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Carrier recombination in dilute
nitride based near infrared
semiconductor lasers

By

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A thesis submitted to the University of Surrey for the
degree of Doctor of Philosophy

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Abstract

This thesis describes and quantifies the roles of the different carrier recombination processes within near infrared GaInNAs single quantum well laser devices. An initial review of the published literature relating to GaInNAs highlighted a number of areas where investigation of the material system would be interesting, including changing the nitrogen concentration, the barrier material, the incorporated strain and the growth technique.

We find that at 1.3μm, at room temperature, the threshold current of MBE grown devices is composed of 70% Auger recombination, 25% monomolecular recombination and 5% radiative recombination, and at 1.5μm, 61% Auger recombination, 31% monomolecular recombination and 8% radiative recombination. In absolute terms Auger is the most significant current path over the entire wavelength range. This dominance of Auger recombination was also found to be responsible for the poor temperature stability of these devices, with the Auger recombination component typically having a $T_0 \sim 50$K.

Calculations of the threshold carrier density along with a break-down of the threshold current were used to evaluate the recombination coefficients; these were found to be $A = 4 \times 10^8 \text{s}^{-1}$, $B = 3 \times 10^{11} \text{cm}^3\text{s}^{-1}$ and $C = 6 \times 10^{29} \text{cm}^6\text{s}^{-1}$ at 1.3μm, and $A = 8 \times 10^8 \text{s}^{-1}$, $B = 6 \times 10^{11} \text{cm}^3\text{s}^{-1}$ and $C = 1.2 \times 10^{28} \text{cm}^6\text{s}^{-1}$ at 1.5μm. These values are comparable to those of InGaAsP and AlGaInAs. Furthermore, these investigations suggest that carrier leakage is negligible in these devices.

Hydrostatic pressure techniques were used to study the effect of changing the band gap on the recombination processes occurring within the devices; this highlighted the importance of the band anti crossing interaction between the conduction band edge and the nitrogen level in GaInNAs devices where it was seen that a longer wavelengths this interaction appears to be weaker.

Replacing GaAs barriers with GaNAs barriers leads to a ~15% reduction in the magnitude of the monomolecular current present, indicating that this should be a useful method of optimising the growth of GaInNAs. An investigation into the effect of strain incorporated within the quantum well of the ~1.5μm devices highlighted the possibility of its use to reduce the threshold carrier density and thus the Auger current within these devices.

Since this work was based on single quantum well devices it shows that the GaInNAs material system is a very promising alternative to conventional InGaAsP and AlGaInAs devices which rely upon multiple quantum wells.
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Chapter 1

Introduction

1.1 Introduction

The ever-increasing use of the internet worldwide and the resulting demand for greater bandwidth for applications such as video and music downloads has spurred on the development of optical fibre communications. Within this thesis, the use of semiconductor lasers as an integral part of the transmitter systems for optical fibre communications will be investigated. A brief introduction to optical fibre communication will be given, followed by an introduction to semiconductor lasers, and the materials that are used to grow them. Particular attention will be paid to the GaInNAs material system as it is the subject of this work.

Within this thesis investigations will be presented that where carried out on the GaInNAs material system in order to determine the dominant carrier recombination mechanisms present within the threshold current of quantum well lasers made from this material. This will be achieved by utilising spontaneous emission and high pressure techniques.

1.2 Optical Communications

In 1966 Kao and Hockham, published a paper "Dielectric-Fibre Surface Waveguides For Optical Frequencies "[1]. This paper was to prove to be the seed for the development of the optical fibre networks that we have today. The first fibre network was deployed in Chicago in 1978 [2], and by the end of 2000 there were approximately 225 million miles of optical fibre in place worldwide [3]. Initially, for optical fibre communications the only available lasers emitted at 850nm, therefore the initial work on optical fibre systems was carried out at this non optimised wavelength. Since these initial lasers with their GaAs/AlGaAs structures, there has been much
development in the range of material systems used to tailor the emission wavelength of lasers. This development has lead to the emission wavelength of today’s lasers being chosen based on the constraints of the modern optical fibre, which will now be outlined.

1.2.1 Transmission wavelengths for optical fibre communications

There are two main wavelengths that are used for optical fibre transmission. The first is 1.31µm, which corresponds to the zero dispersion point of silica fibre (see Figure 1.1a). At this wavelength, any pulses transmitted in the fibre will not be temporally distorted. This is important for high-speed communications, as it prevents two adjacent pulses from overlapping and interfering as they travel along the fibre. The other important wavelength is 1.55µm, which is the absorption minimum of silica-based optical fibre (see Figure 1.1b). At this wavelength, the light pulses in the fibre will travel greater distances before requiring amplification. This low loss reduces the need for expensive amplifier stations.

