Temperature Dependence of the Radiative and Non-Radiative Currents in Visible and Near Infra-Red Semiconductor Lasers

by

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Abstract

We investigate loss mechanisms in 1.3\mu m lasers and in visible lasers operating between 630nm and 690nm by measuring the change in the threshold current with temperature from 77K to 350K and with hydrostatic pressure up to 15kbar.

We compare the variation of threshold current density with temperature in visible lasers with theory and find that the major loss mechanism is carrier leakage to X-minima in the cladding. This conclusion is reinforced by a simple fit to data of threshold current density against hydrostatic pressure, in which the loss mechanism is seen as an activated rate of change of with pressure process with a activation energy roughly equal to the rate at which the X-minima and \Gamma-minimum are approaching each other with pressure. It is further concluded that this leakage is not a problem at room temperature at 670nm but causes the very high threshold current density and sensitivity to temperature seen in 635nm lasers.

We combine pressure and spontaneous emission measurements, the latter carried out at several temperatures above room temperature, to deduce the cause of the high temperature sensitivity of 1.3\mu m lasers. From measurements of the pure spontaneous emission emitted from the side of the devices or from a window etched in the substrate, we conclude that the major loss mechanism and cause of the high temperature sensitivity in 1.3\mu m lasers is Auger recombination. Values deduced for the thermal activation energy associated with the Auger coefficient and the variation of the threshold current with pressure indicate it is a phonon-assisted Auger process. Such a process is only weakly dependent on band structure, which explains why the temperature sensitivity in these lasers was not improved by the introduction of strain.
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Publications


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Chapter 1

Introduction

1.1 A Brief History of the Semiconductor Laser

Semiconductor laser diodes have been in demand as cheap, portable, single-wavelength coherent light sources for many years. The semiconductors used are compounds or alloys of atoms from groups III and V of the periodic table, and more recently from groups II and VI. The more usual elemental semiconductors Si and Ge cannot be used as light sources due to their indirect band gap.

The first to be studied were GaAs homojunction lasers in 1962 [1,2]. The next decade brought better liquid phase epitaxial growth and therefore lower threshold current densities. Improvements were also made in the transition from homojunctions to heterojunctions, bringing enhanced carrier and photon confinement resulting in a
reduction of the threshold current density by two orders of magnitude [3]. In 1975 the first quantum well lasers were fabricated following the invention of the vapour phase and molecular beam epitaxial techniques. The first InGaAsP device grown on InP lasing at 1.3μm using continuous wave (CW) current was reported in 1977 by Oe et al. [4] with a threshold current density ($J_\text{th}$) of 9kA/cm² and almost a decade later the first lasers operating in the visible spectrum were fabricated which could operate using CW: Kobayashi et al. [5] reported CW operation of a laser with a wavelength of 690nm up to 50°C with a $J_\text{th}$ of 4.1kA/cm² at 25°C and a few weeks later Ikeda et al. [6] reported CW operation of a 671nm laser up to 23°C with a $J_\text{th}$ of 6.4kA/cm² at 20°C.

![Figure 1.1: Evolution of the threshold current density of GaAs/AlGaAs lasers [3]. The impacts of various improvements in the crystal growth technologies are clearly marked.](image-url)

**Figure 1.1** : Evolution of the threshold current density of GaAs/AlGaAs lasers [3]. The impacts of various improvements in the crystal growth technologies are clearly marked.
Following the introduction of strain into lasers after suggestions by Adams [7] and Yablonovich and Kane [8] in 1986 the threshold current densities of laser diodes were reduced still further. A laser diode operating in the blue part of the spectrum at 77K was reported in 1991 [9] and recently lasers emitting blue light have been fabricated from nitrides [10]. Figure 1, taken from Thijs [3], shows the development of GaAs/AlGaAs semiconductor lasers.

1.2 The Uses of Semiconductor Laser Diodes

Semiconductor lasers have found many uses. For communications purposes devices lasing at 1.55\(\mu\)m operate at the point of minimum attenuation in standard silica-based optical fibres, whereas devices working at 1.3\(\mu\)m wavelength operate at the point of zero dispersion in such fibres. 1.48\(\mu\)m lasers are used to pump Er\(^{3+}\)-doped fibre amplifiers (EDFA's), and devices with wavelengths below 1\(\mu\)m in the infra-red are used in compact disc players. In the visible spectrum, devices lasing in the red are proving a portable low-cost alternative to the bulky Helium-Neon gas laser for use in laboratories and bar-code readers. They may also be used in displays and in laser pointers, and are currently under development for use in read/write high-density optical storage systems.

1.3 The Application of Temperature and Hydrostatic Pressure

It is necessary in many commercial applications that a semiconductor laser has a low sensitivity to temperature. Measurements of the temperature dependence of the characteristics of the laser allow us to quantify this sensitivity by means of a "characteristic temperature", called \(T_0\), which we define in Chapter 2. In Chapter 4 the
variation of the threshold current density with temperature for visible lasers is measured and modelled. In Chapter 5 both the temperature sensitivity of the threshold current density and of the radiative current in 1.3μm lasers are investigated. We then attempt to identify the cause of the temperature sensitivity in the lasers studied.

Hydrostatic pressure is a useful tool for studying band gap dependent loss mechanisms in semiconductors because the band gap can be increased by increasing the pressure. We may therefore use pressure to observe the onset or reduction of band gap dependent loss mechanisms and predict the behaviour of higher band gap (lower wavelength) devices. The change in threshold current with pressure may be modelled in an attempt to identify the dominant loss mechanism present at atmospheric pressure in a laser device.

1.4 Introduction to Thesis

This thesis investigates the loss mechanisms present in both visible and long-wavelength (specifically 1.3μm InGaAsP) devices, by using the application of hydrostatic pressure and by changing the temperature.

Chapter 2 introduces the basic theory necessary for analysis of the results, such as the effects of strain and hydrostatic pressure on a semiconductor, and gives an outline of the major loss mechanisms found in the devices at the wavelengths studied. Chapter 3 outlines the experimental procedures used, while Chapters 4 and 5 give results and analysis for visible and 1.3μm lasers respectively. The thesis is summarised in Chapter 6.

Briefly, it has been found that the major loss mechanism in visible lasers is leakage in the conduction band X-minima in the cladding. Phonon-assisted Auger
recombination is found to be the major cause of the high temperature sensitivity in 1.3µm devices. It has been shown that the radiative current in 1.3µm lasers is not unusually temperature sensitive.
Chapter 2

Basic Theory

2.1 Introduction

This chapter briefly introduces the basic theory necessary for the analysis and understanding of experimental results shown in later chapters. This has already been covered extensively in several general semiconductor laser text books [11-14] and greater detail can be found in the references given.
2.2 Basic Operation of a Semiconductor Laser

2.2.1 Electronic Transitions

There exist three basic processes involving photons, electrons and holes in a semiconductor laser - those of absorption, spontaneous emission and stimulated emission. These are shown schematically in Figure 2.1, in which the electron and hole involved in each transition are shown in their final positions. Only stimulated emission is desirable for lasing action, as it results in coherent photons all of the same polarisation, emitted in the same direction. Spontaneous emission occurs randomly in all directions, whilst absorption must be overcome for lasing to take place. The gain in the laser cavity must equal all losses in order for the device to lase.

![Figure 2.1: The processes of absorption, spontaneous emission and stimulated emission.](image)

At room temperature, the conduction band contains very few electrons and the probability of emission is therefore much smaller than that of absorption. An electric
current is passed through the device in order to inject electrons into the conduction band and holes into the valence band. When an electron recombines across the band gap with a hole in the valence band, a photon is emitted with an energy equal to the transition energy. This assumes a direct band gap semiconductor, in which the top of the valence band (the $\Gamma$ point) is at the same point in momentum space as the bottom of the conduction band. In a semiconductor where this is not the case, for example silicon, a phonon is also required. This makes the recombination much less likely, and such materials are therefore unsuitable for use as optical emitters.

Once a sufficient density of carriers has been injected into the device there will be enough electrons in the conduction band so that the probabilities of stimulated emission and absorption become equal. At this point the laser diode is said to be "optically transparent". The condition for lasing is given by the Bernard-Duraffourg equation [15]:

$$E_{fc} - E_{fV} > \hbar \nu$$  \hspace{1cm} (2.1)

where $E_{fc}$ and $E_{fV}$ are the quasi-Fermi levels for the conduction and valence bands respectively, $\hbar$ is Planck's constant and $\nu$ is the photon frequency.

### 2.2.2 Optical Feedback

In order to enhance stimulated emission it is necessary to build up a large photon density in the cavity. Therefore some method is required for reflecting a proportion of the light produced up and down the cavity. This is achieved in one of two ways, by mirrors (facets), or by some form of diffraction grating as is used for example in a Distributed FeedBack (DFB) laser. All the devices studied in this work are of the former.
variety, which is shown schematically in Figure 2.2. The facets at each end of the cavity are formed by cleaving along the appropriate crystallographic direction, in this case along (110) planes. This gives rise to a reflectivity of approximately 32%, which may be altered by coating the facets.

Figure 2.2 : Schematic diagram of a Fabry-Perot laser cavity.

The reflections of the light wave set up Fabry-Perot resonances (hence "Fabry-Perot laser") and there are therefore many possible discrete optical modes in the laser. The mode which is closest to the peak of the gain curve is the one which will lase.
The condition for threshold gain $g_\text{th}$ is:

$$\Gamma g_\text{th} = \Gamma \alpha_\text{act} + (1-\Gamma)\alpha_\text{ext} + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right)$$

(2.2)

where $\alpha_\text{act}$ is the loss in the active region, $\alpha_\text{ext}$ is the absorption elsewhere in the device, $L$ is the cavity length (typically between $200\mu\text{m}$ and $1000\mu\text{m}$), $R_1$ and $R_2$ are the reflectivities of the facets and $\Gamma$ is the optical confinement factor, which is a measure of the fraction of the light wave in the active region.

### 2.2.3 Waveguiding

Waveguiding can be achieved by several means: strongly index guided, weakly index guided and gain guided. Gain guiding is the weakest of the three methods. Examples of laser structures using these different guiding techniques can be found in Agrawal and Dutta [12]. Figure 2.3 shows an example of index guiding, which is used in all the lasers investigated in this work. The active region is surrounded by a material of higher band gap, and thus lower refractive index. This results in confinement of part of the light wave to the active region. The light wave decays rapidly in the surrounding medium of lower refractive index.
2.2.4 Carrier and Current Confinement

With the first heterojunctions came a significant improvement in carrier confinement compared to homojunctions. The carriers are now confined to a smaller area resulting in a reduced threshold current density. Further improvement resulted from the introduction of quantum wells. These effects are illustrated in Figure 2.4.

Current confinement can be achieved in several ways. Some devices simply use a non-conducting oxide layer to ensure the current is injected through the centre of the

Figure 2.3: Confinement of the optical wave to the active region, which has a higher refractive index than the surrounding material. A bulk device is shown.
laser device, as shown schematically in Figure 2.5(a).

(a) Homojunction (b) Heterojunction (c) Quantum Well

Figure 2.4: From homojunction (a) through heterojunction (b) to quantum well (c) - an illustration of advances in carrier confinement.

However, in practice the current spreads out considerably before reaching the active region. This is the method used in all the visible lasers described in Chapter 4, which have a ridge waveguide structure shown schematically in Figure 2.5(b). A second method involves growing the device to the active region, then etching away all but the centre few microns to leave a mesa structure. The surroundings of the mesa are then regrown with electrically doped layers resulting in a reverse-bias p-n junction, which will tend to block current through it. A third method uses a semi-insulating layer around the mesa, which can be produced for example by doping the material with iron, which can increase the electrical resistivity to around $10^9 \Omega \text{cm}$. Figure 2.5(c) shows schematically a buried-heterostructure (BH) laser utilising a semi-insulating blocking layer, which is the structure used in all the 1.3µm devices discussed in Chapter 5.
2.3 Finding the Threshold Current

A detector is placed to detect emission from one of the end facets of the laser and the light intensity is measured, as a photodetector voltage, as a function of laser drive current. The threshold current of the laser can then be found from a graph of light against current by one of two methods, shown in Figure 2.6. The first of these, 2.6(a), has been used for the determination of all threshold currents in this thesis. Furthermore, it has been found that in the devices studied the difference between the two methods is typically less than 1% and that the measured variations of threshold current as a function of temperature and pressure are identical within experimental accuracy.
2.4 From Three to Two Dimensions

Although two of the devices investigated in this thesis are bulk (i.e. three-dimensional), most contain quantum wells and are therefore two-dimensional structures. The major advantage resulting from the introduction of quantum wells is the reduced thickness of the active region leading to better confinement of the carriers. Another advantage comes from the density of states, shown in Figure 2.7, which is more efficient for lasing action in two dimensions than in three dimensions as there is a larger proportion of carriers near the band edge. This leads to a reduced threshold carrier density and thus threshold current [16]. Carrier population is shown in the figure as the shaded regions.

Another effect of moving to two-dimensional structures is that it results in confinement of the carriers in the quantum wells, at energies derived from the solution of the Schrödinger equation.
Figure 2.7: The density of states in (a) three dimensions and (b) two dimensions. The shaded regions indicate carrier population.

This confinement energy is shown schematically in Figure 2.8. It is dependent on the effective mass of the carriers and is therefore highest in the conduction band and lowest in the heavy hole band. Also shown are the conduction and valence band offsets, $\Delta E_c$ and $\Delta E_v$. These quantities, together with the confinement energies, are important when considering thermal loss of carriers out of the quantum wells.

2.5 The Effects of Strain

In 1986 it was suggested [7,8] that the inclusion of strain in semiconductor laser diodes would significantly enhance their performance. Up to that point all alloys used in devices were lattice-matched to their substrate material. Most devices investigated in this work have strained active regions. It is also possible to strain the barriers between the quantum wells, in order to compensate for the strain in the quantum wells.
Figure 2.8: Band offsets and the effect of the confinement energy in quantum wells.

The important effects of strain on semiconductors and on laser diodes are given here briefly but for more detailed information the reader is referred to the many articles and papers on the subject [16-22]. All effects are considered for growth along the [001] direction, as is the case with all devices investigated in this work.

2.5.1 Strained Layer Devices

If a layer with lattice constant $a_{layer}$ is grown on a substrate with lattice constant $a_{sub}$, and $a_{layer} > a_{sub}$, then the lattice constant of the layer will contract in the growth plane and therefore expand in the growth direction as described by Poisson's ratio. Therefore the layer is in a state of biaxial stress, resulting in a compressive strain in the growth plane. This situation is reversed for the case $a_{layer} < a_{sub}$, resulting in an in-plane tensile strain. These situations are shown in Figure 2.9, along with the unstrained case.
The standard geometry is also shown. Throughout this work, x is along the cavity direction, y is parallel to the facets, and z is the growth direction. Optical modes with the electric field oscillating in the z direction are called transverse magnetic, or TM modes. Modes with the electric field oscillating in the y direction are transverse electric (TE) modes.

The net strain in the layer plane is given by:

$$\varepsilon_{zz} = \varepsilon_{xx} = \varepsilon_{yy} = \frac{(a_{layer} - a_{sub})}{a_{layer}}.$$  \hfill (2.3)

The strain in the growth direction is given by:

$$\varepsilon_{\parallel} = \varepsilon_{zz} = -2\frac{\sigma}{1-\sigma} \varepsilon_{z}.$$ \hfill (2.4)

where $\sigma$ is Poisson's ratio, which is approximately equal to $\frac{1}{3}$ in a tetrahedral semiconductor.

