air therefore. through equation 5-11, the facet reflectivity may be reduced. It is stressed that reflectivity of the coated facets become independent of the refractive index of the film when the thickness is made equivalent to $\lambda/2$. chapter 5. Therefore the change in
Fig(6) Shows the ASE spectra emitted from the facet of the 1.18% compressively strained laser close to threshold. The different curves are an artefact of the spectrometer. The same spectral features are seen window spectra in fig(5) The spectra were viewed through polaroid filters to reveal the polarization character of each peak. The energy splitting of the two peaks is close to the value calculated for the difference between the E1-HH(z) and E1-LH(z) transition in the QW. This is confirmed by the polarization character of the two peaks. The more intense, longer wavelength peak has a TE character, suggesting it originates from the E1-HH(z) transition, whilst the lower intensity, shorter wavelength peak has a TM character, suggesting the E1-LH(z) transition. The residual TM character of the longer wavelength peak is also seen.

Luminescence from the short wavelength peak shows that the higher energy sub-band is populated with carriers at threshold, even in this most compressively strained sample. Strain splitting of the valence band sub-bands at this strain should act to reduce the valence band DOS reducing the transparency carrier density and so the threshold current. Population of this higher sub-band suggests that this is not the case and may account of the larger than expected threshold current of this device.
Fig(7) Shows the spontaneous emission spectrum emitted perpendicular to the lasing axis through a hole milled in the bottom contact of the laser. The same twin peaked spectral features are seen in the previous facet emission spectra, fig(6). The energy splitting of the two peaks is again very similar to that calculated for the difference between the $E_1$-$HH(z)$ and $E_1$-$LH(z)$ transitions. The continuous curve is used to illustrate that the spectra features seen in fig(6) in the incompletely joined spectra are seen in with an instrument specifically designed to acquire laser emission spectra.
Fig(8) shows an enlarged view of the longer wavelength, residual TM peak in the dominant TE emission, from fig(6). When the two polaroid filters are turned for maximum TM transmission the peak is clearly seen. This confirms its TM nature rather than it being an artifact due to the more intense TE emission breaking through the polaroid due to their less than unity extinction ratio. When polaroids are crossed so that the second polaroid is turned to maximum TE transmission, whilst leaving the first in maximum TE transmission, the peak is lost. The presence of lasing modes on the TM peak is unexpected. However mixing between states away from the zone centre may give rise to a TM component of the mainly TE emission. The states away from the zone centre maybe populated if the laser is pumped into the gain saturation region.
reflectivity of the facets becomes purely a function of the change in refractive index of the external media. The resulting increase in the mirror losses has the effect of increasing the threshold gain and therefore the threshold current. The change in reflectivity was estimated as follows. The refractive index inside the laser was taken to be that of the two 1140Å Al$_{0.3}$Ga$_{0.7}$As barrier layers. This was found to be 3.385 at 297K for a wavelength of 989nm [125]. Taking the refractive index of air to be 1 the reflectivity of the facet is 0.544. A 50:50 n-Pentane:isopentane mix was used as the external medium, mainly because this was the pressure medium of the pressure temperature apparatus being tested at the time. The refractive index was measured to be 1.365 at the lasing wavelength [126]. This would reduce the facet reflectivity to 0.425. The change in threshold gain, calculated from equation 2-6, was 4.94cm$^{-1}$.

Fig(9) shows the LI characteristics of the 1.18% compressively strained laser in air and immersed in a 50:50 n-Pentane:isopentane mixture. The threshold current could be reversibly shifted from 95 to 132mA. The change in threshold current density was 148 kAcm$^{-1}$. An almost negligibly small change in threshold current, ~5mA, was seen in the tensile-strained lasers when they were immersed in the 50:50 amyl-alcohol:castor oil mixture used in pressure experiments. This mixture has an even higher refractive index. Clearly this large change in threshold current in this most compressively strained device cannot be accounted for by the change in gain at a threshold gain of 50cm$^{-1}$. This suggests that these lasers are operating in a region of gain saturation where the slope of the gain current relationship is much shallower. This is consistent with the previous observations showing the quasi-Fermi levels are pushed deeper into the bands resulting in a larger threshold carrier population.

7.3 RECOMBINATION MECHANISMS

7.3.1 NON-PINNING OF THE WINDOW EMISSION

Fig(10) shows the integrated window emission emitted perpendicular to the lasing axis as a function of current in the 1.18% compressively strained laser. Only the most compressively strained lasers were measured as the GaAs substrate became absorbing to the shorter wavelength compressive devices. The sublinear nature of the LI relationship
Fig(9) Shows the LI of the 1.18% Compressively strained laser as it was measured first in Air, then in a liquid 50:50 n-Pentane/isoPentane solution and then in Air. The increase in threshold current is attributable to the reduction in facet reflectivity due to the higher refractive index of the liquid pentane. The resultant increase in mirror losses forces the threshold gain to increase. The reversible nature of the characteristics shows that the laser was not damaged in the process. The estimated 22% change in facet reflectivity was estimated to lead to a increase in threshold gain of 4.9cm⁻¹ at an estimated initial threshold gain of 50cm⁻¹. The observed increase in threshold current density of 148 Acm⁻² could not be accounted for at this initial threshold gain, but maybe accounted for for threshold gain in a more gain saturated region of the gain current characteristic. This observation further supports the previous observation of gain saturated behaviour in these devices.
suggests the presence of extra non-radiative components to the threshold current. Furthermore the light intensity is seen to increase significantly above threshold. This behaviour is contrary to expectation in simple laser theory. Pinning of the spontaneous emission is expected because the recombination rate through stimulated emission at threshold should be equal to the rate at which carriers can be pumped into the structure, effectively clamping the injected carrier population and their resulting recombination processes.

Non-pinning has been observed before [85, 86], and has been attributed to non-uniformities in the longitudinal gain profile of the lasers. This leads to a complex self-consistent relationship between the longitudinal gain and cavity photon density [86]. Further investigation is necessary to establish the cause of the non-pinning behaviour.

### 7.3.2 INTEGRATED WINDOW EMISSION

The carrier density dependence of the current may be studied through measuring the window emission spectra. From equation 2-34 the current flowing in the laser may be expressed in terms of a cubic polynomial of the carrier density. The radiative component of the threshold current is proportional to the intensity of the spontaneous emission integrated across the emission spectrum. This in turn is proportional to the square of the carrier density, equation 2-26. Thus the carrier density or n-dependence of the current flowing into the laser may be measured from the integrated spontaneous emission spectra.

\[ J \propto n^2 \left( \frac{L}{L_0} \right)^z \]

Equation 7-1

where \( z \) is the index corresponding to the \( n \) dependence of the recombination process and \( L \) is the integrated intensity under the emission spectra. Plotting the log of the current density against the log \( L^{1/3} \) will yield a gradient equal to \( z \). Fig(11) shows such a plot for the 1.18% compressively strained laser as a function of temperature. The spontaneous emission emitted through a window milled in the substrate of the laser and collected via a suitably positioned optical fibre. The spectra can readily be integrated by
Fig(10) Shows a comparison between the window and facet emission of the 1.18% compressive laser, the absolute intensities are not comparable between to the two curves. At threshold the recombination rate through stimulated emission is expected to be to become large enough to pin the carrier population, hence all the injected carriers go into stimulated emission and the light/current characteristics above threshold tend to increase linearly. As light emitted perpendicular to the lasing axis is expected to undergo little or no stimulated emission the light/current characteristics are expected to pin above threshold. The increase in light intensity above threshold in the window emission shows that this is not the case in this device. The fractional increase in the light intensity above threshold is defined here as the nonpinning factor.
coupling the other end of the optical fibre straight into the photodetector.

Linear regression was performed on the data on two regions of the curve. From the lowest currents to 1/3 of the threshold current and from 1/3 of the threshold current to threshold. The gradient of the lower section of the curve increased from around 1 to around 2 with temperature. The gradient of the upper section of the curve increased from around 2 to around 3 with temperature. A straight interpretation of equation 2-34 suggests that these non-integer values arise from combination of recombination processes. Thus the characteristics of the lower section of the curve is indicative of a mixing between radiative and monomolecular Shockley Read [68] Hall [69] type recombination. Whilst the upper section of the curve suggests the onset of a thermally activated $n^3$-like processes competing with the $n^2$ like radiative recombination. The increase in the $n$-dependence the upper and lower sections of the curve with temperature can be seen more clearly in fig(12) where the measured index $z$ of Equation 7-1 is plotted as a function of temperature.