The development of optical fibres over the years has led to the production of fibres with lower absorption within the 1.3µm to 1.5µm wavelength range [5, 6]. Modern fibres with lower absorption over the wavelength range 1.3µm to 1.5µm are less sensitive to the need for 1.55µm emission, as absorption at 1.31µm is also low, however, it is still higher than that at 1.55µm. Nevertheless, the prohibitive cost of replacing the existing fibre means that these older fibres will continue to be used for the foreseeable future.
1.2.2 1.55μm for long distance communications

The importance of the development of the 1.55μm laser with regard to increased transmission distance is illustrated in Figure 1.2. From Figure 1.2, it can be seen that 1.31μm and 850nm lasers can be used for short distance, high bit rate transmission. However, the use of 1.55μm devices allows these high bit rates to be extended over much larger distances. This results in reduced operating costs, as the number of amplifier stations can be reduced.

Figure 1.2 Transmission distance versus laser modulation frequency for a variety of optical-fibre/laser-diode sources utilized in optical networks [7]

1.3 The Semiconductor laser

Semiconductor lasers are devices used in the transmitter modules of optical fibre communication systems to provide the light which is modulated to send high volumes of data. Semiconductor lasers were chosen because they are compact in size, reliable, relatively inexpensive, they are efficient devices and their output can be easily modulated. To date there has not been a real contender to replace semiconductor lasers as the light source for optical fibre communications. They can be fibre coupled, allowing integration of the optical components with the electrical components of the system within single modules.

The prospect of a semiconductor laser was initially investigated around the time of the demonstration of the first lasers, by a number of groups [8-10]. Since then their development has been rapid as a result of a large amount of investment into developing the growth technology of liquid phase epitaxy (L.P.E.). Laser operation
Chapter 1 - Introduction

from a semiconductor was first reported from a simple p-n junction GaAs homostructure operating at liquid nitrogen temperatures, and was reported almost simultaneously by four groups: Nathan et al., Quist et al., Hall et al. and Holonyak et al. in 1962 [11-14]. By 1969, pulsed laser operation had been extended to room temperature (RT), again almost simultaneously by a number of groups [15, 16]. This development was surpassed in 1970, when it became possible to produce a high quality double heterostructure consisting of GaAs sandwiched between higher band gap Al$_x$Ga$_{1-x}$As layers. The double heterostructure brought two key advantages over the homojunction; firstly, the lower band gap GaAs region formed a reservoir for the carriers (carrier confinement) where they could recombine across the band gap, secondly, the higher refractive index of GaAs with respect to that of Al$_x$Ga$_{1-x}$As provided better confinement of the optical field. These two improvements resulted in a significant reduction in current required to operate the devices, in fact a reduction of two orders of magnitude was achieved. This enabled continuous wave (CW) operation at room temperature to be achieved for the first time [17]. The original lasers required current densities of 50kA/cm$^2$ to operate in 1962, and by 1975 this had been reduced to 0.5kA/cm$^2$ at 850-880nm[18]. This breakthrough in threshold current resulted from improved growth, and allowed the semiconductor laser to be considered for practical uses, the technologies which permitted this reduction will now be discussed.

Improvements in growth technologies in the late 1970s resulted in the development of molecular beam epitaxy (M.B.E.) and vapour phase epitaxy (V.P.E.). These improved growth techniques allowed for the reproducible growth of thin layers and brought the field of semiconductor lasers into the quantum regime, as layers with thicknesses of the order of 10nm and less became realizable. This work in the quantum regime was started in 1974 by Dingle and Henry [19] and these became known as quantum well (QW) lasers. This new growth scheme has resulted in improved laser performance, through an increase in the carrier confinement. Within quantum well lasers the confinement in one dimension is seen to have a beneficial effect on the density of states, by causing a splitting of the degeneracy of the valence band, thus reducing the density of states at the top of the valence band. Further details of the benefits of quantum wells will be discussed in chapter 2.

In 1986 it was suggested separately by Adams [20] and Yablonovitch and Kane [21] that the incorporation of biaxial strain into the active region of QW devices would
have a beneficial effect. This has proved to be the case as the introduction of biaxial strain to the material reduces the symmetry of the material, which, in turn, reduces the density of states, thereby improving the performance of the laser. This concept has proved very successful, with essentially every laser device now grown incorporating strain in the active region, including all of the devices within this work. The theory of strain will be discussed further in chapter 2.