Therefore,

$$\varepsilon_{\parallel} = -\varepsilon_{z}.$$ \hfill (2.5)

It is often useful to split these strains into axial and hydrostatic components. In so doing, it can be readily seen for example that the introduction of strain alters the band gap of a semiconductor. The axial component is:

$$\varepsilon_{ax} = \varepsilon_{\parallel} - \varepsilon_{z} = -2\varepsilon_{z}.$$ \hfill (2.6)
Figure 2.9: The cases of (a) compressive strain, (b) tensile strain and (c) lattice-matched.

while the hydrostatic component is given by:

\[ \varepsilon_{\text{vol}} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = e_r = \left( \frac{\Delta V}{V} \right). \]  \hspace{1cm} (2.7)

There is a certain maximum strain which may be incorporated into a layer. At a certain thickness of layer, called the critical thickness, it becomes energetically
favourable to relieve the strain through the formation of dislocations. The higher the strain, the thinner the maximum layer thickness which may be grown to a quality necessary for laser operation. Values for the critical thickness times the strain of about 200Å% have been reported for high quality growth of InGaAs on GaAs [18].

2.5.2 Effects of Strain on the Valence Band

The incorporation of strain has little effect on the conduction band of a semiconductor, apart from splitting the degeneracy of the X-minima. However, there are two main effects on the valence band, which are outlined briefly below. We consider first a strained bulk-like semiconductor.

1) The axial component of strain splits the zone-centre degeneracy of the valence band maximum. Compressive strain pushes the hole band which is heavier in an unstrained semiconductor (heavy hole band) up and the light hole band down, tensile strain has the opposite effect.

2) The axial component of strain also introduces anisotropy into the valence band, which follows from the lifting of the degeneracy of the valence band maximum. The hole mass in a compressively strained semiconductor becomes lighter in the x-y plane than in the z-direction, whilst tensile strain has the opposite effect.

These effects are illustrated in Figure 2.10, taken from O'Reilly [18].

The hydrostatic component of strain alters the band gap, increasing it in the case of compressive strain and reducing it with the incorporation of tensile strain.
Figure 2.10: (a) Lattice-matched. $k_\parallel$ is the in-plane $k$-vector, $k_z$ is in the strain ($z$) direction. (b) Tensile strained. (c) Compressively strained.

It is possible by using these effects to engineer the valence band of a semiconductor simply by adding various amounts of strain.

We may now consider strained quantum wells, shown schematically in Figure 2.11 [18]. Figure 2.11(a) shows the unstrained case, in which the states are already split by quantum confinement. The first heavy hole state, denoted by HH1, is highest. Figure 2.11(b) shows the compressively strained case. The heavy hole well is deeper than the
light hole well. In the tensile case, shown in Figure 2.11(c), the light hole well deepens and the lowest transition can be with the first light hole state LH1.

Figure 2.11: The effects of strain on quantum wells. HH and LH denote heavy and light hole states respectively. (a) An unstrained quantum well. (b) Compressively strained. (c) Tensile strained.

2.5.3 Implications for Strained Quantum Well Lasers

There are six important implications of the introduction of strain which are listed below.
1) A lighter mass in the x-y plane in the highest valence band will reduce the carrier density required to achieve population inversion [7,8].

2) In a bulk-like semiconductor in the unstrained case there are equal numbers of carriers at the top of the (degenerate) valence band in momentum states which will recombine to produce photons polarised in the x, y and z directions. Carriers producing photons polarised along x contribute only to spontaneous emission, those along y contribute to TE gain and those along z to TM gain. Thus, only one in three carriers may contribute to laser gain. The heavy hole band consists of one half x and one half y states, the light hole band of one sixth x, one sixth y and two thirds z. As can be seen from Figure 2.12, under compressive strain the heavy hole band moves up with respect to the light hole band and now one half of the carriers (producing y-polarised photons, resulting in TE-polarised light) can contribute to lasing action. In the tensile case two thirds of the carriers contribute to z-polarised photons, and the device will lase with a TM polarisation.

3) Following from point (2), TM gain is suppressed in compressively strained devices and TE gain is suppressed in tensile strained devices.

4) Also from point (2), unwanted spontaneous emission is suppressed.

5) The change in hole effective mass may change the Auger recombination coefficient (Auger recombination is discussed in section 2.6.2) and also the rate of IVBA (section 2.6.3).

6) Strain may change the band offsets and may influence leakage into the barrier regions and into the cladding.

It is important to note that it is not desirable to use a small tensile strain, as this
counteracts the effects of quantum confinement and leads to the equal population of the light hole and heavy hole bands.

Figure 2.12: Proportion of carriers contributing to light polarised in the x, y and z directions in (a) unstrained, (b) compressively strained and (c) tensile strained lasers.

2.6 Loss Mechanisms in Semiconductor Lasers

This section introduces the main loss mechanisms which can be found in semiconductor lasers. Some are more important in long wavelength devices, and others more important in short wavelength devices.
2.6.1 Thermally Activated Leakage Currents

All semiconductor lasers suffer from leakage of carriers out of the active region into the cladding and this effect increases as the temperature increases. It is also possible, as is the case in visible lasers, that as the temperature increases carriers may be excited into indirect conduction band minima, which may be in the cladding. This effect is discussed in section 2.6.4. Indeed, it is the presence of the X-minima which sets an upper limit on the photon energy which can be achieved in the visible lasers investigated in Chapter 4. Both efficiency and threshold current are affected in the manner shown in Figure 2.13, in which we see the threshold current increase with increasing temperature. The efficiency decreases as the temperature increases.

![Figure 2.13](image)

Figure 2.13: The threshold current increases and the efficiency decreases as the temperature is increased.

It is observed that the threshold current of lasers increases approximately exponentially with temperature over a limited temperature range and it is usual to describe the temperature sensitivity of a semiconductor laser diode by the characteristic
temperature, $T_0$. This is defined by the equation [12]:

$$I_{th2} = I_{th1} e^{\frac{T_2 - T_1}{T_0}}$$  \hspace{1cm} (2.8)

where $I_{th1}$ and $I_{th2}$ are the threshold currents measured at temperatures $T_1$ and $T_2$ respectively. This gives:

$$T_0 = \frac{T_2 - T_1}{\ln(I_{th2}) - \ln(I_{th1})}$$  \hspace{1cm} (2.9)

which is the reciprocal of the gradient of a graph of natural log threshold current against temperature. It is for this reason that temperature data is often displayed in this way.

Since the variation of threshold current with temperature does not follow the exponential relationship over a wide temperature range a typical device may have two $T_0$ values quoted, these being one for temperatures up to about 250K-300K and another for higher temperatures. The value of $T_0$ will tend to be lower for higher temperatures (a lower value of $T_0$ denotes a higher temperature sensitivity). This is because thermally activated processes are often the cause for the high temperature sensitivity of lasers. These may be "frozen out" at low temperatures.

2.6.2 Auger Recombination

It will be shown in work presented in Chapter 5 that the dominant loss mechanism in lasers with an operating wavelength around 1.3μm is Auger recombination. This involves three transitions and affects the threshold current density. Two Auger processes are shown in Figure 2.14, the CHCC and CHSH processes. The
recombination of an electron in the conduction band with a hole in the valence band produces no photon, but instead the energy and momentum are used to excite a second electron from the conduction band higher into the conduction band in the CHCC process, or an electron from the spin split-off valence band into the heavy hole band in the CHSH process. Closed symbols denote electrons, open symbols holes.

(a) The CHCC process. (b) The CHSH process.

Figure 2.14: The direct Auger processes, (a) CHCC and (b) CHSH.

In the phonon-assisted processes a phonon is required to conserve momentum. Figure 2.15 shows the corresponding phonon-assisted Auger processes, P-CHCC and P-CHSH [22,23].

The total current density of a long wavelength laser may be written [24]:

\[ J = eAn + eBn^2 + eCu^3 \]  

(2.10)
where $e$ is the electronic charge, $A$ is the coefficient governing non-radiative loss such as non-radiative recombination via impurities, $B$ is the radiative recombination coefficient, $C$ is the Auger coefficient and $n$ is the carrier density.

(a) The P-CHCC process.

(b) The P-CHSH process.

Figure 2.15: Phonon-assisted Auger processes, (a) P-CHCC and (b) P-CHSH.

The coefficient $C$ can be written:

$$C(T) = C_0 e^{-\frac{\Delta E_{act}}{kT}} \quad (2.11)$$

where $C_0$ is a coefficient independent of temperature $T$, $k$ is Boltzmann's constant and $\Delta E_{act}$ is the Auger activation energy, denoting the temperature dependence of the process.
The activation energies used in Chapter 5 for the two direct processes assuming parabolic bands and Boltzmann statistics are [25]:

\[
\Delta E_{\text{act}}(\text{CHCC}) = \frac{m_e E_g}{m_e + m_{hh}}
\]  

(2.12)

and

\[
\Delta E_{\text{act}}(\text{CHSH}) = \frac{m_s (E_g - \Delta)}{(2m_{hh} + m_e - m_s)}
\]  

(2.13)

where \( m_e \) is the electron effective mass, \( m_{hh} \) is the heavy hole effective mass, \( E_g \) is the band gap, \( \Delta \) is the spin split-off energy and \( m_s \) is the spin split-off band effective mass.

Gönül [26] substituted expressions for \( \Delta E_{\text{act}} \) and \( C_q \) into equation 2.11 to derive the following expressions for the direct Auger coefficients, \( C \). From these expressions we can see the band gap (and pressure) dependence of each Auger process.

For the direct CHCC process:

\[
C(\text{CHCC}) \propto \frac{(m_{hh} + m_e)}{(2m_{hh} + m_e)^2} \frac{1}{E_g^3} e\left(-\frac{m_e - E_g}{m_e + m_{hh} kT}\right)
\]  

(2.14)

The expression for the direct CHSH process is:

\[
C(\text{CHSH}) \propto \frac{(m_{hh})^2 m_s (2m_{hh} + m_e - m_s)}{(2m_{hh} + m_e)^2} \frac{1}{E_g \Delta^2 (E_g + \Delta)} e\left(-\frac{m_e - E_g}{2m_{hh} + m_e - m_s kT}\right)
\]  

(2.15)
where $m_v = m_{hh} + m_{lh}$ and $m_{lh}$ is the light hole effective mass.

Looking now at the phonon-assisted Auger processes, Gönül derived the following expression for P-CHCC, using the theory of Haug [27]:

$$C(P-\text{CHCC}) \propto \left( \frac{m_{hh}}{m_c} \right)^2 \left( \frac{1}{E_g^5} \right)^2$$

$$C(P-\text{CHCC}) \propto \left( \frac{2}{m_c} \right) \left( \frac{1}{E_g^5} \right)$$

(2.16)

and for P-CHSH:

$$C(P-\text{CHSH}) \propto \frac{m_{hh}^2}{m_s E_g \Delta^2 (E_g + \Delta)(E_g - \Delta)^2}.$$  

(2.17)

Due to the necessity for conservation of energy and momentum the direct Auger processes are highly sensitive to band structure, and this gives rise to a highly temperature sensitive threshold current. The P-CHCC and P-CHSH processes are less sensitive to the band gap since momentum is conserved by means of a phonon.

Auger recombination is only important in long wavelength lasers. In visible lasers the band gap is so high that Auger recombination can be ignored, see equations 2.14-2.17.

2.6.3 Inter-Valence Band Absorption

Inter-valence band absorption, or IVBA, is a second mechanism important only in long wavelength lasers. An electron recombines with a hole and produces a photon
which is then re-absorbed, the energy being used to excite an electron from the valence band to a higher valence band state. This is illustrated in Figure 2.16. It has previously been shown that this process affects both efficiency and threshold current [28] and to a lesser extent temperature sensitivity [29] but is eliminated in strained layer lasers [30,31].

![Diagram](image)

**Figure 2.16**: Inter-valence band absorption, in which an emitted photon is re-absorbed. The energy is taken up by an electron which is excited from the spin split-off band higher into the valence band.

### 2.6.4 Losses to Conduction Band X-Minima

Lasers with operating wavelengths in the red part of the visible spectrum are discussed in Chapter 4. These lasers have a larger band gap than the long wavelength lasers in Chapter 5 and are unaffected by Auger recombination and IVBA. We show in Chapter 4 that the primary mechanism responsible for the high threshold current densities in these lasers is leakage to conduction band X-minima in the cladding.
We have applied a model for the diffusion current in these devices [32]. This has been used in Chapter 4 to model temperature data from the lasers investigated. The leakage current is described in the model by the following equation:

\[ J_{\text{leak}} = \frac{q D_n n_{cl}}{l_n \tanh \left( \frac{X_p}{l_n} \right)} \]  

(2.18)

where \( n_a \) is the electron density at the interface of the waveguide and p-cladding layer, \( X_p \) is the distance to the p-contact, \( l_n \) is an effective diffusion length and the diffusion coefficient \( D_n \) is given by:

\[ D_n = \mu_n \left( \frac{kT}{q} \right) \]  

(2.19)

where \( \mu_n \) is the minority carrier mobility in the p-cladding layer and \( k \) is Boltzmann's constant. The density of electrons in the X-minima in the p-cladding layer, \( n_{cl} \), is estimated using Boltzmann statistics to be:

\[ n_{cl} = 2 \left( \frac{m_d kT}{2\pi \hbar^2} \right)^{3/2} e^{-\frac{E_{p} - E_{\text{eff}}^X}{kT}}. \]  

(2.20)

\( E_{p} \) is the quasi-Fermi level for electrons in the conduction band, \( m_d \) is the density of states mass and \( E_{\text{eff}}^X \) is determined by the doping density in the p-cladding and given by:

\[ E_{\text{eff}}^X = E_{\text{g}}^X - (E_{fp} - E_{fv}) \]  

(2.21)

where \( E_{\text{g}}^X \) is the indirect band gap energy of the cladding X-minima, \( E_{fp} \) is the Fermi level near the edge of the cladding layer determined by the p-doping density and \( E_{fv} \) is the valence band quasi-Fermi level.
2.7 Hydrostatic Pressure

2.7.1 Effects on Semiconductors and Semiconductor Lasers

The effect of hydrostatic pressure on the band structure of a direct band gap semiconductor is illustrated in Figure 2.17. The Γ- and L-minima move up with respect to the valence band maximum, while the X-minima move down. This has the effect of increasing the direct band gap. Approximate values for the rates of change of the minima with pressure, which are different in each material system and composition, are also shown in the figure. At a certain pressure, the Γ-minimum will cross with either the X- or L-minima and the semiconductor will become indirect.

Figure 2.17: The effect of hydrostatic pressure on the conduction band of a semiconductor.

This increase in band gap leads to other effects. The operating wavelength of a laser decreases and so the optical confinement factor increases. The electron effective mass is proportional to the band gap and therefore also increases with increasing hydrostatic pressure.

In a loss-free laser, the threshold current is expected to increase as the pressure
is increased due to the increase in band gap [33,34].

2.7.2 Hydrostatic Pressure as a Tool to Investigate Loss Mechanisms

Hydrostatic pressure is a very useful tool for the study of loss mechanisms in semiconductor lasers.

As seen in the previous section, the $\Gamma$-minimum is approaching the $X$- and $L$-minima at different rates as pressure is increased. This effect is exploited when investigating loss mechanisms in visible semiconductor lasers since in these devices the $\Gamma$-minimum is already close to the $X$- and $L$- minima in energy. As pressure is increased the probability of electron population of $X$- and $L$- minima increases as they move closer in energy to the $\Gamma$-minimum. In Chapter 4 we report on measurements of threshold current with hydrostatic pressure in visible lasers.

In a long wavelength device we have seen in section 2.6.2 that Auger recombination is an important loss mechanism which decreases with increasing band gap (equations 2.14 to 2.17). The threshold current of a long wavelength laser could therefore be expected to decrease with increasing pressure as Auger recombination is reduced due to the pressure-induced band gap increase.

The change of band gap with hydrostatic pressure also allows us to simulate the behaviour of shorter wavelength devices.