This $n^3$-like process may explain the temperature dependence of the threshold current in these most compressively strained lasers as an ideal laser should reveal only an $n^2$-like dependence. The identity of this apparent $n^3$ type poses an interesting problem as $n^3$-like processes can be associated with Auger recombination. However Auger processes are thought to be strongly quenched at the bandgaps equivalent to the lasing wavelengths of these devices. The probability of an Auger event occurring in these device is expected to be negligibly small. However the large carrier densities expected from gain saturation effects in these lasers would amplify the total Auger current through this $n^3$ relationship. Thus the relatively small magnitude of the Auger that would be expected in these devices would only be seen at large carrier densities. If Auger recombination were the dominant process then the curves presented in fig(12) should ultimately pin at $z$-value of 3. The further increases in temperature that were necessary to show this pinning were not possible with the experimental apparatus used. The maximum $z$-value is greater than 3 but this may be the value may be explicable from the experimental error.

Appendix (2) shows how the leakage current can be expressed in terms of the measured
Fig(11) Shows the intensity integrated across the window emission spectrum, fig(5), for the 1.18% compressive laser as a function of current and temperature. Here the logarithmic current normalised to threshold is plotted against the log of the square root of the integrated intensity. The x-axis maybe read as the log of the injected carrier density in the QW assuming equation(0). This graph allows us to establish the power relationship between the current and well carrier density. Two distinct gradients were measured either side of the threshold current, indicating a change in the recombination regime at this point. At low temperatures the current switches from a $n^{1.7}$ to an $n^{2.26}$ dependence. This shows a mixing between a monomolecular and a radiatively regimes with the radiatively regime dominating towards threshold. At high temperatures the onset of an $n^3$-like process is seen. Such an $n^3$-like process may explain the observed temperature dependence of the threshold current of these laser.
Fig(12) shows the $z$-parameter, equation 7-1, measured from fig(12) as a function of temperature. A clear change from a radiatively dominated, $n^2$-like, to a $n^3$-like process is seen. This shows the onset of an extra thermally activated nonradiative component to the threshold current, one that may explain the observed anomalous temperature dependence of the threshold current in these lasers.
n-dependence in the QW. Essentially the leakage current can be expressed in terms of a Taylor series of the carrier density in the QW. This power series would also give rise to observed n-dependence of the current. Again a further increase in temperature would have resolved this as the n-dependence should move beyond a value of three. The presence of a leakage currents in these devices is contrary to our initial expectations of the behaviour of these lasers as these devices operate at the opposite end of the spectrum to the leakage dominated GaAsP devices. However the presence of leakage currents is supported by the excessively high threshold voltages in these devices, section 7.2.1. The threshold voltage is of a similar magnitude to that in the tensile-strained GaAsP devices and implies that the activation energy of the leakage process is also similar.

7.4 SUMMARY AND CONCLUSIONS

The basis of the work presented in this chapter was the assumption that, due to similar nature of the structure of these lasers, the variation of the threshold current with strain could be understood from the incremental variation of QW composition from laser to laser. Thus the addition of Indium to a GaAs QW should have the opposite effect on the threshold current than the addition of phosphorus to a GaAs QW. In the GaAsP devices a leakage current of unconfined carriers diffusing into the doped cladding regions was found to increasingly dominate the threshold current as phosphorus was added to the QW. The InGaAs devices should tend to free themselves from the effects of this leakage current. The leakage component of the threshold current, already small in the low tensile-strained GaAsP devices would be expected to be negligible in the InGaAs compressively strained lasers. Other loss processes, chapter 1, were not thought to be significant in these lasers. In the absence of loss processes these lasers could be assumed ideal where the threshold current was dominated by radiative recombination processes only. A continuous fall in the threshold current with compressive strain was expected as the strain reduced the radiative component of the threshold current. However the measured threshold current and its temperature dependence did not vary as expected as a function of compressive strain. The threshold current and its temperature dependence at intermediate strains was seen to be virtually strain independent, whilst being seen to increase at the extremes of the strain range. The absolute values of threshold current were consistently greater than those predicted for a simple fixed gain lossless laser model.
This unexpected behaviour was correlated with the following experimental observations. The measured threshold voltage was observed to increasingly depart with strain from the value derived from the lasing transparency condition, reaching some \( \sim 344 \text{ meV} \) greater than transparency at maximum compressive strain. This suggested that the quasi-Fermi level separation was becoming increasingly greater than that at the lasing transparency condition and that the lasers needed to be pumped much harder to reach lasing as the strain was increased.

These observations were consistent with the observed facet and window spectra that showed features originating from higher energy transitions within the QW. Emission from the higher subband in the valance band QW indicated that these states were populated, again suggesting that these lasers had to be pumped hard to reach lasing. In this most compressively strained device the HH(z)/LH(z) splitting was at a maximum. If strain were to show its beneficial effects then the population of the higher energy subband needs to be negligible. Furthermore a 50\% increase in the threshold current was induced in the highest compressively strained laser by increasing the mirror losses when the laser was immersed in a liquid medium. Only a 5\% increase in threshold current was expected suggesting that the laser was operating in a region of gain saturation, a natural consequence of a device that is pumped well above transparency.

The integrated spontaneous emission as a function of temperature showed that the threshold current was increasingly dominated by an \( n^3 \) process at high temperatures. The presence of such a thermally activated process in itself could explain the observed threshold current/strain characteristics of these lasers. However non-radiative processes such as these are not expected in this material system and their presence seem more a consequence large threshold carrier densities due to gain saturation effects.

The identity of this process was not conclusively demonstrated. Two possible candidates were considered. Auger recombination is expected to have an \( n^3 \)-dependence. At a sufficiently high temperature the current should have been dominated by Auger processes. Therefore the \( n \)-dependence of the current would then become fixed on an \( n^3 \)-
dependence. However a further increase in temperature, in accessible to the experimental apparatus, may have revealed a higher order n-dependence still. The probability of an Auger event occurring in these lasers is likely to be small, because of the bandgap of these lasers. However the large carrier densities associated with the gain saturated behaviour of these devices would amplifier the Auger recombination rate through its $n^3$-dependence.

Leakage processes can be expressed in terms of a power series of the carrier density. This may also explain the observed $n^3$-dependence. Higher order terms of this power series would become visible at as the temperature was increased. Again the temperature could not be taken sufficiently high to demonstrate this. However the anomalously high threshold voltages measured in these lasers are of a similar magnitude as those in the tensile strained lasers. Therefore activation energy of the leakage process, estimated from the threshold voltage chapter 6. was also of a similar magnitude to that of the tensile-strained lasers. This makes the leakage process feasible in these devices.

The interesting question arises as to why these lasers are gain saturated in the first place. The presence of a large optical loss mechanism will certainly act to increase the threshold gain and therefore push the laser toward gain saturation. The exact nature of this loss mechanism poses a difficult problem experimentally. IVBA may be a candidate but has been shown to be reduced by strain 1.5μm devices [40,43.44] and is quenched with increasing bandgap. Therefore it is not expected to be significant in these strained ~1μm lasers. If an optical loss mechanism were responsible for the observed high threshold characteristics then it would be expected to become worse with increasing compressive strain or indium content. The enhancement of the TE gain in the compressive regime is not as strong as the enhancement of the TM gain in the tensile regime. This combined with the small optical confinement factor of these single quantum well devices may go some way to explain why the compressive lasers are susceptible to gain saturation effects. The switch between the compressive and tensile regime does not present a significant change in band structure of these devices. Material quality may also be significant in the device performance. Large threshold currents due poor quality material is usually associated with non-radiative recombination through
defects. The increase in recombination rate through defects may act to increase the threshold current but it does not necessarily lead to increased carrier density and gain saturation. The oxidation of Al leading has been shown to cause an increase in the threshold current [71]. This would also have an effect on the reducing the non-radiative lifetime but is not obviously related to optical losses. Moreover, monomolecular processes such as these are expected to be proportional to the carrier density. No direct $n$-dependence of the current was observed. An apparent problem with the AlGaAs/InGaAs interface has been seen before that leads to an increase in the threshold current [127-130]. The introduction of thin (~5nm) GaAs buffer layers between the AlGaAs barriers and the InGaAs well has lead to a marked improvement in device performance. Such a solution may be applied to these lasers and would demonstrate the action of this material related problem.

The fact that the bandgap of the InGaAs can be predicated by two different bowing parameters, chapter 5, may be correlated with the observed characteristics, though the exact mechanism remains unclear. The calculated material bandgap seems one of the few parameters that seems to show an unexpected behaviour with compressive strain. Alloy ordering effects during growth is well documented [97,98] to lead to a shift in the fundamental bandgap. However it is uncertain as to if this has an effect on the gain characteristics or optical losses that could push these lasers into gain saturation.
CHAPTER 8

SELF-HEATING

8. INTRODUCTION

Since they were not bonded down on heat sinks, the use of pulsed power to minimise self-heating effects was necessary in all the devices used in this thesis. In chapter 4 it was shown that the threshold current was independent of duty cycle for duty cycles of less than 0.5%. The timed averaged power supplied to the laser at these low duty cycles appears not to generate sufficient average heating of the laser to make an observable increase in its threshold current. Larger duty cycles have been shown to increase the threshold current, chapter 4. Other self-heating effects have been observed in the time evolution of the optical signal from the laser during the "on" cycle [131-136]. Here we report on another form of self-heating that is seen in the time evolution of the optical signal. The current flowing and the voltage across the laser was constant during the "on" time implying that the power supplied to the laser was also constant. The onset of lasing was distinctly marked by a change from a flat topped optical pulse to a linearly falling one, even though the power supplied to the chip is constant over the "on" cycle. This can be interpreted, section 8.2, through an increase in threshold current due to self-heating effects inside the laser chip. The response of the detector system to pulsed signals has been measured in chapter 4. The droop time of the measurement system was very much greater than the observed fall in the optical signal. Therefore the observed fall in the optical signal was genuine effect of the laser rather than a artifact of the measurement system.