There have been a number of materials studied during the development of semiconductor lasers, starting with GaAs [16]. However, the main material used for optical fibre communications is InGaAsP/InP, with which CW operation was first reported in 1976 at 1.1μm [22]. By 1977 this was extended to 1.31μm [23], meeting the dispersion zero point in silica optical fibre. By 1979 several groups had reported emission at 1.55μm [24-29]. Much research has since been carried out on InGaAsP devices, and their performance has been improved greatly over the years. The current state of the art InGaAsP devices have threshold currents in the region of ~150A/cm² and TΘs of ~50K with emission at 1.55μm [30-34].

In order to obtain the single mode emission preferred for optical fibre communications, the structure of the laser must be modified. The first of these modified structures is the distributed feedback laser [35], (DFB) where the wavelength is forced to be single mode with the use of a phase-shifted grating grown in the structure, however in order to achieve this there is a high cost. An additional benefit of this structure is an improvement in the temperature stability of the device. The alternative to DFB lasers are vertical cavity surface emitting lasers (VCSELs). VCSELs have the single mode and temperature stability benefits of DFB lasers, however they are not as costly to produce and their output is more easily coupled into optical fibre, due to their circular beam characteristics [36]. However, due to their very short cavity in the vertical direction, VCSELs require very high reflectivity (HR) Distributed Bragg Reflector (DBR) mirrors to be grown around the active region. This is achieved by growing a series of quarter wavelength layers with refractive index steps between each layer. The growth of mirrors is easily achievable on GaAs using a stack of GaAs/Al(GaAs) layer pairs. The technique for the growth of these layers was established for use with the original 850nm VCSELs. On InP however, it is difficult to grow HR mirrors, due to the low index contrast obtainable with unstrained
InGaAsP/InP pairs, which requires a large number of layers to achieve suitably high reflectivities.

### 1.4 Available materials for telecoms devices

Some of the materials available for emission in the telecoms wavelength range have already been discussed; these materials along with others are shown in Figure 1.3. Figure 1.3 shows a number of materials, with the lines corresponding to the alloys formed. The merits of a number of these materials will now be discussed.

![Diagram of the band gaps and lattice constants of various materials](image)

**Figure 1.3** Diagram of the band gaps and lattice constants of various materials taken from [37]

#### 1.4.2 InGaAsP

InGaAsP is the current material of choice for the telecoms industry for use with optical fibres. The main restriction on the performance of InGaAsP device's is their poor temperature stability, caused by a large percentage of non-radiative Auger recombination present within the threshold current of these devices at typical operating temperatures. This Auger current is a hole dependent process, which is further exacerbated by the low conduction band offset present within the material, which causes the hole density to be greater than the electron density at threshold. This higher density of holes at threshold results in an Auger recombination component.
which is 80 percent of the threshold current for typical InGaAsP/InP devices [38]. InGaAsP/InP is primarily deployed as DFB lasers.

1.4.3 AlGaInAs

AlGaInAs is the current main competitor to InGaAsP for growth on InP, this is because AlGaInAs has superior electron confinement in comparison to InGaAsP [39]. The increased carrier confinement present within AlGaInAs devices is believed to result in more equal electron and hole densities at threshold. The lower hole density in comparison to the InGaAsP devices reduces the non-radiative Auger recombination process resulting in improved temperature stability. It has been shown that the Auger current present at threshold within a 1.5μm AlGaInAs device is only 55% in comparison to 80% for InGaAsP at room temperature [40]. AlGaInAs lasers are currently succeeding in taking some of the market from the InGaAsP devices at 1.3μm and progress at 1.5μm is promising. As AlGaInAs is also grown on InP its use is also primarily to produce DFB lasers, however there are reports of the use of AlGaInAs active regions in 1.55μm InP-based VCSELs [41]. These however require complex processing.

1.4.4 GaAs Based alternatives

In recent years, there has been a drive to move to GaAs as the growth substrate for telecommunications lasers, due to the superior and well established GaAs/AlGaAs DBRs which where initially used with the original 850nm lasers. To this end a number of GaAs-based active region materials have been investigated including highly strained InGaAs [42, 43], GaAsSb [44, 45], GaInNAs [37, 46-49] and GaInNAsSb QWs [50-55] as well as InAs quantum dots [56]. Within this thesis, the main subject of investigation will be GaInNAs quantum well lasers grown on GaAs, as it appears to be most promising material for GaAs based lasers.