2.8 A Simple Model for the Characteristic Temperature $T_0$ in Long Wavelength Lasers

In Chapter 5 measurements of spontaneous emission are reported. The spontaneous emission is measured either from the side of the devices or from a window
etched in the substrate. The emission has therefore not undergone gain. These measurements are then used to find an effective characteristic temperature for the radiative current, $T_0(I_{\text{rad}})$. This is possible since the radiative current is proportional to the total spontaneous emission rate, where the total (integrated) spontaneous emission rate $L$ is found from equation 2.22, where $R_{\text{spont}}(E)$ is the rate of spontaneous emission at each energy.

$$I_{\text{rad}} \propto L = \int_{-\infty}^{\infty} R_{\text{spont}}(E) \, dE$$

(2.22)

A program was written in C to perform the integration which carried out the following steps, using raw data from the Optical Spectrum Analyser (OSA):

1) Wavelengths were converted to energies.

2) Powers were converted to rates by dividing the power by the photon energy at which each power was measured.

3) The resulting data was integrated using the trapezium rule.

By comparison with the standard equation for $T_0$ given in equation 2.9, an expression may be written for $T_0(I_{\text{rad}})$:

$$\frac{1}{T_0(I_{\text{rad}})} = \frac{\ln(L_2) - \ln(L_1)}{T_2 - T_1}$$

(2.23)

A simple model for the $T_0$ of the radiative current, $T_0(I_{\text{rad}})$, the non-radiative current, $T_0(I_{\text{thrad}})$ and the total threshold current $T_0(I_{\text{th}})$ has been derived by O'Reilly and Silver [35] using equations from Haug [36]. These equations, which describe the
temperature dependencies of the radiative recombination coefficient \( B \) and the carrier at threshold density \( n_{th} \) are as follows for a bulk device:

\[
B \propto T^{-3.2} \tag{2.24}
\]

\[
n_{th} \propto T^{3.2-x} \tag{2.25}
\]

where \( T \) is the temperature. The factor "\( x \)" indicates how the carrier density differs from the ideal case, in which \( x=0 \). As \( x \) increases \( n \) becomes more sensitive to temperature.

If, for example, one wishes to find an expression for the temperature sensitivity of the radiative component of the current, \( T_0(I_{Rad}) \), one would proceed as follows, starting with the equation:

\[
J = eAn + eBn^2 + eCn^3 \tag{2.26}
\]

which has been seen previously as equation 2.10. To find the temperature sensitivity of the radiative part of the total current, the radiative \( (eBn^2) \) term may be re-written in terms of equations 2.24 and 2.25:

\[
J_{Rad}^{bulk} = \frac{B_0}{T^{3.2}} n_0^2 [T^{3.2+x}]^2 . \tag{2.27}
\]

\( B_0 \) and \( n_0 \) are temperature insensitive constants.

Writing the characteristic temperature in the form:

\[
\frac{1}{T_0} = \frac{1}{J_{Rad}} \frac{dI_{Rad}}{dT} \tag{2.28}
\]

one may differentiate equation 2.27 with respect to \( T \) and substitute into equation 2.28
to obtain:

\[ T_{0}^{\text{bulk}}(I_{\text{Rad}}) = \frac{T}{3/2 + 2x} . \]  

(2.29)

Similarly, following the same analysis for the radiative case but using the eCh^3 term of equation 2.26 with equations 2.11 and 2.25, one may obtain an expression for the temperature sensitivity of the non-radiative Auger current:

\[ T_{0}^{\text{bulk}}(I_{\text{NRRad}}) = \frac{T}{9/2 + 3x + \Delta E_{ad} / kT} . \]  

(2.30)

We may now extend the analysis to quantum well devices to find expressions for the temperature sensitivities of the radiative and non-radiative parts of the total current, \( T_{0}^{\text{qW}}(I_{\text{Rad}}) \) and \( T_{0}^{\text{qW}}(I_{\text{NRRad}}) \) respectively. However the quantities \( B \) and \( n_{\text{sh}} \) have different temperature dependencies, again taken from Haug [36]:

\[ B \propto T^{-1} \]  

(2.31)

\[ n_{\text{sh}} \propto T^{1 + x} . \]  

(2.32)

The analysis is identical to that already described for the bulk device, and yields the following equations:

\[ T_{0}^{\text{qW}}(I_{\text{Rad}}) = \frac{T}{1 + 2x} \]  

(2.33)

\[ T_{0}^{\text{qW}}(I_{\text{NRRad}}) = \frac{T}{3 + 3x + \Delta E_{ad} / kT} . \]  

(2.34)
The exact carrier density (n) dependence of the total current I is unknown, and therefore we assume it may be written in the form:

\[ I \propto n^2 \]  
(2.35)

The total radiative emission, which below threshold is purely spontaneous emission is \( L = Bn^2 \) and therefore:

\[ n \propto L^{1/2} \]  
(2.36)

Combining equations 2.35 and 2.36 gives:

\[ I \propto (L^{1/2})^z \]  
(2.37)

Plotting a graph of \( \log(I) \) against \( \log(L^{1/2}) \) yields the value of \( z \) as the gradient.

The equations derived in this section will be used in Chapter 5 along with experimental results to identify the primary cause of the temperature sensitivity and the major contribution to the total current in lasers emitting around 1.3\( \mu \)m.
Chapter 3

Experimental Techniques

3.1 Introduction

The characteristics of the laser diodes investigated in this thesis have been studied by changing both the hydrostatic pressure and temperature of the devices, the reasons for which have been explained in Chapter 2. This chapter explains the various experimental techniques used, as well as some of the important experimental considerations. The basic measurement apparatus used for pressure and temperature measurements is explained. This is followed by a section detailing measurements of spontaneous emission, the results of which are reported in Chapter 5. Finally, some thought is given to two experimental problems, that of duty cycle and pulse width followed by that of the effect the pressure transmitting medium has on the optical
3.2 The Basic Apparatus used for Laser Measurements

Shown in Figure 3.1 is a schematic diagram of the basic system used to gather light/current (L-I) data. A program written in the C programming language [37] enabled results to be taken automatically using a personal computer (PC).

![Schematic diagram of the basic experimental set-up.](image)

Figure 3.1: Schematic diagram of the basic experimental set-up.

All the lasers studied were in unmounted chip form and were pulsed using a Lightwave ILX pulsed/continuous wave (CW) laser current source, which was controlled by the PC via a General Purpose Interface Bus (GPIB) using the IEEE-488 standard. A 47Ω resistor was placed in series with the laser to achieve an approximate 50Ω characteristic of a laser.
impedance matching.

The oscilloscope (CRO) used was a Tektronix 2221A 100MHz digital/analogue scope, which was used exclusively in digital mode. Readings of photodetector voltage and voltage across the laser diode and the 47Ω resistor together were taken from the oscilloscope via the GPIB and stored on the computer. The voltage across the laser was used to check for open circuits.

A boxcar averaging system was used for some early measurements. However, it was later deemed un-necessary for straight-forward L-I measurements (which have a high signal-noise ratio). The oscilloscope was used to provide a small amount of averaging at low light levels or low collection efficiencies. This occurred, for example, when light was collected through the optical fibre in the piston and cylinder high pressure system, in which case a low-noise amplifier was also used.

When measuring laser diodes emitting in the visible part of the spectrum (in practice 635nm-686nm) a large area AC-coupled silicon detector with integral amplifier was used at room temperature. For long wavelength measurements (around 1300nm and 1500nm) a similar germanium detector was used. As these detectors were AC-coupled, they would not work with direct current (DC). The detector response decays after only a few micro-seconds, and measurements made on lasers using pulse widths longer than about 20μs were therefore difficult.

### 3.3 Spontaneous Emission Measurements

Chapter 5 details measurements of spontaneous emission involving a range of injection currents from about one-seventh of the threshold current \( I_{th} \) to just above
threshold current. An Ando AQ-6315A Optical Spectrum Analyser (OSA) was used to measure the spectrum obtained, in conjunction with the ILX current source. Temperature was controlled using a Peltier device. The Ge detector described previously and the CRO were also used to monitor facet output.

The light was focused via a pair of microscope objectives onto an optical fibre with core and cladding diameters of 100μm and 140μm respectively. The fibre was connected directly to the OSA. A program was written using the C programming language to interpret the data from the OSA and integrate under the curve to find the total spontaneous emission, as detailed in section 2.8. For the earliest measurements the wavelength range chosen for the scan was 1000nm to 1500nm but this was later changed to 1050nm to 1450nm since the integrals for the two ranges differed by less than 1%. A smaller scan range gives greater accuracy while keeping the scan time constant. High averaging was deemed unnecessary as two scans taken with high and low averaging showed a difference of less than 0.5%. High averaging significantly increases the scan time.

3.4 The Application of Hydrostatic Pressure

Since experiments in 1762 by Canton [38] to compress water, the application of high pressure has been a valuable technique in the investigation of the characteristics of physical systems.

Two methods have been used to apply hydrostatic pressure to the laser diodes. One uses a piston and cylinder arrangement to apply up to 15kbar pressure at room temperature. The other achieves a maximum pressure of about 8kbar, however the sample chamber of the second system will fit into a cryostat to make simultaneous
pressure and temperature measurements possible.

For detailed discussion of the various sealing techniques used, the use of hydraulic rams, piston and cylinder systems, intensifier systems and other general background information the interested reader is referred to Bridgman [39] and Bradley [40].

Bridgman discusses the effects of pressure on certain properties such as resistance and thermal conductivity. He also explains the intensifier system, as used for many high pressure experiments in this work. A great contribution to sealing techniques was the Bridgman unsupported area seal, in which the seal is maintained by ensuring that the area of the seal is larger on the high pressure side than the atmospheric pressure side. Thus the sealing pressure is always larger than that in the pressure medium.

Bradley explains the engineering of various high pressure cylinders and the workings of the cylinder and piston system. Also discussed are various sealing techniques as well as their limitations, including the O-ring and delta ring combination used in both high pressure systems described in the following sections.

### 3.4.1 The Piston and Cylinder Apparatus [41]

This system, shown in Figure 3.2, consists of two opposing 29mm diameter pistons inside a double cylinder arrangement in which the inner cylinder is under compressive stress from the outer at atmospheric pressure, thus increasing the maximum obtainable pressure before the inner cylinder ruptures.
Figure 3.2: Schematic diagram of the 15kbar system.
The cylinder is filled with a 50:50 mixture of castor oil and amyl alcohol. The latter prevents the oil solidifying at pressures of about 12kbar and over. The pistons are sealed in the cylinder by means of phosphor-bronze delta rings and neoprene O-rings. The O-rings seal up to around 4kbar, at which point there is sufficient force on the unsupported area of the phosphor-bronze ring for it to seal. Fitted to the lower piston is a coil of manganin wire, with an approximate room-pressure resistance of 150Ω. The pressure dependence of the resistivity of this wire is well known and the coil thus acts as a pressure gauge. During the experiment, resistance was measured using a Keithley 177 digital multimeter. This should give an accuracy in measurements of pressure of around 0.1kbar.

The temperature difference between the inside of the cylinder at atmospheric pressure and the laboratory was measured using two thermocouples to measure actual temperature, the "hot" junction of the second being inside the cylinder. It was found as expected that the temperature inside the cylinder does not change significantly over the course of the whole experiment if the temperature in the laboratory remains approximately constant. This, of course, is only true if sufficient time is given between changes in pressure for the temperature inside the cylinder to stabilise. Any change in temperature will affect not only the threshold current of the laser but also the resistance of the manganin wire. For the purpose of this work the temperature of the manganin wire and the laser device under test is taken to be constant. Ideally one would want some method of measuring the temperature inside the cylinder under actual measurement conditions. Measurements of the change of threshold current with time after the pressure is changed show that at least 15 minutes are required after an increase of 10kbar before the temperature inside the cylinder stabilises.
Light is extracted through the upper piston by means of a 100μm core diameter optical fibre epoxy-sealed in a stub and screwed down to the piston. The stub is sealed by means of a single layer of aluminium foil. The foil moulds into any microscopic scratches and irregularities in the metal surfaces of the stub and piston, ensuring a good seal. The upper piston also provides electrical feed-throughs for the current to the laser by means of conical pins hammered into holes in the piston and sealed with vespel seals. The clip for the laser itself is butted up to the fibre, the laser is manually aligned to the fibre, and the clip is then screwed to the stub in which the fibre is glued. Load is applied to the upper piston by means of a hydraulic ram capable of 120 tons. The hydraulic pipes are rated to 700bar, whilst the maximum pressure inside the pipes under measurement conditions is roughly 550bar.

It should be noted that amyl alcohol attacks the epoxy which holds the fibre in place. This is a slow process and many experiments can be run with each fibre-stub before losing the seal, provided the stub is washed with water when the experiment is over. It has recently been found that nail varnish appears insoluble in amyl alcohol, and could therefore be used as a barrier if necessary. This was deemed un-necessary because the lifetime of the epoxy is usually longer than the fibre itself, which occasionally snaps near the stub during handling.

### 3.4.2 The Cu:Be Cell Apparatus [42]

The second system used to apply hydrostatic pressure, shown schematically in Figures 3.3 and 3.4, is quite different to that described in the previous section. Figure 3.3 shows the whole system and Figure 3.4 the cell and pistons. The high pressure cell is a 19mm outer diameter Cu:Be double-walled cylinder. A piston containing a sapphire
window sealed by a tapered nylon ring and O-ring is screwed into the bottom of the cell.

Figure 3.3: The Cu:Be high pressure system.

The upper piston contains the laser mount and is attached to a capillary tube. The upper piston is also sealed by means of a tapered nylon ring and neoprene O-ring. The
The electrical connection to the laser is fed through the capillary to a Harwood three-way coupler and then continues through the upper pressure seal, a short length of capillary containing epoxy. This epoxy is exposed to vacuum to eliminate any air pockets, which would act as leakage paths, and then cured. The capillary itself acts as the second (ground) connection. The third connection to the Harwood coupler is the capillary tube connection to an intensifier system, connected to a hydraulic hand pump. Again, seals in the intensifier are tapered nylon rings and O-rings. The pressure transmitting medium used is n-pentane, through which pressure may be applied hydrostatically in the pressure and temperature range used, being up to 8kbar between room temperature and around 350K.

The temperature of a laser in this system may be changed by insertion of the pressure cell into a cryostat.

![Figure 3.4: The Cu:Be high pressure cell.](image)
3.5 Changing the Temperature of the Laser Diode

Two methods have been used to achieve temperature variation of the laser diode being tested. The first uses a cryostat, the second a Peltier device. Temperatures were measured to an accuracy of ±0.5K.

3.5.1 The Cryostats

Two cryostats have been used during this work. The first is a bath cryostat, in which the outer jacket is pumped down to the order of $10^{-6}$ Torr and the nitrogen bath then filled. A valve controls the flow of nitrogen from the reservoir around the cryostat and thus the cooling rate. This is offset by a heater connected to an Oxford Instruments 3120 temperature controller. The nitrogen must be replenished periodically. It is also possible to pump down the sample space ($10^{-1}$ mbar is adequate) and then to introduce a dry gas such as nitrogen. This ensures there is no water vapour in the sample space which could freeze on the laser facets at low temperatures. Temperatures between 77K and about 450K are achievable using this cryostat.

The second cryostat is a "cold finger" cryostat, in which the laser sits in a mount on a so-called cold finger, which is connected to a nitrogen reservoir which again must be replenished periodically. The sample space is evacuated to a pressure of about $10^{-4}$ Torr. This arrangement is faster than the bath cryostat as cooling and heating (by electrical heaters) is via conduction, not convection. However, the maximum temperature range is 77K to room temperature. Also, one must mount the laser in its clip directly on the cold finger since cooling and heating is by conduction. Therefore, one cannot use the Cu:Be pressure cell for simultaneous pressure and temperature experiments in this
cryostat. The sample space is quite large and not only takes a greater time to pump down compared to the bath cryostat, but must be brought up to room pressure every time the sample is changed. In the case of the bath cryostat, the sample space is small and only a low vacuum is required so only a few seconds are required to evacuate it after changing the sample.