In section 8.4 a model was developed, incorporating heat loss to the lasers surroundings, to describe the temperature variation in the pulse powered laser in terms of a power efficiency parameter. The model provides a simple technique from measuring the absolute radiative power efficiency of the laser from the time variation of the optical signal. Under the constraints of short power pulses, where the on time is very much less than the thermal time constant of the system, the effective heat loss to the lasers surroundings is negligible. Therefore the self-heating can be modelled in the absence of
the thermal resistance to the surroundings, removing a parameter that is very difficult to quantify.

The increase in the threshold current with duty cycle, previously measured, chapter 4 fig(9), was fitted using the self-heating model. This demonstrated that the thermal time constant of the system was at least a factor of fifty greater than the “on” time. Therefore the limiting assumption, described above, under which the measurement of the radiative power efficiency was valid could be assumed to apply.

Heating in a semiconductor arises from non-radiative current processes and ohmic effects. These processes consume electrical power and compete with the power that is supplied to useful radiative processes, thus lowering the radiative power efficiency of the devices. In section 8.8 and 8.9 the correlation between radiative power efficiency and the degree of self-heating was demonstrated. Here the rate of fall of the optical signal is measured as a function of temperature for the 1.00% and 0.82% tensile-strained GaAsP lasers. Previous work, Chapter 6, had shown that the efficiency of these devices falls with increasing strain and temperature through the action of a leakage current. The efficiency of these devices may be estimated through an alternative method in order to test the self-heating model. It was assumed that the radiative power efficiency of these devices approaches 100% at low temperatures between 77 and 250K. The ratio of the radiative to the total current may also be taken as a measure of the radiative power efficiency of the device, in a similar method to that in section 6.2. Good agreement was found between the efficiency calculated from the self-heating with the efficiency derived as above. This analysis suggested that the volume of the laser that is heated is smaller than overall volume of the laser. The exact thermal mass being heated becomes a fitting parameter in this technique and is very close to the active volume of the laser.

8.1 THE TIME EVOLUTION OF THE OPTICAL SIGNAL
A marked change in the pulse shape received from the photodetector was observed at the onset of lasing in all the devices used in this thesis. In fact this change was so distinct that it could be used to mark the onset of lasing. Below threshold the optical signal was characterised by a relatively flat top over the 3μs during which the laser was
Fig(1) Shows the time evolution of the optical signal emitted from the facet of the laser above threshold. The change in gradient above threshold is not an artefact of the measurement system. The voltage across and the current flowing through the laser are always constant over the duration of the pulse implying that the power supplied to the laser is constant. The same fall off of optical signal over time has been seen in all the lasers, compressive and tensile, used in this study. The time scale over which the fall off is seen, $\sim$us, is much greater than that expected for processes associated with carrier dynamics, ps. Thermal processes, due to self-heating effects, seem to be likely candidates for the observed characteristics.

Fig(2) Shows the LI characteristics measured simultaneously at the start of the pulse and delayed by 170ns. The apparent increase in threshold current may be interpreted as an increase in temperature of the device. This can explain the observed pulse shape, fig(1), above threshold. For a constant drive current above threshold the light output of the laser may be seen to fall as the threshold current increases with temperature. Calculations based on previously measured threshold current temperature characteristics suggest that the temperature rise is of the order of 1.48 K/\mu s.
powered. However at threshold the front end of the optical pulse was seen to increase rapidly before the back end of the pulse. At a sufficiently high current above threshold the optical pulse could be seen to fall linearly with time across the duration of the pulse. Fig(1) shows the time variation of the optical signal from currents just above threshold. The photodetector used in these measurements differed from the that used in other measurements in this thesis. This photodetector consisted of smaller photodiode with a faster rise time and a faster pulsed amplifier. The manufacturers data quotes the maximum rise time of the photodiode to be 0.5ns. The detector system was measured [89] to have a rise time of 1.5ns. The speed of this photodetector was important as a slower detector system may integrate out the modulation of the optical signal. The speed of the detector is reflected in the pulse shapes in Fig(1). The ringing at the front end of the flat top current probe signal can be seen to modulate the optical signal peak for peak demonstrating that the photodetector system can at least follow this modulation frequency which is clearly much greater than the linear fall in optical signal. The fall in optical signal was much greater than the observed droop time of the photodetector ~0.2%/μs, chapter 4. It was therefore concluded that the observed pulse shape was an effect intrinsic to the laser chip rather than an artifact of the detector system. Moreover the current probe signal and the junction voltage were found to be constant over the duration of the powering pulse. This implies that the power supplied to the laser was constant over this time.

8.2 MODULATION OF THE OPTICAL SIGNAL THROUGH SELF-HEATING

The fall in the optical signal with time though the power supplied to the laser was constant may be explained in terms of the heating of the laser over the duration of the power signal. This is illustrated in fig(2). If the temperature of the laser were increased then the threshold current would generally increase. If the current above threshold were to remain constant during this increase in temperature then the intensity of the light output would be seen to fall. The light intensity, I, above threshold may be written in terms of the threshold current, I_{th}, and the current, I, as.
Where $\eta_{ext}$ is the external slope efficiency above threshold. The external slope efficiency above threshold is expected to fall with increasing temperature. However for small changes in temperature, $\sim 10$K, the slope efficiency may be assumed to be independent of temperature, fig(2). An increase in threshold current will therefore produce a decrease in light intensity.

$$-\Delta L = \eta_{ext} \Delta I_{th}$$  \hspace{1cm} \text{Equation 8-2}

The change in threshold current with temperature can be expressed in terms of the characteristic temperature $T_0$ of the laser. This may be substituted into Equation 8-1 and rearranged to give the change in temperature as a function of the change in light intensity.

$$\Delta T = T_0 \ln \left( \frac{\Delta L + \eta_{ext} I_{th}}{\eta I_{th}} \right)$$  \hspace{1cm} \text{Equation 8-3}

Where $I_{th}$ is the threshold current at the start of the pulse before any heating has taken place. This was tested on the 1% tensile-strained laser. The characteristic temperature, $T_0$, of this device was measured as 47.7K and the external slope efficiency $\eta_{ext}=7.4 \times 10^{-3}$ V/mA. The threshold current at 19.3C was measured as 388.6mA. The optical signal from the photodetector was seen to fall by 104.7mV over 1.15μs. Thus the temperature change was estimated to be 1.7K over this 1.15μs or 1.48 K/μs.

The shift in threshold current with time could be observed more directly. The functions of the digital oscilloscope allowed measurement of the amplitude of the optical signal at two specified cursor points on the optical pulse separated by time $\Delta t$. These results are shown in Fig(2). The cursor separation was set to 170ns. The characteristic shape of the curves demonstrates that both points on the pulse eventually reach lasing. The LI characteristics at the delayed cursor position show a higher threshold current implying
that the temperature at this time is greater than that at the first cursor position. Also shown in Fig(2) is the data taken with a delay between the two cursors of 300ns. The difference in threshold current was clearly greater still indicating that the temperature has increased further.