1.5 GaInNAs

In 1992, it was observed by Weyers et al., at NTT [57] that the incorporation of a dilute amount of N into GaAs significantly reduces its band gap energy [37]. This large band gap "bowing" with increasing N fraction is a surprising result, as the band gap of GaN at RT (Eg~3.2eV)[58] is considerably larger than that of GaAs (Eg~1.4eV)[58]. This bowing is caused when the GaAsN alloy is formed. The
nitrogen is chemically bonded within the semiconductor crystal, however it acts more like an impurity, forming separate energy levels above the bottom of the GaAs conduction band (CB). This leads to the formation of a nitrogen related band, which pushes the GaAs energy levels downwards and hence reduces the band gap energy as illustrated in Figure 1.4. this is well described by the band anti crossing (BAC) model [59]. The formation of a separate energy level is due to the difference of the Bohr radius of nitrogen and arsenic, the nitrogen atom is about half the size of the arsenic atom and its electronegativity is significantly larger. This large difference in the Bohr radius also causes growth problems, as it prevents large amounts of nitrogen being reliably incorporated into a crystal, because of strain issues. The strain incorporated when large amounts of nitrogen are added to the lattice can cause dislocations which have serious detrimental effects on device performance.

![Figure 1.4](image.png)

Figure 1.4 Effect of nitrogen on band structure. the illustration on the left is GaAs, on the right is that of GaNAs

For nitrogen concentrations of about 2%, the band gap of the GaAsN alloy approaches 1eV at room temperature, making this material system a candidate for semiconductor lasers emitting at the communications wavelength of 1.3μm.

The Bohr radius mismatch, the corresponding strain together with the low growth temperatures required result in GaNAs being very difficult to grow, leading to poor material quality and corresponding high defect densities.

The incorporation of large amounts of indium into the quantum well compensates for the strain caused by the nitrogen, whilst reducing the band gap. This material has a unique ability to be grown at a fixed wavelength with a range of strains.
In the last few years, advances in growth techniques have led to the development of GaInNAs edge-emitting lasers with threshold current densities as low as 200-300 A/cm²/perQW at 1.3μm [60-63] which is comparable to those reported for InGaAsP-based lasers. The growth of single quantum well lasers which operate at room temperature is possible with GaInNAs, whereas single quantum well InGaAsP lasers will not lase at room temperature. This is as a result of the higher optical confinement provided by the GaAs/AlGaAs waveguide due to the larger refractive index difference compared with InGaAsP/InP.

Initial investigations of GaInNAs as a laser material were spurred on by the promise of a highly temperature stable laser, resulting from the large electron confinement provided by the large conduction band offset [37]. However to date there has been little experimental evidence to support this original hypothesis. The current drive behind the study of GaInNAs is the prospect of relatively simple growth of VCSELs at long wavelengths as has already been achieved at 1.3μm [64]. A detailed historical review of the development of the device performance of long-wavelength GaInNAs-based semiconductor lasers will be given in chapter 3.

1.6 Thesis outline

Much has been discovered about the various carrier recombination mechanisms present in GaInNAs lasers, and how their relative magnitudes depend on temperature and carrier density at relatively short wavelengths. The challenge here is to study how these processes change as the emission wavelength of the laser increases towards 1.55μm. For practical lasers the key question is how significant each process is at lasing threshold and how sensitive this is to temperature.

In this thesis, measurements and theoretical modelling will be presented that will enable the determination of the magnitude of the recombination processes present at threshold and their variation with temperature and wavelength. This will help to improve the present understanding of GaInNAs-based lasers and suggest approaches that could be undertaken to improve their characteristics. An outline of how this work will be presented is now given.

In Chapter 2, the necessary theory to understand the body of this thesis will be introduced and discussed, including a description of the analysis used for the data obtained through experimental work. This includes an introduction to basic laser
operation principles, a description of the different recombination mechanisms possible within these devices and an introduction to some of the terms to be used in describing the properties of the devices such as a definition of the threshold current.

In Chapter 3, a review of GaInNAs lasers is presented, here the literature concerning the development of the GaInNAs material is investigated, from its initial proposal in 1996 through to the present day, dealing with both the 1.3μm and the 1.5μm wavelength regimes. Further recent developments such as the use of antimony in the active region will also be discussed.

In Chapter 4, the techniques used to obtain the data shown in the following results chapters are outlined, such as the methods used to make electrical and thermal contact with the devices. Within this chapter there is also a description of some of the experimental setups used for this work such as the closed cycle cryostat system and the hydrostatic pressure apparatus.