The pump system used in both cases was a standard rotary and diffusion pump arrangement.

3.5.2 The Peltier Heater/Cooler

For fast temperature measurements from about 290K to 350K at ambient pressure a Peltier device mounted under a laser clip was used. The whole assembly is attached to a heatsink which is cooled naturally by air-flow around the laboratory. A water-cooled heatsink would allow a larger temperature range, but one would lose the portability of the system. The lower temperature limit is set not only by the efficiency of the heatsink but also by ambient humidity, which changes the dew-point. Condensation forming on a laser facet seriously (though temporarily) degrades laser operation.

3.6 Choice of Pulse Width and Duty Cycle

Choice of pulse width is very important when characterising semiconductor laser diodes. All laser diodes measured in this work were in unbonded chip form and were therefore pulsed to avoid adverse heating effects. The shorter the pulse the smaller the chance of heating the device, but the worse the signal-to-noise ratio.

For most measurements, the pulse width used was 1-2μs, at a frequency of
230Hz. This frequency is not a multiple or sub-multiple of the mains supply. It has been reported [43] that the average rise in temperature of the laser under test is less than 0.5K when using a duty cycle such as this. Further, the threshold current was not seen to increase (due to increasing temperature) with increasing pulse width until much higher pulse widths and frequencies than those used, the exact value of which depended on device geometry and lasing wavelength. Typical values where the onset of heating was observed were pulse widths of over about 6µs or shorter pulses of 2 or 3µs at frequencies of over about 10kHz. When using the Si detector no effects of heating could be seen on the oscilloscope screen with pulse widths and frequencies lower than these. At longer pulse lengths the pulse shape shown in Figure 3.5 was observed.

![Figure 3.5: The effect of current heating on the optical detector pulse.](image)

This figure shows an oscilloscope plot of voltage (from the detector) against time when measuring a laser above its threshold current. The plot on the left shows the normal response of the photodiode. On the right the laser starts to lase but after a few micro-seconds it heats up due to the electrical current and so the light output drops.

The Ge detector used was too slow to observe any heating effects. It should also
be noted that, as has been previously mentioned, the detectors used were AC-coupled, and therefore very long pulse widths (for example over about 20μs) could not be resolved. The threshold current was measured as a function of pulse width and frequency for long wavelength lasers in order to observe the onset of heating, with similar results to the short wavelength case (in which heating could be observed on the CRO).

For measurements at very low injection currents when using the Optical Spectrum Analyser, a pulse width of 3μs was used at a frequency of 5kHz for some early measurements presented in this work. For later experiments a frequency of 10kHz was used to increase the signal to noise ratio. No change in threshold current was seen when using these duty cycles (1.5% and 3%, respectively) compared with the lower duty cycle used for other measurements (0.03%).

3.7 The Effect of the Pressure Media

The threshold current density depends, among other things, on the reflectivities of the end facets. If the laser diode is immersed in a liquid, as it was during the pressure measurements, the reflectivities of the facets will decrease or increase due to the change in refractive index outside the laser. Table 3.1 shows measured threshold currents in air and n-pentane and Table 3.2 in air and castor oil/amyl alcohol for many of the devices investigated.

No simple pattern may be seen from these results. Therefore, if corrections to threshold currents measured in pressure experiments are deemed necessary, each device must be taken individually. It can, however, be seen that the longer wavelength 1.3μm devices are, in general, more greatly affected.
Table 3.1: Threshold currents in air and n-pentane.

<table>
<thead>
<tr>
<th>Device</th>
<th>Coated</th>
<th>$I_{th}(\text{air})$</th>
<th>$I_{th}(\text{n-pentane})$</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3µm bulk</td>
<td>No</td>
<td>25.2</td>
<td>27.6</td>
<td>9.5</td>
</tr>
<tr>
<td>8QW 1.3µm</td>
<td>No</td>
<td>18.9</td>
<td>20.4</td>
<td>7.9</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4QW 1.3µm</td>
<td>No</td>
<td>19.7</td>
<td>21.7</td>
<td>10.2</td>
</tr>
<tr>
<td>-1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DQW IBM 686nm</td>
<td>10%, 90%</td>
<td>16.1</td>
<td>17.5</td>
<td>8.7</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3QW 656nm</td>
<td>$\lambda/2, \lambda/2$</td>
<td>39.8</td>
<td>42.6</td>
<td>7.0</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk 659nm</td>
<td>No</td>
<td>62.6</td>
<td>66.5</td>
<td>6.2</td>
</tr>
<tr>
<td>4QW 632nm</td>
<td>No</td>
<td>69.2</td>
<td>70.7</td>
<td>2.1</td>
</tr>
<tr>
<td>-0.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DQW 672nm</td>
<td>No</td>
<td>32.9</td>
<td>41.5</td>
<td>26.1</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The initial increase of threshold current is not a serious problem since mostly we are only interested in the relative change in threshold current density and not in its absolute value.
Table 3.2: Threshold currents in air and 50:50 castor oil:amyl alcohol.

<table>
<thead>
<tr>
<th>Device</th>
<th>Coated</th>
<th>$I_a$(air)</th>
<th>$I_a$(oil/alcohol)</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3μm bulk</td>
<td>No</td>
<td>16.2</td>
<td>20.8</td>
<td>28.4</td>
</tr>
<tr>
<td>8QW 1.3μm</td>
<td>No</td>
<td>15.2</td>
<td>19.6</td>
<td>28.9</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4QW 1.3μm</td>
<td>No</td>
<td>19.1</td>
<td>23.2</td>
<td>21.4</td>
</tr>
<tr>
<td>-1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DQW IBM 686nm</td>
<td>10%, 90%</td>
<td>17.6</td>
<td>18.0</td>
<td>2.2</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3QW 656nm</td>
<td>$\lambda/2$, $\lambda/2$</td>
<td>37.8</td>
<td>36.8</td>
<td>-9.7</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk 659nm</td>
<td>No</td>
<td>68.2</td>
<td>72.9</td>
<td>6.9</td>
</tr>
<tr>
<td>4QW 632nm</td>
<td>No</td>
<td>71.1</td>
<td>75.3</td>
<td>5.9</td>
</tr>
<tr>
<td>-0.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DQW 672nm</td>
<td>No</td>
<td>23.4</td>
<td>29.0</td>
<td>23.9</td>
</tr>
<tr>
<td>+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A more worrying problem is that of the change of density of the pressure transmitting medium with pressure, which will lead to a change in its refractive index. This will introduce a pressure-dependent change in threshold current density which is not due to the changing conditions inside the laser itself but is purely an artifact of the
experiment. No data has been found in the literature concerning the refractive index of castor oil and its pressure and wavelength dependencies. However, the change of refractive index with pressure for isopentane has been reported by Langer and Montalvo [44]. We have measured a value of 1.4 for the refractive index of the castor oil and amyl alcohol mixture at 633nm by measurements of the reflections of the incident and refracted light rays at room temperature and atmospheric pressure. Results for isopentane are reproduced in Figure 3.6, using the equation given in the afore-mentioned paper. The dashed line shows this curve normalised to 1.4 at atmospheric pressure. Data for other liquids and gases [45-48] show similar behaviour for the change of refractive index with pressure in every case.

One may estimate the effect of the change in refractive index on the threshold current by considering the initial change in threshold current when each laser is placed in the pressure transmitting liquid (Tables 3.1 and 3.2). From the following mathematical equation:

\[
\frac{\partial I}{\partial P} = \frac{\partial I}{\partial n} \cdot \frac{\partial n}{\partial P}
\]

we may derive the following:

\[
\Delta I = \frac{I_l - I_a}{n_l - n_a} \cdot \frac{\Delta n}{\Delta P} \cdot \Delta P'
\]

where the symbols have the following meanings:

- \(I_l\) and \(I_a\) are the threshold currents in the liquid and in air respectively,
- \(n_l\) and \(n_a\) are the refractive indices in the liquid and in air respectively,
- \(\Delta n/\Delta P\) is the change in refractive index with pressure and
- \(\Delta P'\) is the change in pressure considered.
It is clear from Figure 3.6 that $\Delta n/\Delta P$ is not linear. Therefore all corrections in this work use values for the change in refractive index with pressure taken directly from the data of Langer and Motalvo [44] (Figure 3.6), after normalisation at atmospheric pressure for measurements in the castor oil/amyl alcohol mixture.

![Figure 3.6](image)

**Figure 3.6**: Solid line - change of refractive index with pressure for iso-pentane [44]. Dashed line - The same line normalised to a refractive index of 1.4, as measured at atmospheric pressure for castor oil/amyl alcohol at 633nm.

For the 672nm laser described in Chapter 4 the correction to the threshold current at 10kbar is 2.1mA, which represents an increase in threshold current of 1%. The change in refractive index of the semiconductor due to the change in band gap has been reported for visible lasers by Moser et al. [49]. Using the formula given in that paper we calculate that this change is ten times smaller than the change in refractive index of the pressure-
transmitting medium over 10kbar and is therefore neglected.

It must be stressed that equation 3.2 gives only a first approximation to the correction to the threshold current which is required. Some points to note are listed below.

1) The method used to measure the refractive index of the castor oil/amyl alcohol mixture carries an error of at least ± 7%.

2) We are assuming that the refractive index and change in refractive index with pressure is the same for n-pentane as for iso-pentane.

3) All refractive index values were measured at 633nm. Data from Datta et al. [50] give the refractive index of glass at 800nm as approximately 1.56 and at 1800nm as approximately 1.52. Similar measurements on a solution of NH₄Cl - H₂O [51] give a refractive index of 1.364 at 500nm and 1.356 at 700nm. Assuming a similar wavelength dependence for our liquids gives a change from 633nm to 1300nm which is still within the experimental error for our measurement of refractive index.

4) We are assuming the initial change in threshold current when each laser is placed in the liquid to be linear over that change in refractive index. We further assume that it may be extrapolated linearly to higher values of refractive index.

A proper experimental investigation of the change of refractive index with pressure would clearly be useful for future analysis but the estimates made above indicate that the effects are small and would not affect any of the conclusions in this thesis.
Chapter 4

Visible Laser Diodes

4.1 Introduction

Semiconductor lasers operating in the wavelength range 630nm to 690nm are commercially important for a number of applications, for example in bar-code readers, laser pointers and displays. They are ideal replacements for Helium-Neon (He-Ne) gas lasers, which are bulky and fragile and require higher power consumption. The low wavelength means a smaller focused spot size than that obtainable using lasers emitting in the infra-red, making visible lasers ideal candidates for high density optical storage [52].

Visible lasers have seen improvements in temperature sensitivity, high power operation and threshold current density since the first CW AlGaNp red lasers were
reported in 1985. As with other material systems it has been found [53] that moderate (up to 1%) compressive and tensile strains improve the threshold current density ($J_\text{th}$). Valster et al. reported in 1992 [54] a $J_\text{th}$ of 760A/cm$^2$ and a power of 45mW for a compressively strained device lasing at 632nm. Mannoh et al. [55] reported a value for the characteristic temperature $T_0$ of 144K in a compressively strained 677nm laser measured between 20°C and 50°C. In 1994 Bour [56] reported operation of a tensile strained single quantum well device lasing at 633nm with a $J_\text{th}$ of 400A/cm$^2$. He also reported a value for $J_\text{th}$ of 175A/cm$^2$ for a laser emitting at 680nm. In the same year he reported a tensile-strained laser with an emission wavelength of 620nm and a $J_\text{th}$ of 800A/cm$^2$ [57]. Geels et al. [58] reported CW power output from an array of 687nm lasers of 30W at a current of around 35A.

A range of tensile and compressively strained devices lasing between 635nm and 686nm supplied by Philips in Eindhoven and IBM in Zürich have been investigated in this work. The chapter begins by briefly detailing the motivation for this work. Each laser investigated is then described and results of pressure and temperature experiments are given. The chapter ends with an analysis of the results obtained.

4.2 Motivation for this Work

Visible lasers emitting in the red have higher threshold current densities and lower values for the characteristic temperature $T_0$ than lasers based on the GaAs/AlGaAs material system emitting around 900nm. There has long been some uncertainty over the exact cause of the temperature dependence and the high threshold current densities in red visible lasers. Bour et al. [59] explain these in terms of drift leakage current, while
in an earlier paper Hagen et al. [60] believe recombination in the depletion region plays a large role in explaining the temperature dependence. This work aims to identify the major source of current leakage in visible-light emitting lasers. The indirect X and L conduction band minima are near in energy to the Γ-minimum and therefore, as explained in sections 2.6.4 and 2.7.2, the major reason for the high threshold current densities in these devices is expected to be carriers populating these indirect conduction band minima. We will explain the leakage of carriers from the active region into the cladding in terms of diffusion currents.

Work by Prins et al. [61] involving low temperature high pressure photoluminescence in a miniature diamond anvil cell [62] and calculations using a program written by Meney [63] show that the X-minima in the AlGaInP barriers and cladding are lower than those in the GaInP quantum wells or bulk active regions with no applied bias. Prins was unable to exactly locate the position of the L-minima, but has determined that they are more than 175meV above the Γ-minimum at atmospheric pressure. However, theoretical work by Meney et al. [32] shows leakage in L-minima to be unimportant.

The following section of this chapter details each laser and gives a schematic diagram of the material composition of each device investigated.

4.3 Device Details

Three lasers supplied by Philips Optoelectronics Centre [64] and one from IBM [65] have been investigated.

All lasing wavelengths were measured either using a 1m Spex spectrometer, a
0.3m Spex Minimate spectrometer or a HP70950A Optical Spectrum Analyser at a temperature of 293±2K at atmospheric pressure, to an accuracy of about 1nm. Each laser was subjected to hydrostatic pressure in order to bring the conduction band minima closer together in energy, and the temperature sensitivity of each device was measured to obtain a value for the characteristic temperature $T_0$ as explained in section 2.6.1, in many cases as a function of pressure.

4.3.1 Devices Supplied by Philips Optoelectronics Centre

All but one of the devices were supplied by Philips Optoelectronics Centre. The lasers were grown by metal-organic chemical vapour deposition. An n-doped cladding layer of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ was grown on an n-type GaAs substrate. Next comes the active region, which will be described for each laser diode in the appropriate section. In the quantum well devices this active region was surrounded by a separate confinement structure consisting of $(Al_{0.4}Ga_{0.6})_{0.5}In_{0.5}P$. There followed a p-doped cladding layer of the same composition as the n-doped cladding layer after which came a 0.1µm layer of GaInP. Finally came a top layer of GaAs into which a 7µm ridge had been defined. The n-dopant was Se, to an approximate concentration of $5-7\times10^{17}$ cm$^{-3}$ and the p-dopant was Zn, at an approximate concentration of $3-5\times10^{17}$ cm$^{-3}$.

Due to the low level of doping in the p-cladding, spreading of the current below the ridge is expected to be very limited [66]. Therefore all values of the threshold current density $J_n$ have been calculated assuming no current spreading.

The three Philips lasers investigated are shown in Figure 4.1. Also shown are approximate positions of the lowest X-minima in each structure, calculated using a
program written by Meney [63]. Details of each individual device may be found in section 4.4. For material parameters see Appendix II.