8.3 THE ORIGIN OF THE HEATING EFFECTS

The question now arises as to what causes the observed temperature change inside the laser chip. It is plausible that self heating effects originate from non-radiative current processes and ohmic heating within the device. Thus a measure of the heating due to these processes may give a measure of their relative contribution to the lasing efficiency of a particular device. This would be true if all the heat generated in the device would give rise to an increase in temperature of the device and not be dissipated into the surroundings. The increase in temperature would be checked by the dissipation of heat to the surroundings. The measured change in temperature would then be lower than the expected temperature change due self-heating in a thermally isolated device alone giving rise to a higher efficiency. If the laser were powered for a short enough time, shorter than the thermal time constant of the laser cooling to the surroundings, then the laser could be expected to be effectively thermally isolated from its surroundings. Thus the increase in temperature could be considered to be due to intrinsic processes alone. This situation may be approached with the pulsed conditions under which these devices are operated. A more detailed analysis of the heating and cooling process is presented below, section 8.4. A simple estimate of the thermal isolation of the chip can be made from the limiting case when all the power supplied to the laser is converted into heat. Treating the laser as a single homogenous mass of material the resulting temperature increase may simply be estimated from its mass and specific heat capacity. The mass of six lasers were measured giving the average mass of a single device of 5x10^{-4}g. The specific heat capacity of the device was assumed to be close to that of GaAs=0.327 Jg^{-1}K^{-1} [137]. An over estimate of the power supplied to the laser was 2V at 200mA for 2\mu s. Thus the increase in temperature was calculated to be 4.7x10^{3} K or 0.0024 K/\mu s. This value is clearly much less than the previously measured temperature change of 1.48 K/\mu s. Therefore an over estimate of the power supplied to the laser greatly under estimates the measured temperature rise in the device.
This may imply that the effective volume that is heated is much smaller than the total volume of the laser. The ratio of the volume of the SCH under the current stripe and the total volume of the laser is \(~4.4 \times 10^{-4}\). This value is of the order of the ratio of the active volume of the laser to its total volume. Thus the power density can be scaled by a similar factor giving a proportionally greater temperature rise. Therefore the heating is generally confined to the active region of the laser and therefore the device is thermally isolated from the laser clip.

8.4 HEATING/COOLING MODEL

8.4.1 HEATING

The temperature change in a laser may be modelled in terms of the heating of a given mass of material connected to the outside would via some thermal resistance. This is shown in Fig(3). Only a given fraction of the power that is supplied to the device is converted in to heat. The fraction of the input power that is converted to light is written as \(\eta_p\) and is termed the radiative power efficiency. Therefore the fraction of electrical power that is converted to heat is given by.

\[ P_{\text{heat}} = IV(1 - \eta_p) \]

Equation 8-4

Where \(I\) is the current and \(V\) is the voltage. The power that is lost through cooling through the thermal resistance \(R\) is written as.

\[ P_{\text{out}} = \left( \frac{T - T_{\text{ext}}}{R} \right) \]

Equation 8-5

Where \(T_{\text{ext}}\) is the ambient external temperature and \(T\) is the temperature of the body being heated. The net rate of heating is given by the difference between the power supplied to the mass and the power lost from the mass.
Fig(3) Shows a schematic representation of the self heating model proposed for these devices. A fraction, \((1-\eta_p)\), of the power supplied to the laser of mass \(m\) is converted into heat. This heating is countered by the rate at which the laser cools to atmosphere. The difference between the rate of heating and the rate of cooling leads to a net heating of the laser which raises its temperature.

Fig(4) Shows the variation of the temperature of the laser during steady state pulsed operation. A sufficient time after switching on the laser the temperature rise during the “on” cycle is balanced by the temperature fall during the “off” cycle. This is the steady state condition. The minimum temperature of the laser will be somewhat greater than the external atmospheric temperature. For sufficiently small duty cycle, such that the “off” time is much greater than the “on” time, the laser will have enough time to cool down to the ambient temperature. This is the general operating condition of the laser found empirically in chapter 4.
\[ IV(l - \eta_p) \left( \frac{T - T_{in}}{R} \right) = \frac{dQ}{dt} = mC \frac{dT}{dt} \]  

Equation 8-6

Where, m, is the mass being heated and C is its specific heat capacity. Hence the net rate of change of heating \( \frac{dQ}{dt} \) can be related to the rate of change of temperature through the mass and specific thermal capacity of the material. This differential equation has the solution of:

\[ \ln\left( IV(l - \eta_p)R - (T - T_{in}) \right) = -\frac{t}{mCR} + D \]  

Equation 8-7

D is a constant of integration.

8.4.2 COOLING

When the power supplied to the laser is switched off the device starts to cool down. The rate of cooling is governed by the thermal resistance only.

\[ \frac{dQ}{dT} = mC \frac{dT}{dt} = \frac{T - T_{in}}{R} \]  

Equation 8-8

This may be integrated to give the time variation of the temperature as.

\[ \ln(T - T_{in}) = -\frac{t}{mCR} + E \]  

Equation 8-9

Where E is a constant of integration.

8.5 STEADY STATE CONSTANT DUTY CYCLE HEATING

All the lasers were powered by a continuous periodic stream of pulses. The temperature will be seen to rise and fall with each successive heating and cooling cycle gradually increasing the average temperature of the device above ambient. This increase in the average temperature would not be expected to increase indefinitely. After a sufficient amount of time the temperature rise due to the heating cycle would be balanced by the
temperature lost during the cooling cycle. The "off" time would be sufficient for the device to cool down to the same starting temperature from where it was heated. The heating and cooling cycle would then repeat again continuously. This is illustrated in Fig(4). Here \( T_s \) is the starting temperature of the body above the ambient temperature. \( T_{\text{ambient}} \), ambient temperature external to the body and \( T_f \) is the final temperature at the end of the heating cycle. Equation 8-7 and Equation 8-9 may be solved with these boundary conditions.

### 8.5.1 HEATING CYCLE

At the start of heating when \( t=0 \) the temperature must equal the starting temperature, \( T_s \), allowing a solution to the integration constant \( D \) in Equation 8-7.

\[
D = \ln\left( IV (1 - \eta_p) - (T - T_{\text{ambient}}) \right)
\]

Equation 8-10

Thus during the heating cycle the device temperature as a function of time becomes.

\[
T(t) = IV (1 - \eta_p) R - \left[ IV (1 - \eta_p) R - (T_s - T_{\text{ambient}}) \exp\left( \frac{-t}{mCR} \right) \right]
\]

Equation 8-11

The maximum temperature during the "on" cycle may be found by simply setting \( t \) to \( t_{\text{on}} \) in Equation 8-11. As the "on" time is increased toward infinity or the device is operated CW then the temperature of the laser tends to a constant.

\[
T(\infty) = IV (1 - \eta_p) R + T_{\text{ambient}}
\]

Equation 8-12

### 8.5.2 COOLING CYCLE

During cooling the temperature falls from \( T_f \) to \( T_s \). Thus the constant of integration, \( E \). in Equation 8-9 becomes.
Thus the time dependence of the temperature during cooling can be expressed as.

\[
T(t) = (T_s - T_{\text{ext}}) \exp\left(\frac{t_{\text{off}} - t}{mCR}\right) + T_{\text{ext}}
\]

Equation 8-14

When the time equals, \( t_{\text{off}} \), the temperature equals, \( T_s \), the starting temperature. If the power is switched off and the body is left to cool down completely then the temperature will eventually reach ambient external temperature, \( T_{\text{ext}} \).

### 8.5.3 RADIATIVE POWER EFFICIENCY

Equation 8-11 may be used to calculate the radiative power efficiency, \( \eta_r \), of the device. Differentiating this gives.

\[
\frac{dT}{dt} = \frac{IV(1 - \eta_r)R - (T_s - T_{\text{ext}})}{mCR} \exp\left(\frac{t}{mCR}\right)
\]

Equation 8-15

The exponential prefactor comprises of the difference between a heating term \( IV(1-\eta_r)R \) and a cooling term \( (T_s - T_{\text{ext}}) \). If the "on" time is sufficiently short much less than the thermal time constant of the system then the exponential term in Equation 8-17 tends toward 1. Also, for sufficiently long "off" times the starting temperature, \( T_s \), will be expected to approach that ambient external temperature, \( T_{\text{ext}} \), as the body reaches thermal equilibrium with its surroundings. Therefore \( (T_s - T_{\text{ext}}) \) will tend towards zero after several thermal time constants. These limiting cases will be shown to apply in section 8.5.4. The rate of change of temperature may be approximated by.

\[
\frac{dT}{dt} = \frac{IV(1 - \eta_r)}{mC}
\]

Equation 8-16

Thus the rate of increase in temperature becomes constant and independent of the thermal resistance. This is equivalent to the body being thermally isolated from its
surroundings or the thermally resistance tends toward infinity. Equation 8-16 can be rearranged to give the radiative power efficiency.

\[ \eta_r = 1 - \frac{mC}{IV} \frac{dT}{dt} \]  

Equation 8-17

Here the volumetric reduction factor, \( r \), has been incorporated into the Equation 8-17. This accounts for the fact that the heating may be highly localized around the active region of the laser, section 8.3. This parameter is found by fitting the results in section 8.8. All the other parameters in Equation 8-17 can be measured directly from the optical pulse shape except the specific heat capacity of the material. However the greater unknown, the thermal resistance has been eliminated.

8.5.4 THERMAL TIME CONSTANT FROM DUTY CYCLE HEATING

The limiting conditions over which the approximate Equation 8-17 is valid may be tested from the measurements of threshold current vs. duty cycle previously presented in chapter 4 fig(9). Here the "on" time was kept constant at 1\( \mu \)s whilst the "off" time was varied. The threshold current was estimated at the turn of the LI characteristics due to the low external slope efficiencies above threshold. Increase in device temperature as the "off" time was decreased was estimated from the threshold current vs. temperature relationship for this laser given in chapter 6. Fig(5) shows the variation of device temperature as a function of the "off" time. The temperature does seem to approach a constant value around the external ambient temperature for long "off" times and low duty cycles. This is consistent with the threshold current becoming independent of duty cycle for low duty cycles, the experimental conditions maintained throughout these thesis. Though the errors incurred during these estimations, the prudent use of extremely long "off" times ~ 5ms compared to the short "on" time of 1\( \mu \)s gives confidence that the limiting assumptions of Equation 8-17 apply. The heating and cooling model may be developed further to fit these characteristics. The temperature at the end of the heating cycle and the beginning of the cooling cycle are equal. Equation 8-11 and Equation 8-14 may be equated for a heating time equal to \( t_{on} \) and a cooling time equal to zero.
Fig(5) Shows the temperature of the laser as a function of repetition period, from the data derived in chapter 4, fig(9). As the duty cycle is increased the time averaged power supplied to the laser is increased. This leads to a net rise in temperature. For CW operation of the laser the temperature will rise until the rate of cooling exactly balances the rate of heating. The temperature will be expected to reach a finite value as the repetition period reaches zero. This finite temperature has been used as a fitting parameter for equation 8-18 in performing a regression onto the data points. The greater the CW operating temperature the smaller the time constant of the system has to explain the observed characteristics. The resulting thermal time constants generated from the regression are shown. For the greatest CW operating temperatures the thermal time constant is still a factor of 50 greater than the pulse width. If the thermal time constant of the system is sufficiently long relative to the pulse width driving the laser, then the heating temperature rise in the laser may be considered linear and independent of the thermal resistance connecting the heated body of the laser to the external environment.
Rearranging gives.

\[
T_v - T_{\text{ext}} = \frac{IV(1 - \eta_p)[1 - \exp\left(-\frac{t_{\text{on}}}{mCR}\right)]}{\exp\left(\frac{t_{\text{off}}}{mCR}\right) - \exp\left(-\frac{t_{\text{on}}}{mCR}\right)}
\]

Equation 8-18

As the, \(t_{\text{on}}\), goes to infinity \(t_{\text{off}}\) goes to zero and the temperature, \(T_v\), approaches, \(T(\infty)\). Equation 8-12. Equation 8-18 was fitted to the data in fig(5) by using least squares regression with, \(T(\infty)\), as a fitting parameter. The values of, \(T(\infty)\), used and the thermal time constant, \(mCR\), derived from the fit are shown. The larger \(T(\infty)\) becomes, the smaller the thermal time constant has to be in order to account for the fall in device temperature with repetition period. The smallest thermal time constant of 0.052ms was still a factor of fifty greater than the pulse width used 1\(\mu\)s. Thus measurements of the self-heating over a period of 810ns may be considered to be relatively independent of the thermal resistance and the conditions over which Equation 8-17 is valid can be considered to apply.

8.6 EXPERIMENTAL

8.6.1 HEATING AS A FUNCTION OF TEMPERATURE

Equation 8-17 implies that the rate of change in temperature of the device is a function of the radiative power efficiency, \(\eta_p\). This has been demonstrated to be strongly strain and temperature dependent in the tensile laser in chapter 6. The relative proportion of power that goes into either radiative or leakage processes may be changed simply by varying the overall temperature of the device. A resultant increase in the rate of self-heating would be expected as the temperature is increased because the leakage current has been shown to increase with temperature. Non-radiative recombination of carriers that have leaked into the barrier regions may give rise to the self-heating. The rate of change of temperature over the pulse as a function of the external temperature was measured in the 1\% tensile-strained laser, the laser most susceptible to leakage currents.
Fig(6) Shows the variation of threshold current, measured at the start of the pulse and then delayed by 810ns, as a function of temperature for the 1.00% tensile-strained laser. As the rate of heating is expected to be related to the radiative power efficiency of the laser the difference between the time delayed threshold currents would be expected to increase with the onset of an extra nonradiative component to the threshold current. The onset of the leakage current in this previously measured device can be seen to be correlated with the increased self-heating of this device.
Fig(7) This shows the rate of change of threshold current, taken from time delayed threshold current measurements, with temperature for the 1.00% and the 0.82% tensile-strained laser. Previous measurements, chapter 6, have shown that the leakage current is greater in the 1.00% tensile-strained laser than the 0.82% laser. This difference is clearly reflected in the rate of change of threshold current, which implies that the more leaky device undergoes stronger self-heating.
An increase in self-heating is observed with temperature. This is shown in Fig 6 where the difference in threshold current between the two cursor positions, separated by 810ns, can be seen to increase with temperature.

8.6.2 HEATING AS A FUNCTION OF STRAIN
A reduction of the leakage component of the threshold current has also been demonstrated as the strain is reduced in the tensile-strained lasers, chapter 6. Therefore a corresponding reduction in the self-heating should be seen in a device of a smaller strain. The self-heating as of function of temperature has been observed in the 0.82% tensile-strained device. This is shown in comparison with the data for the 1% tensile strained device, fig(7). Again the expected behaviour is observed. The rate of change of temperature over the pulse is seen to increase with external temperature in both devices but does not increase as rapidly with temperature in the 0.82% strained device than the 1% strained device. Thus we conclude that the rate of change of temperature during the pulse with external temperature is correlated with the action of the leakage current. This supports the fundamental assumption of the self-heating model, that degree of self-heating is dependent on the radiative efficiency of the device.

8.7 SPECIFIC HEAT CAPACITY OF SEMICONDUCTORS
The data in fig(6) may be used to calculate the radiative power efficiency of these devices using Equation 8-17. However the specific heat capacity of the complex multilayered structure is not known. It is instructive to examine the specific heat capacities of various binary and ternary compound [137].

<table>
<thead>
<tr>
<th>Material</th>
<th>$C_p$ (J/(g K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP</td>
<td>0.322</td>
</tr>
<tr>
<td>InAs</td>
<td>0.352</td>
</tr>
<tr>
<td>Material</td>
<td>Specific Heat Capacity</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>GaAs</td>
<td>0.327</td>
</tr>
<tr>
<td>GaP</td>
<td>0.313</td>
</tr>
<tr>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>0.340</td>
</tr>
</tbody>
</table>

These values vary little from one another hence the error in the choice of a specific heat value would be considered minimal and systematic in nature. The specific heat capacity does vary with temperature. Fig(8) shows the variation of specific heat capacity with temperature measured for GaAs [138]. This curve is well understood theoretically [139] but of interest here is the plateau of specific heat capacity that is observed at temperatures above 300K.

### 8.8 THE RADIATIVE POWER EFFICIENCY ESTIMATED THROUGH SELF-HEATING

The increase in rate of change of threshold current with temperature shown in Fig(6) can be used to calculate the radiative power efficiency through Equation 8-17. The change in temperature over the 810ns period was estimated from difference between the threshold current measured at the two cursor positions and the threshold current temperature characteristics. The threshold voltage was taken to be the transition energy at the lasing wavelength, 1.656 Volts. This was assumed to be constant over the entire temperature range. The specific heat capacity was taken from the characteristic presented in fig(8) The mass of the laser was previously measured, section 8.3, as $5 \times 10^{-4}$g. The radiative efficiency as a function of temperature for the 1.00% tensile-strained laser was estimated by another technique for comparison. It was assumed that the radiative power efficiency was equal to the ratio of the radiative to the total threshold current to a first approximation. Thus the radiative power efficiency could be estimated from the threshold current/temperature characteristics previously presented in chapter 6. The radiative efficiency was assumed to be 100% at low temperatures between 77 and 250K, where the threshold current was seen to vary linearly. This linear temperature dependence was used to extrapolate the magnitude of the radiative current in the super linear region as before, section 6-2. Thus the excess
Fig(8) Shows the variation of the specific heat capacity of GaAs with temperature. The specific heat capacity is seen to vary in a gentle linear manner for temperatures above 300K. Such characteristics can be used to model the temperature dependence of the radiative power efficiency from the measured self-heating effects in these devices.
Fig(9) Shows the radiative power efficiency for the 1.00% device estimated from two different techniques. The first technique assumes that the radiative power efficiency is proportional to the ratio of the radiative current to the threshold current. The radiative current may be estimated from the linear region of the threshold current temperature characteristics in a similar manner to the analysis performed in chapter 6. The second method calculates the radiative power efficiency from equation 8-17 using the self-heating measurements presented in this chapter. The reasonably good agreement between the two techniques demonstrates that self-heating measurements are a viable technique for measuring the radiative power efficiency.
Fig(10) shows the radiative and nonradiative components to the threshold current calculated form self-heating measurements for the 1.00% tensile-strained laser. These measurements assume that the radiative power efficiency is proportional to the ratio of radiative current to the threshold current. The fundamental features of the calculated radiative and leakage components of the threshold current for this device, chapter 6, are seen in these measurements. Refinement of these self-heating measurements are feasible and offer a new way of making measurements of the radiative and nonradiative components of the threshold current.
current could be estimated and the ratio of the excess to radiative current was taken. This is illustrated in Fig(9). The calculated radiative efficiency from the self-heating effects was fitted to this by varying the volumetric reduction ratio \( r \). This was found to be 0.0007, a value slightly in excess of the ratio of the SCH region to the total volume of the laser of 0.0004. This value may be assumed to be equal to volume of the active region of the laser without serious change to the calculated efficiency. The data was could not described by a volumetric ratio of 1, again suggesting that the heating is localized around the active region.