Figure 4.1: Schematic diagram of the Philips (a) bulk laser, (b) compressive laser and (c) tensile laser at threshold. The solid lines show the valence band and conduction band $\Gamma$-minimum. The dotted lines show the calculated positions of the lowest $X$-minima. The dot-dashed lines show the positions of the conduction and valence band quasi-Fermi levels, $E_c$ and $E_v$ respectively. All energies are in meV.
4.3.2 Device Supplied by IBM

One device investigated was supplied by IBM in Zürich. Its material composition around the active region is shown schematically in Figure 4.2. It had a cavity length $L_{cav}$ of $500\pm5\mu m$, as measured by optical microscope. Its facets were coated to 90% reflectivity at the rear and 10% reflectivity at the front. The ridge was $5\mu m$ wide. The 0.19μm Zn-doped (p-type) and Si-doped (n-type) cladding layers meet a 0.14μm wide parabolically graded separate confinement structure, graded from $(Al_{0.3}Ga_{0.7})_{0.2}In_{0.8}P$ to $(Al_{0.3}Ga_{0.7})_{0.2}In_{0.8}P$, surrounding the active region.

![Figure 4.2: Schematic diagram of the laser supplied by IBM. The concentration of aluminium is also shown.](image)

This gives rise to a confinement region whose refractive index is also graded, a structure known as GRaded INdex Separate Confinement Heterostructure (GRINSCH).

The active region consisted of two $100\AA$ wide 1% compressively strained $Ga_{0.33}In_{0.67}P$ quantum wells with a $(Al_{0.3}Ga_{0.7})_{0.2}In_{0.8}P$ 40Å wide unstrained barrier.
4.4 Experimental Results

4.4.1 Bulk Unstrained Laser ($\lambda_{\text{lasing}} = 659\text{nm}$)

The active region of this laser consisted of 800Å of Ga$_{0.52}$In$_{0.48}$P. The bandstructure diagram is shown schematically in Figure 4.1(a). The laser had a cavity length of 300±5μm and its lasing wavelength was measured to be 659nm at room temperature.

Shown in Figure 4.3 is a graph of threshold current density $J_\text{th}$ against temperature, $T$, up to room temperature.

![Graph of threshold current density against temperature](image)

![Log graph of threshold current density against temperature](image)

Figure 4.3: Threshold current density against temperature for the bulk 659nm laser.

The value of the characteristic temperature, $T_0$, found for values of temperature around and below room temperature was 132K.
Figure 4.4: Threshold current density for the bulk 659nm laser plotted as a function of pressure at four temperatures. The $J_{th}$ values were calculated at atmospheric pressure by Meney et al. [32] and extended to higher pressures using experimentally determined pressure coefficients.

Figure 4.4 shows $J_{th}$ plotted as a function of hydrostatic pressure, $P$, at four temperatures, 308K, 318K, 328K and 338K. The values of $J_{th}$ at atmospheric pressure were calculated using the theoretical model outlined in section 2.6.4 involving diffusion current, over 90% of which was found to be in the barrier and cladding X-minima at room temperature. Reasonable agreement with experiment in this and all other devices investigated was obtained with fitting parameters of 2.6ns for the non-radiative lifetime and 0.22µm for the effective diffusion length, both reasonable values. Shown in Figure 4.5 is the variation of the value of $T_{th}$ with pressure obtained from Figure 4.4. As pressure increases, the $\Gamma$-minimum in the active region moves closer in energy to the X-minima, and it can be seen from the figure that the laser becomes more temperature sensitive. One could expect from this result that longer wavelength lasers in this material
system would be less temperature sensitive, whilst lasers emitting at shorter wavelengths would be more temperature sensitive.

![Graph showing the characteristic temperature $T_0$ for the bulk 659nm laser as a function of pressure.](image)

**Figure 4.5**: Values for the characteristic temperature $T_0$ for the bulk 659nm laser as a function of pressure.

### 4.4.2 1% Compressively Strained ($\lambda_{\text{lasing}} = 672\text{nm}$)

The band structure for this device is shown schematically in Figure 4.1(b). It had 1% compressively strained quantum wells and a cavity length of 300±5μm. The active region consisted of two 80Å quantum wells of Ga$_{0.38}$In$_{0.62}$P in a (Al$_{0.4}$Ga$_{0.6}$)$_{0.3}$In$_{0.7}$P 60Å barrier inside 1200Å of material identical to the barriers. Its lasing wavelength was measured to be 672nm.

The temperature dependence of the threshold current is shown in Figure 4.6.
Figure 4.6(a) also shows the theoretical calculation.

![Figure 4.6](image)

**Figure 4.6**: (a) Experimental and modelled (dashed line) threshold current density and (b) log\(_\text{e}\) threshold current density as a function of temperature for the 672nm compressive laser.

The theory used in this calculation has been described in section 2.6.4 and involves diffusion current only. Over 90% of the diffusion current was calculated to be at room temperature in the X-minima. Values for \(T_0\) of 103K above room temperature and 172K below room temperature were deduced from Figure 4.6(b).

The pressure dependence of this device was investigated up to about 12kbar, as shown in Figure 4.7. We attempt to gain some further insight into the mechanism responsible for the rapid increase of the threshold current density at around 7kbar by using the method of Blood et al. [67] to make a fit to the excess current. Blood says that
the spontaneous current density at threshold $J_{\text{spont}}$ is proportional to the square of the
energy location of the gain peak, $(h
u_{\text{max}})^2$ [33].

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4_7}
\caption{Threshold current density as a function of pressure for the 672nm compressive laser. The dashed line is the expected increase of current with pressure.}
\end{figure}

Differentiating with respect to pressure, we then equate the rate of change of $h
u_{\text{max}}$ with pressure to the rate of change of the band gap with pressure. The measured rate of change of lasing energy with pressure for this device was 6.7meV/kbar and is shown in Figure 4.8. Prins [68] shows a value for the rate of change of band gap with pressure for a 1% compressively strained sample, measured by low temperature photoluminescence in a diamond anvil cell of around 7.7meV/kbar. We find that the difference between the use of 6.7meV/kbar and 7.7meV/kbar results in final values for rate of change of the activation energy which differ by only 1%.
We may now write the expected increase of threshold current density with pressure as follows [67]:

\[
\frac{1}{J_{\text{th}}}, \frac{dJ_{\text{th}}}{dP} = \frac{2}{h\nu_{\text{max}}}, \frac{dE_g}{dP}.
\]

(4.1)

This current is shown on Figure 4.7 as a dashed line. Any current above this may be defined as an excess current \( J_{\text{excess}} \). This we then attempt to fit with the exponential expression shown in equation 4.2 containing an activation energy \( \Delta E_{\text{act}} \), the value of which will give us an indication as to the leakage mechanism responsible for this excess current.
The excess current is plotted in Figure 4.9, in which the value for $\frac{\Delta E_{\text{act}}}{\Delta P}$ as deduced from the slope of the graph is also shown. Its value was found to be 9.0meV/kbar. This value agrees well with the measured rate at which the $\Gamma$- and $X$-minima are approaching one another, being 8.8meV/kbar. This uses an experimentally determined rate of change with pressure for the $X$-minima in the barriers and cladding of -2.1meV/kbar [68]. This value was used for all three quantum well devices investigated.

![Figure 4.9](image)

*Figure 4.9*: Plot used to find the activation energy $\Delta E_{\text{act}}$ for the leakage mechanism in the 672nm compressive laser.
A second method may be used to find the expected increase of the radiative current, as used by Göntil [26]. She uses equations from Hang [36] and Ghiti [69] and finds an expected increase of about 3% over 4kbar for a 635nm laser. Applying this value to the data from the three quantum well lasers in this chapter, we find only a 1% difference in the rate of change of the activation energy with pressure between the two methods.

4.4.3 0.7% Tensile Strained Device (λ_{d=635nm})

The third Philips device to be investigated was a laser with an active region consisting of four 0.7% tensile strained 80Å wide quantum wells in 60Å wide barriers. The material composition in the quantum wells was Ga_{0.65}In_{0.35}P.

![Figure 4.10](image_url) (a) Experimental and modelled (dashed line) threshold current density and (b) log threshold current density against temperature for the 635nm tensile laser.
This device had a cavity length of 500±5µm and its lasing wavelength was measured to be 635nm. Its band structure is shown schematically in Figure 4.1(c).

Figure 4.10 shows the temperature dependence of the threshold current density. The dashed line in Figure 4.10(a) is the theoretically modelled variation. Values for $T_0$ of 124K and 47K were found from Figure 4.10(b) below and above room temperature respectively. Figure 4.11 shows the variation of $\log(J)_{th}$ of the threshold current density against temperature at two different pressures, for a second similar device. As we have seen in section 4.4.1, the laser becomes more temperature sensitive as pressure increases.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4_11.png}
\caption{Log threshold current density as a function of temperature at two pressures for the 635nm tensile device.}
\end{figure}

Figure 4.12 shows the variation of threshold current density with pressure.
Figure 4.12: Threshold current density as a function of pressure for the 635nm tensile device. The dashed line is the expected increase of radiative current density with pressure.

The rate of change of lasing energy with pressure is plotted in Figure 4.13, giving a value of 9.2meV/kbar. In Figure 4.14 the excess current density has been plotted and yields a value for $\Delta E_{\text{exc}}/\Delta P$ of 10.9meV/kbar. This again compares well with the experimentally determined rates at which the $\Gamma$- and $X$-minima are approaching one another, 11.3meV/kbar.
Figure 4.13: The variation of lasing energy with pressure for the 635nm tensile laser.

Figure 4.14: The deduced activation energy for the leakage mechanism.
4.4.4 IBM 1% Compressively Strained Device ($\lambda_{\text{lasing}} = 686\text{nm}$)

The device supplied by IBM had a similar strain and operating wavelength to the Philips device reported in section 4.4.2 and was therefore subjected to hydrostatic pressure for comparison. Its lasing wavelength was measured to be 686nm.

The experimental variation of the threshold current with pressure is shown in Figure 4.15. This data has been previously presented by Hawley [43]. The dashed line is the expected variation of the threshold current with pressure.

![Figure 4.15](image)

**Figure 4.15**: Variation of the threshold current density with pressure for the IBM 686nm compressive laser. The dashed line is the expected rate of increase of radiative current density with pressure.

Figure 4.16 shows the rate of change of lasing energy with pressure, giving a value of 7.1meV/kbar which compares exactly with the value for the rate of change of
band gap with pressure [68].

Figure 4.16: The rate of change of lasing energy with pressure for the IBM device.

The excess current is plotted in Figure 4.17, giving a value for $\frac{\Delta E_{\text{act}}}{\Delta P}$ of 9.2meV/kbar. The rate at which the $\Gamma$- and $X$-minima are approaching each other in this device was deduced to be 9.2meV/kbar. This compares exactly with the determined value of the activation energy, again indicating that leakage in the $X$-minima is the dominant loss mechanism.

Shown in Figure 4.18 is a graph of threshold current against temperature at 0kbar and 3.8kbar. Again, the device becomes more temperature sensitive as the $X$-minima move closer to the $\Gamma$-minimum with increasing pressure.
Figure 4.17: The plot to deduce the activation energy of the leakage mechanism in the IBM compressive 686nm laser.

Figure 4.18: \( \log_e \) threshold current density with temperature at two pressures for the IBM laser.
4.5 Analysis of Results

Shown in Table 4.1 is a summary of some important results. Values in the table give the threshold current density at room temperature in air $J_{th}(RT)$, values for the characteristic temperatures below and above room temperature $T_0(low)$ and $T_0(high)$ respectively, the value of $T_0$ at a higher pressure $T_0(HP)$ and the approximate energy separation between the lowest confined conduction band $\Gamma$ state in the well and the lowest $X$-minima, $\Delta E^{\Gamma-X}$. This splitting is given at atmospheric pressure and uses theoretical values obtained from a program by Meney [63]. The value of pressure at which $T_0(HP)$ was measured is given in brackets.

Table 4.1: Some important experimentally measured parameters and the theoretical splitting of the $\Gamma$- and cladding $X$-minima.

<table>
<thead>
<tr>
<th>Laser</th>
<th>$J_{th}(RT)$ (kA/cm²)</th>
<th>$T_0(low)$ (K)</th>
<th>$T_0(high)$ (K)</th>
<th>$T_0(HP)$ (K)</th>
<th>$\Delta E^{\Gamma-X}$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk 659nm</td>
<td>3.5</td>
<td>132</td>
<td>84</td>
<td>64 (2.0 kbar)</td>
<td>270</td>
</tr>
<tr>
<td>-1% 672nm</td>
<td>1.1</td>
<td>172</td>
<td>103</td>
<td>-</td>
<td>335</td>
</tr>
<tr>
<td>-0.7% 635nm</td>
<td>1.9</td>
<td>124</td>
<td>52</td>
<td>42 (2.1 kbar)</td>
<td>255</td>
</tr>
<tr>
<td>+1% IBM</td>
<td>0.7</td>
<td>-</td>
<td>73</td>
<td>49 (3.8 kbar)</td>
<td>-</td>
</tr>
</tbody>
</table>

We have used the value given in the above table for the splitting between the lowest $\Gamma$ state in the quantum well and the lowest $X$ states.
A graph of threshold current density against this splitting has been plotted for the +1% 672nm laser and the -0.7% 635nm laser and is shown in Figure 4.19. Pressure data from Figures 4.7 and 4.12 was used, taking a value for the change in X-minima of -2.1meV/kbar from Prins [68]. A value for the rate of change of the \( \Gamma \)-minimum for the compressively strained laser of 6.7meV/kbar has been used and for the tensile strained device of 9.2meV/kbar, as these are the measured values for the rates of change of lasing energy for these devices.

![Graph showing threshold current densities of 672nm and 635nm lasers](image)

**Figure 4.19**: The threshold current densities of the 672nm compressive (closed circles) and 635nm tensile (open squares) lasers at room temperature plotted as a function of the calculated splitting between the well \( \Gamma \)-minimum and cladding X-minima.

Both devices show a similar trend at similar values for the \( \Gamma \)-X splitting,
indicating that this does indeed appear to be responsible for leakage at these wavelengths. Any difference in splitting value at which the sudden increase in threshold current density occurs in the two devices may be easily explained in terms of the accuracy of the theoretical values for the $\Gamma$-$X$ splittings.

Using the model of Blood et al. we have found values for $\Delta E_{\text{exc}} / \Delta P$ for the Philips compressive, IBM and tensile lasers. These compare well with the experimental rate at which the $\Gamma$- and $X$-minima are expected to approach one another with pressure. These are summarised in Table 4.2 along with the expected rate at which the lasing energy, measured in this work, and the $X$-minima, again taken from Prins [68] as 2.1meV/kbar, are approaching one another. This is given as $\Delta E_{\Gamma-X} / \Delta P$ in the table.

Table 4.2 : Comparison between $\Delta E_{\text{exc}} / \Delta P$ and $\Delta E_{\Gamma-X} / \Delta P$.

<table>
<thead>
<tr>
<th>Laser</th>
<th>$\Delta E_{\Gamma-X} / \Delta P$ (meV/kbar)</th>
<th>$\Delta E_{\text{exc}} / \Delta P$ (meV/kbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips Compressive</td>
<td>8.8</td>
<td>9.0</td>
</tr>
<tr>
<td>Philips Tensile</td>
<td>11.3</td>
<td>10.9</td>
</tr>
<tr>
<td>IBM Compressive</td>
<td>9.2</td>
<td>9.2</td>
</tr>
</tbody>
</table>

This is in agreement with pressure results on a bulk visible laser by Hawley [43], who found a rate of change of activation energy with pressure of 11meV/kbar. This conclusion also agrees with the conclusion reached by considering the modelled threshold currents. Our model [32], described in section 2.6.4, considered leakage in $\Gamma$, $X$ and $L$ states but found that in all cases leakage in $X$-minima in the cladding accounted
at room temperature
for over 90% of the total current. These electrons then escape to the electrical contact.