The difference between the radiative efficiency estimated from both techniques arises from two sources. First is the experimental accuracy with which the self-heating data can be measured. The cursor function on the digital oscilloscope used to measure the difference between the threshold currents after a given time delay was the limiting factor in the accuracy of the self-heating measurements. Refinements in the measurement apparatus are feasible. This should improve the accuracy of the measurements. The second factor is the fact that the technique of estimating the radiative efficiency is also susceptible to error. The exact range over which the threshold current can be seen to vary linearly can be misinterpreted. This can lead to an error in the interpretation of the rate of change of radiative current with temperature. As the excess current is based on an extrapolation of this slope an increasing temperature dependent error is introduced into the measurements.

Overall the two techniques compare well in the estimation of the radiative efficiency of the device. Both the correct trend and magnitude are seen. The calculated efficiency using the self-heating technique has been used to calculate the magnitude of the radiative and non-radiative components of the threshold current, fig(10).

8.9 SUMMARY

The work presented in this chapter was prompted by the consistent observation, across all the lasers used in this thesis, of the change of the optical pulse shape from the laser at threshold. In fact the change in pulse shape was so distinct that it could be used to mark the onset of lasing. At threshold the front end of the optical signal was seen to
increase more rapidly than the back end of the signal. At a sufficiently high current above threshold the optical signal was seen to decrease linearly with time. The power supplied to the laser was demonstrated to be constant over the duration of the pulse. Moreover the change in pulse shape was shown not to be an artefact of the measurement system. Therefore the observed change in pulse shape of the optical signal was a genuine effect intrinsic to the laser.

The front end of the pulse was shown to reach basing at a lower current than the back end of the pulse. This apparent increase in threshold current over time was interpreted as an increase in threshold current due to self-heating of the device. The difference in the threshold currents at the front and back end of the pulse and the previously measured threshold current temperature characteristics were used to estimate the rate of self-heating in a device. This was found to be 1.48 K/μs for the 0.68% tensile-strained laser at 20°C. This value was much greater than that estimated, assuming a 100% heating efficiency of the whole the laser over the duration of the pulse. This implied that a narrowly defined active region was being heated.

A model was developed to account for the self-heating in the laser under pulsed conditions. The temperature change in the laser could be quantified in terms of a radiative power efficiency parameter as the degree of self-heating was believed to be related to the fraction of the power supplied to the laser that was converted into heat. Thus analysis of the self-heating data could yield the absolute radiative power efficiency of the device. The limiting assumptions of this analysis was that the duration of power pulse was much smaller than the thermal time constant of the laser as in cooled to the atmosphere. Under these conditions the temperature change in the device could be assumed to be independent of the of the cooling to its surroundings. Conveniently this removes the effective thermal resistance of the system from the analysis, a parameter that is very difficult to quantify.
The thermal time constant of the system could be derived from the same model. The increase in threshold current with duty cycle, chapter 4 fig(9), was fitted using the model. The regression on the curve showed that the thermal time constant was at least 10 times greater than the duration of the power pulse. Therefore the limiting conditions over which the radiative power efficiency could be estimated could be assumed to apply.

According to the model the self-heating was governed by the magnitude of the radiative power efficiency of the laser. The worse the radiative efficiency then the greater the self-heating as proportionally more of the power supplied to the laser is converted into heat. This was tested on the leakage dominated 0.82 and 1.00% tensile-strained lasers. Previous work in chapter 6 had shown that the radiative efficiency of these devices was limited by a thermally activated leakage current of unconfined carriers diffusing into the doped cladding regions. Therefore increasing the temperature or increasing the strain should act to increase the self-heating. This was demonstrated to be the case. The self-heating in the 1.00% tensile laser was indeed greater than in the 0.82% tensile laser. Also the self-heating increased more rapidly in the 1.00% laser than the 0.82%. Therefore a strong correlation between the radiative efficiency and the self-heating was demonstrated.

Previous work on these devices had also shown that the radiative efficiency of the device could be estimated from the threshold current temperature characteristics. At low temperature between 77 and 250K the device was assumed to be 100% efficient. Therefore the measured threshold current could be assumed to be equal to the radiative current. The gentle linear increase of the threshold current with temperature in the low temperature regime was assumed to be continuous into the high temperature regime. Therefore the excess current could be estimated. The ratio of the excess current the radiative current was assumed to be equal to the radiative power efficiency. The variation of the radiative efficiency measured in this manor was
compared to that measured though self-heating measurements. A reasonably good agreement between the two was established. This agreement was limited by the accuracy of the self-heating measurements, which with a little extra effort have the potential of being improved.

Therefore a new technique for measuring the absolute radiative power efficiency in lasers has been demonstrated. The limiting assumptions of the technique have been shown to apply. Furthermore a strong correlation between the expected degree of self-heating and the radiative efficiency of the device, the fundamental assumption of the model, has been demonstrated. This has demonstrated a link between the self-heating of the device and the leakage current of thermally activated carriers diffusing into the doped cladding regions. Moreover the radiative efficiency from the self-heating model shows good agreement with the efficiency measured though a different technique, giving confidence in its results. The technique has the advantage of being relatively simple to apply and requires a minimal amount of equipment. This makes it amenable to use with other measurement systems, such as the pressure rig with no extra investment in equipment.
CHAPTER 9

9. THESIS SUMMARY

9.1 BACKGROUND

The basis for the work in this thesis was to investigate the dominant recombination processes that occur in a range of strained layer single QW GaAsP and InGaAs lasers operating between 980 and 749nm. Previous work had shown that the limiting nonradiative recombination process tended to be wavelength dependent. Long wavelength semiconductor lasers operation at 1.5μm have have been shown to have up to 80% of their threshold currents dominated by Auger recombination. IVBA has also been shown make a significant contribution to increasing the threshold current in these devices. The incorporation of strain within the active layers of these devices has proved a practical method of counteracting the effects of these two processes. The reduction of the threshold current in these lasers with the application of externally applied hydrostatic pressure can be correlated with the quenching of Auger processes through the increase of the direct bandgap with pressure. A similar reduction in threshold current with pressure can be seen in shorter wavelength devices operating at 1.3μm. Taking the reduction of Auger recombination with bandgap to its natural limit suggest that some operating wavelength exists where Auger processes will make an insignificant contribution to the lasers threshold current. The threshold current of such a device would be expected to have a low intrinsic temperature sensitivity, a characteristic desirable on a commercial basis.

Lasers operating in the visible region of the electromagnetic spectrum have also been investigated. A increase in the threshold current of these lasers with externally applied hydrostatic pressure has been seen. The increase in the threshold current is explicable in terms of a leakage current of unconfined carriers diffusing into the cladding regions of the lasers heterostructure. Hydrostatic pressure acts to close the difference between the X-Γ states and the L-Γ states. This results in the lowering of the effective heterobARRIER energy discontinuity allowing injected carriers to flow out of the SCH region. Increasing the operating wavelength of the laser allows for a
greater bandgap discontinuity between the materials forming the heterostructure, thus improving the carrier confinement in the heterostructure.

These two wavelength dependent loss processes are dominant at opposite end of the electromagnetic spectrum. It is therefore possible to conceive of a range of operating wavelengths where both these effects are minimised. Such lasers should therefore tend to be ideal devices. It was this concept that was investigated in this thesis. The lasers used in this study varied only by an incremental change in the composition of the single QW. Phosphorus was added to an unstrained GaAs QW, which shortened the lasing wavelength and moved the lasers towards the leakage dominated regime. In a set of complementary samples Indium was gradually incorporated into the QW. This had the opposite effect of increasing the lasing wavelength and moving the lasers towards the Auger dominated regime.

9.2 TENSILE LASERS
An increase in the threshold current with strain, temperature and pressure has been measured in the highest tensile-strained shortest wavelength GaAsP devices. The temperature dependence of the threshold current also increases with tensile strain in these lasers. An increase in the threshold current with externally applied hydrostatic pressure can be explained in terms of a leakage current of unconfined carriers flowing into the cladding regions of the device. This arises from the reduction in the heterobarrier as pressure closes the $\Gamma$(barrier)/X(cladding) bandedge separation. The presence of a leakage current can also explain the increase in threshold current with strain and temperature and the increase temperature dependence of the threshold current with strain.

The strain dependence arises from the increase in the bandgap of the QW material relative to the fixed bandgap of the SCH; the QW's become shallower with strain. The quasi-Fermi level splitting at threshold is at least equal to the transition energy in the QW. Therefore the quasi-Fermi levels approach the band edges in the SCH. This implies that an increasing population of carriers resides outside the QW as the QW become shallower with tensile strain. Thus proportionally more carriers are unconfined by the SCH, increasing the leakage current with tensile strain.
The temperature dependence of the threshold current stems from the thermal activation of carriers out of the SCH and into the cladding regions. A change from a gentle linear variation of threshold current with temperature at low temperature, to a rapid exponential variation high temperature was seen in all the lasers that were tested. This change is indicative of a change from a radiative recombination regime (the linear variation), to a leakage dominated regime (the exponential variation), as carriers were increasingly thermally excited over the barrier/cladding heterobarrier. The measured activation energy for this process was close to the estimated activation energy based on our understanding of the leakage process. The increase in the temperature dependence of the threshold current with strain is accountable in terms of the reduction of the activation energy of the leakage process as the QW's become shallower with strain.

Measurements of the strain, temperature and pressure dependence of the threshold current in the tensile-strained devices in conjunction with a sophisticated computer model has demonstrated that a leakage current increasingly dominates the threshold current of the shorter wavelength devices. Furthermore the underlying mechanism for this leakage current has also been shown in more detail. Modelling these device shows that the threshold current seem to be sensitive carriers populating the X-minima of the heterostructure, suggesting that carriers leaking through the X-minima of the structure governs the leakage process. This view is further supported by observation of the loss of lasing at 6kbar, the pressure at which the barrier material becomes indirect at the X-I' crossover.

This sets an important fundamental limit of the effectiveness of the heterostructure to confine carriers within the active region of the laser, at least for this material system. Increasing the X-Γ separation reduces the activation energy of the leakage process. Thus one effect is improved at the expense of the other. Therefore a trade off between the two effects has to be made.
9.3 COMPRESSIVE LASERS

The longer wavelength compressively strained devices should be practically free of the effects of leakage currents and dominated by radiative process only. Therefore a decrease in the threshold current with increasing wavelength is expected as compressive strain acts to reduce the radiative component of the threshold current. This is not observed experimentally. The threshold current and its temperature dependence was virtually independent of strain over most of the strain range, whilst at the greatest compressive strains, the threshold current and its temperature dependence is actually seen to increase. A departure of the threshold current strain characteristics from those calculated for an ideal radiatively dominated device is observed suggesting that some other factor is acting to increase the threshold current of these devices.

The anomalous threshold current characteristics can be correlated with several experimental observations. The measured threshold voltage was seen to be greater than that expected from the Bernard Duraffourg condition for all the compressive lasers. The threshold voltage was observed to be independent of strain, suggesting an increase in the quasi-Fermi level splitting expected from the Bernard-Duraffourg transparency condition. This implied that the lasers were having to be pumped harder to reach lasing, opposite to the desired effects of strain. The higher than expected threshold voltage and hence larger than expected quasi-Fermi level splitting at threshold, was also consistent with the presence of luminescence from higher lying subbands. In this most compressively strained laser the presence of carriers in the higher valance subband need to be negligible if strain is to show its beneficial effects. Luminescence from these higher lying subbands demonstrates the presence of carriers in these states. This higher energy transitions was shown to arise form the El LH(z) transition, whilst the fundamental basing transition originated from the lower energy El HH(z) transition.

A possible explaination as to why these devices have to be pumped so hard to reach lasing, is that the threshold gain needed to achieve lasing is high. If a device is pumped sufficiently hard the gain current relationship will tend to roll over. The gain current relationship becomes saturated. This means that the increase in gain for a
given increase in current becomes smaller. Therefore an increasing number of carriers have to be pumped into the device to achieve lasing, giving proportionally more carriers in higher energy states. The quasi-Fermi level splitting would also have to be higher to achieve this carrier population.

Inducing extra mirror losses would increase the gain needed for threshold. This was achieved by immersing a laser in a liquid medium. The change in the refractive index from air to liquid will reduce the reflectivity of the facets. A corresponding increase in the threshold current was measured. However the increase in the threshold current was very much greater than expected from the reduction in facet reflectivity. The behaviour was consistent with that of a laser operating in a gain saturated region, where a small increase in threshold gain would be matched by a large increase in the threshold current.

Gain saturated behaviour also seemed to be accompanied by the presence of some thermally activated nonradiative current mechanism, in the most compressively strained devices. The presence of such a mechanism could account for the abnormally high temperature dependence of these lasers. Examination of the integrated spontaneous emission spectra showed an increase in the carrier density or n-dependence of the current flowing into the laser. The change from a square n-dependence to a cubic n-dependence towards threshold, was seen with temperature. A change from a radiatively to a nonradiative regime was assumed. Two different explanations of the this behaviour have been presented. Full identification of this n³-process was not achieved. However two possible explanations were presented.

A cubic n-dependence has in the past been shown to be associated with Auger recombination, as Auger is a three body process. This might be interpreted as being consistent with the our initial assumptions about Auger processes becoming increasingly significant towards longer operating wavelengths. Any residual Auger may be amplified in a gain saturated device through its cubic n-dependence and inflated carrier densities. However the n-dependence of the current would be expected to pin at a cubic dependence as at a sufficiently high temperature Auger
recombination should dominate all other recombination processes. This was not seen.
though extending the measurements to higher temperatures, beyond that achievable by
the experimental apparatus, might have shown this to be the case.

A higher power $n$-dependence may also be associated with a leakage-like process.
such as that observed in the tensile strained lasers. The leakage current may be
expressed as an exponential of the QW carrier density. Expanded as a Taylor series
the $n$-dependence of the leakage current has a series of increasing power terms. The
argument for a leakage current, though contrary to our initial assumptions, is the
higher than expected threshold voltages. The measured threshold voltages are similar
to those measured for the tensile lasers. Therefore the activation energy of the leakage
process, estimated from the threshold voltage, is also similar. Again, if taken to a
sufficiently high temperature, these higher power terms could have been measured as
the $n$-dependence should move beyond a cubic.

The nonradiative processes described in either explanation of the observed $n$-
dependence could only be expected in these InGaAs lasers if abnormally high carrier
densities, those associated with gain saturated operation, were present. The underlying
cause of the gain saturation in these lasers was not found experimentally and should
be the subject of further research. However these InGaAs laser may naturally be
susceptible to being pushed into the gain saturated region. The single QW well and
the weaker gain characteristic (compared with the tensile regime) of compressive
lasers means that these lasers may be more readily pushed into the gain saturation
region.

9.4 SELF-HEATING EFFECTS
Other effects were noticed in these lasers. Of particular interest was the time evolution
of the optical signal from the laser when measured under pulsed conditions. A
constant power was supplied to the laser over the period of a few microseconds which
resulted on an optical signal above threshold that was seen to fall linearly with time. A
change from a flat top optical pulse below threshold to a linearly decreasing pulse
above threshold was seen. In fact the change was so distinct it could be used to mark
the onset of lasing. The front end of the optical pulse was shown to reach threshold at a lower current than the back end of the pulse. This effect was attributed to self-heating effects in the laser. Under condition of constant power and therefore current, self-heating would act to increase the threshold current. The excess current above threshold would be reduced, thereby reducing the intensity of the optical signal with time. A higher current was needed to bring the back end of the optical signal into lasing as, by that time, the laser had reached a higher temperature.

A heating/cooling model was developed to quantitatively model this effect. It was assumed that any nonradiative recombination processes would ultimately generate heat in the device. Therefore the fraction of the current flowing into the laser that went into nonradiative recombination, the quantum efficiency of the device, would govern the amount of self-heating in the device. This was demonstrated to be the case on the GaAsP lasers. It had already been shown that the leakage current increased with both tensile strain and temperature. Therefore the self-heating should also have increased with tensile strain and temperature. The rate of fall of the optical signal increased as either the temperature or the strain were increased. Therefore a correlation between device self-heating and leakage current was demonstrated.

The radiative efficiency of these devices could be calculated from the change in self-heating with temperature due to this leakage current. The radiative efficiency of these devices, calculated from the self-heating model, showed good agreement with the estimated efficiency from threshold current temperature measurements.