Further, Meney has found that in the 0.7% tensile strained 635 nm laser the leakage current is five times that of the radiative current at 350 K, while in the 1% compressively strained 672 nm laser at 350 K the radiative current is roughly five times larger than the leakage current. This he attributes to the larger conduction band offsets in the longer wavelength device. It may be seen from Figures 4.4 (bulk), 4.6 (compressive) and 4.10 (tensile) that there is excellent agreement between experiment and a theory considering diffusion current, over 90% of which is in the X-minima. Leakage does not seem to be a large problem at 672 nm at room temperature. This is in agreement with previous work by Bour [56], who reports that the leakage current may be negligible at room temperature above 660 nm, but it remains a problem at 633 nm.

All the lasers whose values for $T_0$ have been measured at different pressures showed a decrease in $T_0$ at higher pressure. Clearly the cause of the temperature sensitivity in these devices is also band gap dependent, and is due to thermal loss of electrons into the X-minima in the barriers and cladding followed by diffusion towards the electrical contact.

It may be seen considering Figures 4.6 and 4.15 that the threshold current densities of the two 1% compressively strained lasers behave in a similar manner with pressure, regardless of the differences in their structures. Therefore the same leakage mechanism is likely to be dominant in the IBM laser as in the Philips laser, a conclusion corroborated by the excellent agreement of the experimentally determined rate of change of activation energy with the rate at which the $\Gamma$- and X-minima are approaching one another in all three quantum well lasers investigated.
4.6 Conclusion

We conclude that the cause of the high threshold current density and high temperature sensitivity of lasers operating between 630 and 690nm is current leakage in the X-minima in the cladding region. This is based on both a theoretical model and on a simple fit to experimental data giving a rate of change of activation energy with pressure for the leakage process within 4% of the experimentally determined rate at which the Γ- and X-minima approach one another with pressure.
Chapter 5

1.3μm Semiconductor Laser Diodes

5.1 Introduction

Laser diodes designed to operate at 1.3μm are of commercial importance in communications systems since this is the wavelength of zero dispersion in a standard silica optical fibre.

Devices lasing around 1.3μm have been investigated for several years, however several questions still remain. One of the most important of these is the origin of the relatively high temperature sensitivity in these devices. While it is agreed that quantum well lasers are in general less temperature sensitive than bulk devices [70], many believe Auger recombination to be unimportant in determining the temperature sensitivity of 1.3μm lasers, for example Garbuzov et al. [71] and Seki et al. [72]. O'Gorman et al.
[73], Ackerman et al. [74] and Zou et al. (1.5μm lasers) [75,76] attribute the temperature sensitivity of the threshold current to the temperature sensitivity of the differential gain. Bernussi et al. [77] attribute the high temperature sensitivity in strained InGaAsP lasers to variations of the differential gain and transparency carrier density. O'Reilly and Silver [35] and Li and Bradford [78] disagree, believing that the temperature sensitivity of these lasers is due to Auger recombination. This conclusion was reached in the early 1980's by Dutta and Nelson [79,80]. Casey [81] argues that the temperature dependence of the gain is the main factor for the temperature sensitivity up to a temperature of about 250K but above this it is dominated by Auger recombination and carrier leakage. However, some groups argue that carrier leakage is not a problem, finding its contribution to be around 1% of the total current [82], even at 350K [83].

The lasers investigated in this chapter are all of semi-insulated planar buried heterostructure (SIPBH) design (see section 2.2.4) and were grown by low-pressure metal-organic chemical vapour deposition (LP-MOCVD). 1% compressive and tensile strained multiple quantum well (MQW) devices were investigated, as well as unstrained bulk lasers.

We now present the measured change of threshold current with temperature for each device, followed by results of measurements of spontaneous emission. We compare these results with theory and identify the major loss mechanism as Auger recombination and deduce that this is the origin of the high temperature sensitivity of these devices. The dependence of the threshold current on pressure is then presented for each device.
5.2 Device Details

All devices investigated had as-cleaved (uncoated) facets. Devices used for the various measurements were cleaved (by the supplier [84]) to lengths of 500μm and 1000μm, as measured under an optical microscope to an accuracy of ±5μm. The structures of the devices around the active region are shown schematically in Figure 5.1, along with their conduction and valence band offsets, calculated using a program written by Silver [85]. Wavelengths were measured using an optical spectrum analyser (OSA) to an accuracy of approximately 1nm.

5.2.1 Unstrained Bulk Device

The unstrained bulk devices consisted of 1.5μm of In_{0.21}Ga_{0.79}As_{0.62}P_{0.38}. The lasing wavelengths at 295K were measured by an OSA at a drive current roughly 10% above threshold and found to be 1319nm and 1308nm for the 1000μm and 500μm length devices respectively.

5.2.2 Device Incorporating 1% Compressive Strain

These devices had 8 55Å In_{0.85}Ga_{0.15}As_{0.67}P_{0.33} quantum wells in 0.2% tensile strained barriers. They were found to lase at 1324nm and 1323nm for the 1000μm and 500μm cavity lengths, respectively.

5.2.3 Device Incorporating 1% Tensile Strain

The tensile devices had 4 120Å In_{0.5}Ga_{0.5}As_{0.78}P_{0.22} quantum wells in 0.3% compressively strained barriers. The devices lased at 1332nm and 1324nm for the 1000μm
Figure 5.1: Schematic diagram of the (a) bulk, (b) compressively strained and (c) tensile strained structures at threshold. The dot-dashed lines show the positions of the conduction and valence band quasi-Fermi levels, $E_c$ and $E_v$ respectively. All energies are in meV.
and 500μm long devices, respectively.

5.3 Measurements of Threshold Current as a Function of Temperature

The variation of the threshold current with temperature was measured from approximately 77K up to about 350K. Shown in Figure 5.2 is a graph of threshold current against temperature for the three devices, bulk unstrained, 1% compressively strained and 1% tensile strained.

![Graph of threshold current against temperature](image)

Figure 5.2: Variation of threshold current with temperature for the three laser structures.

All devices had a cavity length of 500μm in order that better direct comparison could be made. Figure 5.3 is a graph of the natural log of the threshold current against temperature, plotted in order to find a value for $T_0$ as explained in section 2.6.1. We will
call this value $T_0(I_0)$ to avoid confusion later when considering the radiative current.

As can be seen from Figure 5.3, the $T_0(I_0)$ values for the three devices do not vary considerably, with values of 47K, 53K and 46K above a temperature of 300K for the bulk unstrained, 1% compressively strained and 1% tensile strained devices, respectively. These values were obtained using a least squares fit. The fit was good in all cases. These results imply that the introduction of strained quantum wells has not significantly reduced the high temperature sensitivity of these devices.

![Figure 5.3](image)

**Figure 5.3**: Ln threshold current with temperature. The deduced value for the $T_0$ of each laser above room temperature is given.
5.4 Measurements of Spontaneous Emission

5.4.1 The Method

Having measured the temperature dependence of the threshold current $T_0(I_n)$ of the three lasers, measurements of spontaneous emission were made to determine the temperature sensitivity of the radiative current, $T_0(I_{rad})$, as explained in section 2.8.

Devices with cavity lengths of 1000$\mu$m were used for these measurements in order to maximise the area over which spontaneous emission is emitted. Devices of this cavity length can be expected to have slightly better values for $T_0(I_n)$ than those described in the previous section.

The first measurements were made by observing the pure spontaneous emission from the side of the devices. Light from the facet cannot be used for this analysis, as stimulated emission and spontaneous emission which has undergone gain and absorption are also detected. Furthermore, emission from the side of a device is only expected to be useful in a buried heterostructure device. In a ridge laser, for example, the layer constituting the active region extends to the edges of the device and so the spontaneous emission undergoes reabsorption. This could be expected to alter the spectrum.

The spectra were inspected prior to integration for any sign of scattered stimulated emission, which would manifest itself as a spike on the spontaneous emission curve. This effect is shown in Figure 5.4 in which the current was slowly increased from just below threshold (Figure 5.4(a)) to just above (Figures 5.4(b),(c) and (d)). No stimulated emission was seen under actual measurement conditions, even at drive currents well above threshold.
Figure 5.4: Four spontaneous emission spectra. (a) Drive current is just below threshold. (b), (c) and (d) Drive current increased above threshold. The vertical axis has arbitrary units, and is different for each curve. As a guide, the peak power of the wide spontaneous emission curve remains approximately constant in each case.

5.4.2 Results - 1.3µm Bulk Device

An example of the spectra measured is shown in Figure 5.5. For the sake of clarity only spectra at five currents are shown. The threshold current is just below 28mA. At and above the lasing threshold, the carrier density in the laser pins due to the increased photon density. The point at which the device begins to lase can therefore clearly be seen as a saturation of the spontaneous emission. Shown in Figure 5.6 are the values required from a graph of spontaneous emission rate against current to find the characteristic temperature of the laser, $T_0(I_a)$, and an effective $T_0$ value for the radiative
current, $T_o(I_{Rad})$. Equations 2.9 and 2.23 were used.

Figure 5.5: Examples of the spontaneous emission spectra obtained from the side of the bulk laser.

Two experimental runs were carried out on the bulk device, on two separate days. The results from the first of these is shown in Figure 5.7. A value for $T_o(I_a)$ of 49K was deduced for the curves obtained on both experimental runs, which compares exactly with the $T_o(I_a)$ value found from observing facet emission for this device. A value for $T_o(I_{Rad})$ of 157K was obtained for the first run and 168K for the second run. This spread of results is acceptable given the possible susceptibility of the experiment to changes in temperature in the lab, which could lead to movement of the laser relative to the fibre and microscope objectives.

Using equation 2.29 and assuming the quantity $x$ to equal zero, as it should in
Figure 5.6: The values required from a graph of spontaneous emission rate against current to obtain values for $T_0(I_{th})$ and $T_0(I_{rad})$ from equations 2.9 and 2.23.

Figure 5.7: Spontaneous emission rate as a function of current at 299K, 318K and 331K, as measured from the side of a bulk laser.
the ideal case, we predict a maximum value for the temperature sensitivity of the radiative current $T_0(J_{\text{rad}})$ to be 200K at a temperature of 300K. This compares well with the value of 163K averaged over both experimental runs. This value indicates that the radiative current is reasonably well behaved and $T_0(J_{\text{rad}})$ is much higher than the value for $T_0(I_d)$ of 49K. It therefore appears that the high temperature sensitivity is due to a non-radiative process.

Figure 5.8 shows a graph of $\ln(I)$ against $\ln(L^{1/2})$. The straight lines are least squares fits.

![Figure 5.8](image)

**Figure 5.8**: Graph of $\ln(I)$ against $\ln(L^{1/2})$ for the bulk laser. The gradient at each temperature is also shown.

Table 5.1 contains the gradients of the curves for each temperature range, for each of the experimental runs. As can be seen, the gradients are all close to three.
Table 5.1: Gradients from graphs of ln(I) vs ln(I^{1/2}) for both runs on the 1.3\,\mu m Bulk device.

<table>
<thead>
<tr>
<th>Run</th>
<th>T(K)</th>
<th>Gradient</th>
<th>T(K)</th>
<th>Gradient</th>
<th>T(K)</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>299</td>
<td>2.9</td>
<td>318</td>
<td>3.0</td>
<td>331</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>302</td>
<td>3.0</td>
<td>314</td>
<td>3.1</td>
<td>331</td>
<td>3.1</td>
</tr>
</tbody>
</table>

A gradient of 2.9 has also been found by analysing data from a paper by Girardin et al. [86] in which a graph of spontaneous emission from the side of a quantum well 1.55\,\mu m device is shown. It may be seen using equation 2.37 that this implies that the current is mainly dependent on the cube of the carrier density. From equation 2.26 this is the Auger current, which is proportional to Cn^3.

We now present results which show that the radiative current is similarly well-behaved in the cases of compressive and tensile strained 1.3\,\mu m lasers, and that Auger recombination again dominates the total threshold current.

5.4.3 Spontaneous Emission Results on a 1\% Compressively Strained Device

The first measurements were taken from the side of the laser, as in the bulk case. This device seemed more sensitive to movement of the mounts when the system was heated and cooled than the bulk device, and therefore results taken on different days showed a higher spread in values of T_g(I_{rad}).

Figure 5.9(a) shows a graph of spontaneous emission against drive current for the three different temperatures, and Figure 5.9(b) a graph of ln(I) against ln(I^{1/2}) with least
squares fits to the data. It should be noted that any change in the collection factor which could hugely increase errors of $T_{0}(I_{rad})$ will not have such a profound effect on the values of the gradients, as the main reason for error is thought to be a change in collection factor due to movement of the fibre with respect to the laser when the temperature is changed.

![Graphs showing spontaneous emission rate and ln(I) against ln(L^\alpha).]

**Figure 5.9**: Spontaneous emission from the side of a compressively strained laser. (a) Spontaneous emission rate as a function of current at three temperatures. (b) ln(I) against ln(L^\alpha). Gradients are also shown.

A value for the overall laser characteristic temperature $T_{0}(I_{th})$ was deduced as 50K from Figure 5.9(a) as opposed to a value of 54K found from facet measurements. An average value for the radiative characteristic temperature $T_{0}(I_{rad})$ was found to be 309K. However, over several experimental runs the spread of results gave an error in $T_{0}(I_{rad})$
of about ±80K. The values for the gradients from Figure 5.9(b) are 3.1, 3.1 and 3.0 for
temperatures 300K, 311K and 327K respectively.

It was decided that a window should be fabricated in the substrate of a device in the hope that this would improve the reproducibility of the results by keeping the collection factor constant. A window in such a device is possible since its substrate, InP, is non-absorbing at the wavelengths measured. Details of window fabrication can be found in Appendix I.

5.4.4 Window Emission Results on a 1% Compressively Strained Device

It was noted that less light was obtained through the window than out of the side of the device. It is possible that the etching process had not completely removed the contact layer.

Three experiments were conducted. In the first, the system was focused and optically aligned to give the maximum signal only at the lowest temperature (Figure 5.10), in the second only at the highest temperature (Figure 5.11) (in which case the experiment was started at the highest temperature and temperature was decreased during the experiment) and in the third the system was optimised at every temperature (Figure 5.12). The results for $T_o(I_{rel})$ from these three experiments may be found in Table 5.2, while the gradients at each temperature may be found on the appropriate graphs. Also shown in Table 5.2 are the values deduced for $T_o(I_d)$ both from facet measurements and from Figures 5.10 to 5.12.
Figure 5.10: (a) Spontaneous emission rate and (b) $\ln(I)$ against $\ln(L^{1/2})$ graphs for window emission from a compressively strained laser, optimised at low temperature.

Table 5.2: Results of window measurements on a 1.3µm 1% compressively strained laser.

<table>
<thead>
<tr>
<th>System optimised at ...</th>
<th>$T_0(I_{\text{Res}})$</th>
<th>$T_0(I_{\text{f}})$ (graph)</th>
<th>$T_0(I_{\text{f}})$ (facet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest Temperature</td>
<td>356</td>
<td>58</td>
<td>57</td>
</tr>
<tr>
<td>Highest Temperature</td>
<td>234</td>
<td>58</td>
<td>57</td>
</tr>
<tr>
<td>Every Temperature</td>
<td>322</td>
<td>55</td>
<td>57</td>
</tr>
</tbody>
</table>
A changing collection factor is the reason for this spread of values for $T_0(I_{rad})$.

Figure 5.11: (a) Spontaneous emission rate and (b) ln$I$ against ln($L'^{1/2}$) graphs for window emission from a compressively strained laser, optimised at high temperature.