The advantage of the self-heating model is that an absolute value for the radiative power efficiency can be made directly from the measurements. Furthermore the equipment needed to make these measurements is the same as that needed to capture the fundamental light/current characteristics of the laser, assuming that the response of the photodetector is sufficient to follow the time variation of the optical signal.
9.5 FURTHER WORK

The work on the tensile strained GaAsP lasers suggests that the leakage of carriers out of the SCH region is governed by carriers flowing through the X-minima of the SCH. The variation of the leakage current with the position of the X-minima in the SCH was modelled and showed that the leakage current was minimal with a large Γ-X separation in the barrier regions, such that the Γ-minima was the lowest lying band edge. This prediction was supported by the observed loss of lasing at a 6 kbar, the pressure at which the Γ-X separation becomes zero. This hypothesis can be tested further by growing a range of lasers similar in design to the ones used in this thesis, that vary only by an incremental shift in the composition of the barrier material, rather than the QW. The composition of the Al$_x$Ga$_{1-x}$As barriers may be varied as follows: $x=0.2, 0.25, 0.3, 0.35, 0.4$. Thus a range of lasers will be produced where the Γ-X separation approaches crossover at an aluminium concentration of 0.4. The lower aluminium concentrations should have shallower QW’s. Therefore carriers should be less well confined within the QW. However the Γ-X separation is greatest in these lasers, therefore the leakage out of the SCH should be the least. The threshold current of these devices should increase with the aluminium concentration of the barrier material according to the predictions of the computer model.

Pressure measurements on these lasers should show that the switch off at the Γ-X cross over should occur at progressively lower pressures as the aluminium concentration of the barrier is increased. The lasers with an aluminium concentration of 0.4 should fail to lase at ambient pressure as the barrier is at cross over.

A second parameter that can be varied is the aluminium concentration of the Al$_x$Ga$_{1-x}$As cladding regions. The cladding regions were already indirect in all the devices tested. Reducing the aluminium concentration of the barrier to a point just before the Γ-X cross over may act to reduce the leakage current. This will reduce the Γ(cladding)/Γ(barrier) band offset lowering the heterobarrier perceived by electrons in the Γ-states. However lowering the aluminium concentration will increase the X(cladding)/Γ(barrier) heterobarrier. An optimum aluminium concentration should exist where the leakage current is minimised. In fact there may also be some interaction
between the X(barrier)/X(cladding) heterobARRIER. Pressure measurements on a range of samples that vary in aluminium concentration of both the barrier and cladding material should illuminate the process of carrier flow across the SCH region. This will demonstrate the criteria for optimising the design of the SCH region to minimise leakage currents.

The compressively strained lasers have been shown to suffer from the effects of gain saturation. The larger carrier densities needed to achieve lasing appear to give rise to an unidentified carrier loss mechanism, either Auger recombination or leakage over the heterobARRIER. The variation of the threshold current with temperature and pressure could be used to resolve which of these processes occurs in this laser. Increasing the temperature will increase the proportion of Auger or leakage current with respect to the useful radiative current. The variation of the threshold current with pressure at this elevated temperaure would illuminate which mechanism was dominating. If Auger processes were increasing with temperature then the threshold current of the device should fall with pressure as Auger is quenched by increasing bandgap. Conversely if leakage processes were dominant then the threshold current would be expected to increase with pressure. In fact a family of pressure temperature curves could be produced which would show the variation of the radiative quantum efficiency of the laser with temperature. This technique is general and could be applied to most devices to resolve the different current processes in the laser. Fitting a family of curves would be simplified as many of the fitting parameters should be common to each curve in the family. If more curves were produced than fitting parameters then great confidence in the fit could be achieved.

Pressure/temperature measurements were tried on the compressive lasers. However the refractive index of the liquid pressure medium, even at ambient pressure caused a large variation in the threshold current, due to the operation of these devices in a gain saturated regime. It would be hard to distinguish whether any increase in threshold current was due to the variation of the refractive index with pressure or the onset of leakage current. One solution to this problem is to use a gas pressure medium. The refractive index of the gas would be similar to that of air and would be expected to
show only a small variation with pressure. The induced mirror losses due to change in the refractive index of the medium would be minimised.

If leakage currents were present in the compressive lasers then they might be reduced by optimising the design of the SCH such that the current path through the X-minima in the barrier was reduced. Self-heating effects similar to those measured in the tensile lasers have been seen in the compressive devices. The removal of the current going into loss mechanisms should eliminate the self-heating effects.

The root cause of why these devices are gain saturated in the first place has not been answered. Increasing the number of QW should reduce the degree to which each well needs to be pumped in order to reach lasing. This would move the laser away from the gain saturated region and so reduce its threshold current. A corresponding reduction in the threshold voltage should also be seen as the lasers should operate closer to the transparency condition.

Poor material quality and in homogeneity in the QW widths etc. may explain the characteristics of these lasers. However these effects would have to explain the consistent strain and temperature dependence of the threshold current. Such deleterious effects would be expected to occur more randomly across a batch of samples and be reflected in the threshold current. Other research on InGaAs/AlGaAs lasers has shown that the InGaAs/AlGaAs interface seems to govern the threshold current of these lasers [128-130]. It has been shown that placing a GaAs buffer layer intermediate between the InGaAs QW and AlGaAs barriers improved the performance of the laser. Growing a set of lasers similar to the design used in this thesis with the extra GaAs buffer layers would immediately confirm whether this material problem was undermining the performance of these devices.

Finally improvements could be made on the self-heating measurements used to measure the radiative power efficiency of these devices. This could easily be achieved with better integration of the optical signal to improve the signal to noise ratio. The self-heating measurements could be extend to measure different samples, such as an
Auger dominated device. The temperature range over which these measurements were taken could be extended. At extremely low temperatures, thermally activated loss processes should be frozen out, virtually eliminating the self-heating in a device. If self-heating were observed then the question where did arise from needs to be answered. The self-heating should also reflect the pressure dependence of the threshold current.
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CIRCUIT FOR UNITY GAIN PULSE AMPLIFIER USED IN IV MEASUREMENTS

NPN 2N2222

PNP 2N2907
APPENDIX 2

Carrier Density Dependence Of The Leakage Current.

Here we develop an expression for the carrier dependence of the leakage current in terms of the measured carrier density dependence of the spontaneous emission. When measuring the integrated spontaneous emission intensity as a function of current, the light intensity is proportional to the square of the carrier density in the QW. The unconfined carrier density in the cladding regions is coupled to the well density by the quasi-Fermi level, $F_c$, across the SCH region. The carrier density in the first state in the QW is given by [140]:

$$n_w = \frac{m k T}{\pi \hbar^2 L_z} \ln \left[ 1 + \exp \left( \frac{(E_c - F_c)}{kT} \right) \right]$$

Equation 1

Where $m$ is the carrier effective mass in the plane of the well, $k$ is Boltzman’s constant, $T$ is the temperature, $L_z$ is the width of the QW, $E_c$ is the energy of the confined state in the QW. The unconfined carrier density in the barrier regions, giving rise to the leakage current is given by:

$$n_l = N_c \exp \left( -\frac{\Delta E_{act}}{kT} \right)$$

Equation 2

Where $\Delta E_{act}$ is the activation of energy of the leakage process and $N_C$ is the density of states in the conduction band of the cladding region. This activation energy may be related to the electron quasi-Fermi level in the device.

$$\Delta E_c = Q_c + V_c + (E_c - F_c)$$

Equation 3

Where $Q_c$ is the band offset energy in the conduction band and $V_c$ is the depth of the QW to the confined state.

Thus the leakage carrier density in the cladding regions can be expressed as follows by
substituting Equation 3 in Equation 2.

\[ n_i = N_c \exp \left( \frac{-(Q_c - V_c)}{kT} \right) \exp \left( \frac{-(E_c - F_c)}{kT} \right) \]

Equation 4

Therefore the carrier density in the QW can be described in terms of the unconfined carrier density in the cladding regions by substituting for the \( \exp \{-(E_c-F_c)/kT\} \) term in Equation 4 in Equation 1

\[ n_w = \frac{mkT}{\pi \hbar^2 L_z} \ln \left[ 1 + \frac{n_i}{N_c \exp \left( \frac{-(Q_c - V_c)}{kT} \right)} \right] \]

Equation 5

In the diffusion limited leakage regime, the leakage current is proportional to the unconfined carrier density Equation 6-2.

\[ J_i = \Gamma n_i \]

Equation 6

Where \( \Gamma \) is a constant of proportionality, a function of the carrier charge, diffusion coefficient, diffusion length and width of active. Therefore the leakage current density may be described in terms of the well carrier density

\[ J_i = \Gamma N_c \exp \left( \frac{-(Q_c + V_c)}{kT} \right) \left[ \exp \left( \frac{\pi \hbar^2 L_z n_w}{mkT} \right) - 1 \right] \]

Equation 7

The exponential term may be expanded as a power series to give the \( n \) dependence of the leakage current of the form.
\[ J_1 = \beta \left[ \frac{n_w}{1! \phi} + \frac{n_w^2}{2! \phi} + \frac{n_w^3}{3! \phi} + \frac{n_w^4}{4! \phi} + \ldots \right] \]

Where \( \beta \) and \( \phi \) are constants.

Equation 8