If the system is optimised at one temperature only, then the collection factor can only remain constant or decrease with temperature. Consider the case where the system has been optimised only at the lowest temperature. If the collection factor decreases as the temperature increases less light is collected, making the spontaneous emission saturation points between each temperature too close together and so leading to an artificially high value of $T_0(I_{rad})$. To illustrate this, consider the following equation:
\[ L_{\text{meas}} = cL_{\text{emit}} \]  \hspace{1cm} (5.1)

The light collected is equal to the collection factor multiplied by the total light emitted into the solid angle captured by the lens or fibre. If \( c \) has a value of 100\% throughout the experiment, the measured light values could be, for example, 1, 2 and 4 in order of increasing temperature. However if the collection factor starts at 100\% for the lowest temperature and thereafter drops by 10\% for each temperature measured, the light values will be 1, 1.8 and 3.2. This will make the laser look less temperature sensitive than it really is, resulting in a value of \( T_0(L_{\text{rad}}) \) which is too high.

Conversely, if one optimises only at the highest temperature, a decrease in the

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**Figure 5.12** : (a) Spontaneous emission rate and (b) \( \ln(I) \) against \( \ln(L^{1/2}) \) graphs for window emission from a compressively strained laser, optimised at each temperature.
collection factor will result in the spontaneous emission saturation points being too far apart, giving a value for $T_{o}(I_{rad})$ which is too low.

If the system is optimised at all temperatures the collection factor can be kept as close to constant as possible, with human error during optimisation being the largest problem. If one averages the results of the experiments which were optimised at one temperature only a value for $T_{o}(I_{rad})$ of 295K is found, compared to 322K for the experiment in which the system was optimised at all temperatures. This gives us some insight into the way this experiment should be conducted in the future. The mounts in which the fibre and laser sit should be manufactured from one small piece of material to avoid relative movement with temperature.

It is clear that throughout the measurements of spontaneous emission the collection factor changes with temperature, due to expansion and contraction of the laser mount as the temperature was changed but even with this uncertainty clear conclusions can be drawn.

5.4.5 Spontaneous Emission Results on a 1 % Tensile Strained Device

Many readings of spontaneous emission were taken from the side of the device during a single experimental run. The temperature was cycled from low temperature to high temperature, then to low temperature again and so on. The system was optimised at every temperature. These results are shown in Figure 5.13. Each temperature is accurate to ±1K. Figures 5.13(a), 5.13(b) and 5.13(c) give results at temperatures of 305K, 316K and 321K respectively, while Figure 5.13(d) gives a graph of $\ln(I)$ against $\ln(L^{1/2})$ for the first run from each temperature, along with the gradients of each line.

The differences in the light levels taken at constant temperature are mainly due
to human error during optimisation, and are therefore difficult to quantify. However, they
do give us an idea of the error limits of this experiment. The small differences method
gives us a maximum error for $T_o(I_{rad})$ of around $\pm 25\%$, the majority of which is human
error during optimisation. This gives us an error value for all values of $T_o(I_{rad})$ found in
this work.

A value for $T_o(I_{rad})$ of 230K was deduced, for $T_o(I_n)$ we found a value of 55K
and all the gradients of $\ln(I)$ against $\ln(L^{1/2})$ were a little lower than those for the
compressive and bulk cases being approximately 2.7.

![Graphs of spontaneous emission rates and ln(I) against ln(L^{1/2})](image)

**Figure 5.13** : Spontaneous emission rates from the side of a tensile strained laser at
(a) 305K, (b) 316K and (c) 321K. In (d) a graph of $\ln(I)$ against $\ln(L^{1/2})$ has been
plotted for one set of results at each temperature. The gradients are given in the inset.
The results from at least two experiments are shown in each graph.

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5.4.6 Analysis of Results

Table 5.3 summarises the experimental values for $T_0(I_{Rad})$ and $T_0(I_{th})$ found for all the lasers investigated.

Table 5.3: Summary of values of temperature sensitivities of 1.3µm lasers.

<table>
<thead>
<tr>
<th></th>
<th>$T_0(I_{Rad})$</th>
<th>$T_0(I_{th})$ (graph)</th>
<th>$T_0(I_{th})$ (facet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>163K</td>
<td>49K</td>
<td>49K</td>
</tr>
<tr>
<td>Compressive, side</td>
<td>309K</td>
<td>50K</td>
<td>54K</td>
</tr>
<tr>
<td>Compressive, window</td>
<td>322K</td>
<td>55K</td>
<td>57K</td>
</tr>
<tr>
<td>Tensile</td>
<td>230K</td>
<td>57K</td>
<td>55K</td>
</tr>
</tbody>
</table>

As with the bulk case we see that the radiative current in the quantum well devices is well behaved as predicted by theory, which gives a value for $T_0(I_{Rad})$ of 300K at $T=300K$ with $x=0$, using equation 2.33.

For the bulk laser, using equation 2.29 and the measured value for $T_0(I_{Rad})$ of 163K, we obtain a value for $x$ of 0.17. In the tensile laser using equation 2.33 a value for $x$ of 0.15 is found. The results for the compressive laser imply a value for $x$ slightly less than zero, which is difficult to explain with our simple model where the mechanisms we consider lead to $x \geq 0$. The most ideal behaviour of carrier density with temperature is given in equations 2.25 and 2.32 where $x=0$. We feel justified in all cases to approximate the value of $x$ to zero, to within experimental error.

Since the radiative current is well behaved and $T_0(I_{Rad})$ is much larger than $T_0(I_{th})$ in all cases we conclude that the cause of the high temperature sensitivity in the lasers is due to a non-radiative process. The gradients of the graphs of $\ln(I)$ against $\ln(I^{1/2})$ for each laser imply that this process is Auger recombination. These conclusions agree with
similar work by Braithwaite et al. [87], who reported values for $T_{\text{th}}(I_{\text{rad}})$ of 301K and 265K for unstrained and 1% compressively strained 1.5μm lasers respectively, with a value for $T_{\text{th}}(I_{\text{th}})$ of 60K in both cases. The gradients measured in that work were 3.0±0.1. Our conclusions are also in agreement with work carried out on a 1.5μm 1.6% tensile strained laser [88], which gave a value for $T_{\text{th}}(I_{\text{rad}})$ of 242K and an average gradient of 2.7.

5.4.7 Identification of the Dominant Auger Process

We now attempt to identify the dominant Auger mechanism, considering those explained in section 2.6.2. We use equations 2.12 and 2.13 for the Auger activation energies for the direct CHCC and CHSH processes $\Delta E_{\text{act}}(\text{CHCC})$ and $\Delta E_{\text{act}}(\text{CHSH})$ respectively. The effective masses in these equations are the in-plane quantum well effective masses and we approximate these by using the growth (z) direction bulk effective masses calculated by Silver [85].

We now use standard equations to derive the Luttinger parameters ($\gamma$) [89] for the valence band masses. From these $\gamma$ values we will be able to estimate the in-plane ($x$-$y$) masses necessary for our calculations.

$$m_{hh} = \frac{1}{(\gamma_1 - 2\gamma_2)}$$  \hspace{1cm} (5.2)

$$m_{lh} = \frac{1}{(\gamma_1 + 2\gamma_2)}$$  \hspace{1cm} (5.3)

These equations give values for $\gamma_1$ and $\gamma_2$ of 7.95 and 2.87 respectively. We now use
the following equations from O'Reilly [18] to estimate the in-plane quantum well mass for the compressive case:

\[ m_{\text{QW}}^{\text{comp}}(\text{in-plane}) = \frac{1}{\gamma_1 + \gamma_2} = 0.09 \]  \hspace{1cm} (5.4)

and for the tensile case:

\[ m_{\text{QW}}^{\text{ten}}(\text{in-plane}) = \frac{1}{\gamma_1 - \gamma_2} = 0.20 \]  \hspace{1cm} (5.5)

Equations 5.4 and 5.5 are valid for large strains, which is the case in our devices. These equations yield 0.09 and 0.20 for the compressive and tensile cases respectively. We use a value for the spin split-off mass \( m_s \) of 0.13 [90] and a value for the spin split-off energy \( \Delta \) of 0.22eV [91]. Substituting these values into equations 2.12 and 2.13 gives approximate values for the Auger activation energies of the direct CHCC and CHSH processes, as shown in Table 5.4. The term \( m_{hh} \) in equations 2.12 and 2.13 indicates the highest valence band in these calculations. Also shown are the non-radiative values for \( T_0 \) assuming dominance of the total current by each direct Auger process, using equations 2.30 and 2.34 and assuming \( x=0 \). Under these circumstances \( T_0(I_{th})=T_0(I_{NRad}) \). All are much lower than the measured values for \( T_0(I_{th}) \) given in Table 5.3. A direct Auger process is therefore unlikely to be responsible for the temperature dependence of the threshold current. A more rigorous theoretical evaluation of the strained in-plane quantum well masses is not expected to yield results for the activation energies which vary by more than 10% from those calculated here.
Table 5.4: Estimated direct CHCC and CHSH Auger activation energies using equations 2.12 and 2.13.

<table>
<thead>
<tr>
<th>Laser</th>
<th>$\Delta E_{ac}(\text{meV})$</th>
<th>$T_0(I_{\text{NRad}})$ (K)</th>
<th>$\Delta E_{ac}(\text{meV})$</th>
<th>$T_0(I_{\text{NRad}})$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHCC</td>
<td>110</td>
<td>34</td>
<td>85</td>
<td>39</td>
</tr>
<tr>
<td>1% Compressive</td>
<td>360</td>
<td>18</td>
<td>255</td>
<td>23</td>
</tr>
<tr>
<td>1% Tensile</td>
<td>200</td>
<td>28</td>
<td>160</td>
<td>33</td>
</tr>
</tbody>
</table>

We now consider equations 2.30 and 2.34, which give expressions for the temperature sensitivities of the non-radiative current for the bulk and quantum well lasers respectively. Setting $x=0$ and rearranging for $\Delta E_{ac}/kT$ these equations are as follows:

$$\frac{\Delta E_{ac}}{kT} = \frac{T}{T_0^\text{bulk}(I_{\text{NRad}})} - \frac{9}{2}$$  \hspace{1cm} (5.6)

for the bulk case and:

$$\frac{\Delta E_{ac}}{kT} = \frac{T}{T_0^\text{QW}(I_{\text{NRad}})} - 3$$  \hspace{1cm} (5.7)

for the quantum well case. We have previously deduced that the temperature sensitivity of the laser is caused by the temperature sensitivity of the non-radiative current and so, using $T_0(I_h) = T_0(I_{\text{NRad}})$ and values of $T_0(I_h)$ from Table 5.3, we find values for $\Delta E_{ac}/kT$ at $T=300K$ of 1.6 in the bulk case and 2.4 in the quantum well case giving activation energies of 40meV and 60meV respectively. These values are consistent with phonon-assisted Auger recombination, in which the activation energy is of the order of the LO phonon energy [16], which has a value of 36meV in GaAs and 41meV in InP.
Neither direct band to band Auger process in Table 5.4 has an activation energy comparable to those we have found. This strongly implies that the cause of the temperature sensitivity in 1.3μm lasers is phonon-assisted Auger recombination, although we are unable to determine by this method which phonon-assisted process is responsible. Using the exact values for x for the bulk and tensile cases found earlier of 0.17 and 0.15 respectively gives values for ΔE^\text{as}/kT of 1.1 and 2.0 and thus for ΔE^\text{ext} of 28meV and 52meV, and makes no difference to our conclusion.

The value for T_0(I_{rad}) in the tensile strained laser is lower than that in the compressively strained laser. One possible reason for this may be the quantum well widths in the two devices. The compressive device has quantum well widths of 55Å while the tensile device has well widths of 120Å and so the tensile laser is therefore tending more towards the bulk case, which has a theoretically predicted value for T_0(I_{rad}) of 200K (section 5.4.2 from equation 2.29) as opposed to 300K for quantum well lasers (section 5.4.6 from equation 2.33). Its value for T_0(I_{rad}) is therefore lower than that in the compressive case.

5.4.8 Suggestion for Improvement of Spontaneous Emission Measurements

As already mentioned the main problem with these measurements of spontaneous emission was that the collection factor changed with temperature. Two methods are proposed to remedy this. Firstly, the system may be optimised at every temperature studied, in an attempt to keep the collection factor as high as possible. This has been tried, and results in some improvement. Secondly, a new laser mount is proposed in which the laser and fibre are mounted close to one another (without microscope objectives) on the same piece of brass. Brass was chosen for its low linear expansion.
coefficient. This is expected to improve the situation greatly. The new mount is presently under construction, after measurements and drawings by S. Sweeney [92].

5.5 High Pressure Measurements

High pressure measurements were conducted on the three devices to test for the presence of Auger recombination, which is a band gap dependent loss mechanism. The Auger recombination rate decreases with increasing pressure due to the pressure-induced increase in band gap (section 2.6.2 equations 2.14 to 2.17). Therefore we expect the threshold current to decrease as pressure is increased.

![Figure 5.14](image_url): Normalised threshold current against pressure for each of the three devices. For comparison a 1.5μm device is also shown [43].
Figure 5.14 shows a graph of normalised threshold current against pressure for the three devices investigated. These currents have been corrected according to the method given in Chapter 3 for the change in refractive index of the pressure-transmitting medium with pressure. Also shown are the results for a 1.5μm InGaAs device, with 1.6% tensile strain and 4 quantum wells, taken from [43] which is presented for comparison. It should, however, be noted that no correction has been made for the change of refractive index of the pressure medium with pressure for this device, as the original current data was not available. It can be seen that this device exhibits a higher rate of decrease of threshold current with pressure than any of the three 1.3μm devices investigated. With correction for the change of refractive index in the 1.5μm device measurement this effect will be even more pronounced. For comparison, the uncorrected data for all three 1.3μm devices reached a normalised threshold current of around 90% at 10kbar. An increase in pressure produces an increase in band gap and therefore this behaviour is indicative of a band gap dependent loss mechanism, such as Auger recombination.

Shown in Figure 5.15 are the lasing spectra from the high pressure experiment on the bulk device, as taken by the OSA. The increase in lasing energy $E_{\text{lasing}}$ as the pressure is increased can clearly be seen, from which a change in lasing energy with pressure $dE_{\text{lasing}}/dP$ of 8.7meV/kbar has been deduced (by least squares fit). This is shown in Figure 5.16. The measured rate of change of lasing energy with pressure for the 1.5μm device shown in Figure 5.14 was 9.6meV/kbar [43]. Spectra were taken at 1.2 times threshold. From the magnitudes of the peaks in Figure 5.15 it can be seen that the absolute power measured at each pressure seems to vary fairly randomly, indicating that the laser may be moving in the clip. This makes efficiency readings taken using this
equipment invalid.

Figure 5.15: The lasing peak of the bulk laser measured at different pressures. It can clearly be seen that the collection efficiency is changing with pressure. The current used for the measurements in all cases was $1.2xI_{th}$.

In Figure 5.17 is a graph of high pressure results from Silver et al. [93] on a 1.48µm 1% compressively strained laser. This device lases at 1.3µm at about 12kbar. The pressure results on the 1.3µm 1% compressively strained device have been added.
to these results and the threshold current of the 1.3μm device has been normalised to the 12kbar point of the Sliver data for comparison.

Figure 5.16: Rate of change of the lasing energy with pressure for the bulk device. The energy at each pressure was read from Figure 5.15.

The gradients are very similar, indicating that the 1.3μm laser is behaving with pressure in much the same way as the 1.48μm laser.
Figure 5.17: (a) Data from Silver et al. [93], in which a 1480nm laser was subjected to hydrostatic pressure. Superimposed on this is data from the pressure experiment on the compressively strained device, whose threshold current has been normalised to the Silver data at its atmospheric pressure point. (b) As (a), but ln threshold current is plotted. Gradients across a similar wavelength range are given.

5.6 Conclusions

Table 5.5 shows a summary of the results found for these lasers. Values given are the lasing wavelengths for the 500µm and 1000µm long devices, $\lambda_{\text{las}}$, average values for $T_o(I_{th})$ (for the 1000µm long devices), $T_o(I_{Rad})$ and the gradients of the ln(I)
against ln(1/L^2) graphs and finally values of the threshold current densities at atmospheric pressure at room temperature for the 500μm and 1000μm long devices, J_th.

Table 5.5: Summary of results for 1.3μm lasers.

<table>
<thead>
<tr>
<th>Laser</th>
<th>λ_{aslig} (nm)</th>
<th>T_0(J_h) (K)</th>
<th>T_0(J_{rad}) (K)</th>
<th>Gradients (average)</th>
<th>J_th (A/cm^2) 500/1000μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>1308/1319</td>
<td>49</td>
<td>163</td>
<td>3.0</td>
<td>1850/1420</td>
</tr>
<tr>
<td>+1%</td>
<td>1323/1324</td>
<td>56</td>
<td>316</td>
<td>3.1</td>
<td>1400/1100</td>
</tr>
<tr>
<td>-1%</td>
<td>1324/1332</td>
<td>55</td>
<td>230</td>
<td>2.7</td>
<td>1500/1050</td>
</tr>
</tbody>
</table>

Which loss mechanism dominates?

It has been found from the high pressure work that the dominant loss mechanism in 1.3μm lasers is band gap dependent, and decreases with increasing band gap. Spontaneous emission measurements show that this loss mechanism depends on the carrier concentration cubed, and is therefore identified as Auger recombination.

Which Auger process is dominant?

From our deduced values for the Auger activation energy this has been identified as phonon-assisted Auger recombination, in agreement with work by Fuchs et al. [94]. Haug [95] calculated that phonon-assisted Auger recombination should be an important consideration. Theoretical results of the trend in the Auger coefficients C with pressure were compared by Göntil [26] with experimental results of the variation of the threshold
current with pressure carried out on a laser emitting at 1.531\(\mu\)m at atmospheric pressure which supports this conclusion, since we have seen from figure 5.17 that the threshold current of our 1.3\(\mu\)m laser has a similar pressure dependence as a 1.48\(\mu\)m laser lasing at 1.3\(\mu\)m.

What is the cause of the high temperature sensitivity?

We have found that in all cases the radiative current is well-behaved, with values of \(T_0(I_{\text{rad}})\) of around 160K for bulk devices and 300K for quantum well devices which are far higher than \(T_0(I_n)\) in all cases. The radiative current is therefore not thought to be the reason for the low measured \(T_0(I_n)\) values of around 50K. We believe that phonon-assisted Auger recombination, which has an expected \(T_0(I_{\text{rad}})\) value of around 60K, is the cause of the high temperature sensitivity.

It has been shown that phonon-assisted Auger recombination is the dominant contribution to the current and the major cause of the high temperature sensitivity in 1.3\(\mu\)m lasers.

Why has strain not improved \(T_0(I_n)\), as was originally predicted [7]?

Original predictions assumed direct band-to-band Auger recombination. We have shown that the dominant current path is phonon-assisted Auger recombination, which is not as sensitive to the changes in the band structure which are brought about through the application of strain. Strain has not decreased the temperature sensitivity remarkably, even though threshold current densities are improved. The temperature sensitivity is dependent upon the relative sizes of Auger current and radiative current, and although
strain decreases Auger, it can clearly be seen from the gradients of the \( \ln(I) \) vs \( \ln(L_{1s}^{1s}) \) graphs that Auger is still by far the dominant current path. This is illustrated by work by O'Reilly and Silver [35], in which they calculate that \( T_0(I_a) \) does not improve until the radiative current density is comparable in size to the non-radiative (Auger) current density.
Chapter 6

Thesis Summary

6.1 Summary of Results and Conclusions

The work in this thesis has addressed the problems of the high temperature sensitivity and high threshold current density in short wavelength AlGaInP red lasers and 1.3 μm InGaAsP lasers.

We began by summarising the progress of the semiconductor laser in Chapter 1, and in Chapter 2 gave some basic theory necessary for the understanding and analysis of the results obtained in later chapters. This theory included the effects of strain on a semiconductor and on a laser, a discussion of loss mechanisms in lasers and a model for the characteristic temperature $T_o$ of long wavelength lasers. Chapter 3 reviewed the experimental methods used, including details of high pressure systems, cryostats and the
effects of the pressure transmitting medium on the threshold currents of the lasers tested. In Chapters 4 and 5 we presented results and analysis of visible and 1.3μm lasers respectively.

6.1.1 Visible (λ=635-686nm) Lasers

Results have been presented of the variation of the threshold current densities with both pressure and temperature for three strained and one bulk laser. The pressure results have been analysed for the strained devices using a simple activation energy fit to the data. Also the temperature results have been analysed for all the lasers supplied by Philips Research in Eindhoven using a diffusion current model. In all cases it was found that the dominant leakage current was in the conduction band X-minima in the cladding. This is also the cause of the low $T_o$ in these devices, since the $T_o$ became steadily worse as the wavelength decreased and the $\Gamma$-minimum moved closer to the X-minima.

This carrier leakage via the X-minima was found to be a problem at room temperature only in the shortest wavelength device investigated, at 635nm.

In conclusion we have found:

The temperature sensitivity and high threshold current density in visible lasers is due to carrier leakage in the conduction band X-minima in the cladding.
6.1.2 1.3μm Lasers

We have presented the variation of threshold current with temperature for 1% compressively strained, 1% tensile strained and bulk lasers. We have found similar values for $T_0$ in each device of around 50K. We then presented measurements of spontaneous emission from each device and have found an effective $T_0$ for the radiative current, which we have called $T_0(I_{rad})$. We compared the values obtained (around 300K for the strained devices and around 200K for the bulk device) with theory presented in Chapter 2, and found that the radiative current is well-behaved as a function of temperature and that $T_0(I_{rad})$ is much higher than $T_0(I_{th})$.

We have found from further analysis of the spontaneous emission results that the total current is Auger dominated. The activation energies found for the Auger process compared well with those expected for a phonon-assisted process. We have therefore concluded that the cause of the temperature sensitivity of 1.3μm lasers is Auger recombination.

We then presented the variation of the threshold current with hydrostatic pressure and found little difference in the three devices. It was found that the threshold current decreased at a reduced rate compared with a 1.5μm laser, but that the rate was similar when compared to the point at which the emission wavelengths were equal. The same loss mechanism, Auger recombination, appears to be dominant at both wavelengths.

In conclusion we have found:

The temperature sensitivity in 1.3μm lasers is due to phonon-assisted Auger recombination which also explains why the introduction of strain in quantum well lasers has not decreased the temperature sensitivity of the threshold current as much as had
6.2 Further Work

There are many possibilities for further work which are listed below.

6.2.1 Experimental Methods

The most important unknown contributing to results presented in Chapters 4 and 5 is the change in refractive index with pressure of the pressure transmitting media used. It is important that this be quantified over the full range of wavelengths as a function of pressure.

As has been previously mentioned in this work, a new mount for conducting spontaneous emission measurements is under construction. This should significantly reduce errors.

6.2.2 1.3μm Lasers

It would be instructive to carry out measurements of spontaneous emission at low temperatures, where Auger recombination should not be a problem. The gradient of a graph of ln(I) against ln(L^10) should then equal two, indicating that the current is dominated by the radiative component. This would reinforce the validity of this method and also allow us to locate the temperature at which Auger recombination becomes a problem. To this end it has been proposed that a simple cryostat be designed and constructed, enabling a fibre to be mounted close to the sample.
6.2.3 Pressure Experiments

A new high pressure system is currently under construction, with which it is hoped that a pressure of 40kbar may be achieved. Using samples lasing at three or four different wavelengths, this will allow us to obtain the threshold current with pressure from 1.55μm to around 600nm. It will then be possible to see the threshold current reduce as Auger recombination is reduced at higher wavelengths, level off around 1μm as Auger is eliminated, increase due to increasing band gap in the regime where radiative current dominates and then increase swiftly as the conduction band X-minima become a problem for carrier leakage. It may then be possible to extrapolate the gradient at which radiative current dominates to higher wavelengths to obtain a direct measure of the magnitude of the Auger current relative to the radiative current.
Appendix I

This appendix details the method used and supplied by Ahmad [96] for the fabrication of windows in the substrate of semiconductor lasers.

The laser is first boiled in trichloroethylene to clean it. It is then stuck to a glass slide p-side down using photoresist, which may be easily removed using acetone without damaging the device. Photoresist is then spun onto the entire substrate of the laser and baked in the oven. The laser is aligned with a 50μm slit and the photoresist is exposed using ultra-violet light. The laser is washed in de-ionised water and dried to reveal a 50μm slit from one facet of the device to the other defined in photoresist. The slit is then further defined using photoresist to give a slit roughly 200μm in length. The laser is again baked in the oven and then placed in the ion-beam miller, where it is milled at liquid nitrogen temperature for the required time. This time will depend on the substrate material and the depth of window required. Typical milling times range from fifteen minutes to three-quarters of an hour. The laser is finally cleaned with acetone and inspected under the microscope. The entire process may then be repeated from the beginning if the window is not deep enough.

The laser's light/current characteristics are measured before and after the process to ensure there is no damage during processing.
References


[23] G. Jones, Physics Department, University of Surrey, private communication


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A.T. Meney, Physics Department, University of Surrey, private communication

Devices supplied by A. Valster, Philips Optoelectronics Centre, Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands

Devices supplied by P. Roentgen, IBM Research Division, Zürich Research Laboratory, Optoelectronics Department, Säumerstrasse 4, CH-8803 Rüschlikon

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[84] Devices supplied by P.J.A. Thijs, Philips Optoelectronics Centre, Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands. For material parameters see Appendix III.

[85] Program written by M. Silver, University of Surrey


[88] S. Sweeney and A.F. Phillips, University of Surrey, unpublished


[92] S. Sweeney, Department of Physics, University of Surrey


[96] C.N. Ahmad, Physics Department, University of Surrey, private communication
Appendix II

Shown in Table II.1 are the values used in the program written by Meney [63] to calculate material parameters for AlGaInP visible lasers.

Table II.1: Values for interpolation of AlGaInP parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>InP</th>
<th>GaP</th>
<th>AlP</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luttinger parameters $\gamma_1$</td>
<td>5.28</td>
<td>4.05</td>
<td>3.08</td>
<td>6.78</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>1.53</td>
<td>1.10</td>
<td>0.73</td>
<td>1.92</td>
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<tr>
<td>$\gamma_2$</td>
<td>2.20</td>
<td>1.53</td>
<td>1.17</td>
<td>2.70</td>
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<tr>
<td>Electron effective mass $m_e/m_0$</td>
<td>0.077</td>
<td>0.15</td>
<td>0.22</td>
<td>0.0665</td>
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<td>Band gap $E_g(\Gamma)$ (eV) (T=0K)</td>
<td>1.424</td>
<td>2.87</td>
<td>4.4</td>
<td>1.519</td>
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<td>Spin-orbit splitting $\Delta$ (eV)</td>
<td>0.108</td>
<td>0.08</td>
<td>0.07</td>
<td>0.341</td>
</tr>
<tr>
<td>Varshni parameter $\alpha$ (eV/K)</td>
<td>$3.54\times10^{-4}$</td>
<td>$7.24\times10^{-4}$</td>
<td>$2.78\times10^{-4}$</td>
<td>$5.32\times10^{-4}$</td>
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<tr>
<td>Varshni parameter $\beta$ (K)</td>
<td>136.0</td>
<td>201.0</td>
<td>200.0</td>
<td>204.0</td>
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<tr>
<td>Lattice constant $a$ (Å)</td>
<td>5.87</td>
<td>5.45</td>
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<td>Conduction band hydrostatic deformation potential $a_e$ (eV)</td>
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<td>-5.54</td>
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<td>1.27</td>
<td>1.70</td>
<td>3.15</td>
<td>1.16</td>
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<tr>
<td>Valence band average $E_{v,av}$ (eV)</td>
<td>-7.04</td>
<td>-7.40</td>
<td>-7.93</td>
<td>-6.92</td>
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(Table continued on next page)
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<tr>
<th>Parameter</th>
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<th>GaP</th>
<th>AIP</th>
<th>GaAs</th>
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<tr>
<td>Shear deformation potential b (eV)</td>
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<td>-1.6</td>
<td>-1.7</td>
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<tr>
<td>Elastic constant $C_{11}$ ($10^{12}$ dyn cm$^2$)</td>
<td>1.02</td>
<td>1.41</td>
<td>1.32</td>
<td>1.18</td>
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<td>Elastic constant $C_{12}$ ($10^{12}$ dyn cm$^2$)</td>
<td>0.58</td>
<td>0.62</td>
<td>0.63</td>
<td>0.54</td>
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<tr>
<td>Band gap $E_p(X)$ (eV)</td>
<td>2.310</td>
<td>2.360</td>
<td>2.420</td>
<td>1.986</td>
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<td>$a(X)$ (eV)</td>
<td>2.723</td>
<td>3.467</td>
<td>4.87</td>
<td>2.667</td>
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<tr>
<td>$b(X)$ (eV)</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Band gap bowing parameter (eV)</td>
<td>0.70</td>
<td>1.14</td>
<td>0.00</td>
<td>(InGaP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(InAlP)</td>
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<td></td>
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<td></td>
<td>(AlGaP)</td>
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Appendix III

Shown in Table III.1 are the values used in the program written by Silver [85] to calculate material parameters for InGaAsP lasers.

Table III.1: Values for interpolation of InGaAsP parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>InAs</th>
<th>GaAs</th>
<th>InP</th>
<th>GaP</th>
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</thead>
<tbody>
<tr>
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<td>0.0665</td>
<td>0.079</td>
<td>0.17</td>
</tr>
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<td>Heavy hole effective mass $m_{hh}/m_0$</td>
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<td>0.382</td>
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<td>0.79</td>
</tr>
<tr>
<td>Light hole effective mass $m_{lh}/m_0$</td>
<td>0.0225</td>
<td>0.08</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>Band gap $E_g$ (eV)</td>
<td>0.36</td>
<td>1.42</td>
<td>1.35</td>
<td>2.74</td>
</tr>
<tr>
<td>Spin-orbit splitting $\Delta$ (eV)</td>
<td>0.380</td>
<td>0.340</td>
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</tr>
<tr>
<td>Lattice constant $a$ (Å)</td>
<td>6.058</td>
<td>5.653</td>
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</tr>
<tr>
<td>Valance band average $E_{v,av}$ (eV)</td>
<td>-6.68</td>
<td>-6.84</td>
<td>-7.04</td>
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<tr>
<td>Conduction band hydrostatic deformation potential $a_e$ (eV)</td>
<td>-5.88</td>
<td>-8.06</td>
<td>-6.18</td>
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<tr>
<td>Valence band hydrostatic deformation potential $a_v$ (eV)</td>
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<td>1.16</td>
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<td>1.7</td>
</tr>
<tr>
<td>Shear deformation potential $b$ (eV)</td>
<td>-1.62</td>
<td>-1.53</td>
<td>-1.35</td>
<td>-1.35</td>
</tr>
<tr>
<td>Elastic constant $C_{11}$ ($10^{12}$ dyn cm$^{-2}$)</td>
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<td>1.18</td>
<td>1.62</td>
<td>1.41</td>
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<tr>
<td>Elastic constant $C_{12}$ ($10^{12}$ dyn cm$^{-2}$)</td>
<td>0.45</td>
<td>0.54</td>
<td>0.58</td>
<td>0.62</td>
</tr>
<tr>
<td>Band gap bowing parameter $\gamma$ (eV)</td>
<td>0.41 (InGaAs)</td>
<td>0.79 (GaN)</td>
<td>0.28 (InPAs)</td>
<td>0.21 (GaPAs)</td>
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</table>