In Chapter 5, the wavelength dependence of the recombination mechanisms are investigated for MBE grown GaInNAs devices, showing that the threshold current of the GaInNAs devices is dominated by Auger recombination at all of the wavelengths considered, where Auger recombination increases with wavelength. The cause of this high Auger component will be shown to be due to an Auger coefficient (C) of similar magnitude to that of InGaAsP and AlGaInAs. Study of the carrier dependence of the threshold current will also show that the devices are dominated by non-radiative recombination consistent with Auger recombination. This work on the carrier dependence of the threshold current density also appears to show that there is no significant carrier leakage within these devices, in contrast to some observations in the literature.

In Chapter 6, the pressure dependence of the GaInNAs devices will be studied. It will be shown that the effect of the nitrogen level – conduction band interaction plays a large part in the pressure dependence of these devices. The 1.5μm devices will be shown to have a pressure insensitive threshold current in contrast to the 1.3μm devices which show a rapid increase in threshold current with pressure. This large difference is the result of a reduced interaction between the nitrogen level and the conduction band. This is supported by theoretical BAC model calculations.
Additionally within this chapter a calculation of the variation of the Auger recombination coefficient with wavelength is presented.

In Chapter 7, the optimisation of MBE grown devices will be discussed. Within this chapter the effect of changing the barrier material from GaAs to GaNAs will be studied along with the affect of the strain incorporated in the quantum well. It will be shown that the main benefit of changing from GaAs barriers to GaNAs barrier is manifested in a reduction in the monomolecular current present within the threshold current of the device. It will also be shown that strain can be used to reduce the threshold carrier density, and as a result the Auger current component of the threshold current. This work once again reinforces our suggestion that there is no significant carrier leakage within the GaInNAs lasers studied at room temperature.

In chapter 8, MOCVD grown devices will be considered and the recombination mechanisms making up their threshold current investigated. We will show that for these MOCVD devices the monomolecular current component is particularly high compared with MBE grown devices. We show that this increased monomolecular current may be linked to unintentional carbon incorporation during the MOVPE growth.

In Chapter 9, the conclusions, from this work will be discussed highlighting the main findings of this work. A proposal of further interesting and useful work will be presented.
Chapter 2

Background Theory

2.1 Introduction

This chapter will introduce the basic theory needed to understand the operation of the semiconductor laser diodes considered within this thesis. More detailed descriptions of the physics introduced here can be found in numerous textbooks on the subject such as Agrawal and Dutta, "Semiconductor lasers" [4] and others [65-67]. This chapter will also deal with the experimental theory required to understand the data and analysis presented in the remainder of this thesis.

2.2 Band structure

The basic band structure of a simple direct band gap bulk semiconductor can be approximated by Figure 2.1.

![Figure 2.1](image-url)  
Figure 2.1 A simplified schematic of a semiconductor where the Conduction band (CB), heavy hole band (HH) light hole band (LH) and spin split off (SO) are shown, with the shaded areas representing filled states.
In order to describe these bands it is common to make a parabolic approximation of the band dispersion. This approximation gives us the energy for both an electron and a hole at the band edge as in equations (2.1) and (2.2) respectively [67].

Here $E_c$ and $E_v$ are the band edges for the conduction band and valence band respectively, $m_e^*$ and $m_v^*$ are the effective masses for electrons and holes, and $h$ is Plank’s constant divided by $2\pi$.

$$E_c = \frac{\hbar^2 k^2}{2m_e^*}$$  \hspace{1cm} (2.1)

$$E_v = \frac{\hbar^2 k^2}{2m_v^*}$$  \hspace{1cm} (2.2)

The probability of finding an electron at a given energy $E$, either in the conduction band $f_c(E)$ or in the valence band $f_v(E)$ is given by the Fermi Dirac distribution as follows in equations (2.3) and (2.4), respectively [67].

$$f_c(E_c) = \frac{1}{\exp\left(\frac{(E_c - F_c)/k_bT}{+1}\right)}$$  \hspace{1cm} (2.3)

$$f_v(E_v) = \frac{1}{\exp\left(\frac{(E_v - F_v)/k_bT}{+1}\right)}$$  \hspace{1cm} (2.4)

where $F_c$ and $F_v$ are the quasi Fermi levels for the conduction and valence bands respectively, $k_b$ is the Boltzmann constant and $T$ is the absolute temperature.

Following from this it is clear that the probability of finding a hole in the valence band is $[1 - f_v(E)]$.

These initial functions for the band dispersion and probabilities can now be used to understand the basic transitions within the laser devices being considered here.

### 2.3 Basic Transitions

Within this thesis, we will be considering devices which are based upon a number of basic optical transitions between the bands of the material constituting the device. The basic transitions are shown in Figure 2.2, these three processes are the fundamental processes present in a laser device, or to varying extent in any material.
The first of the three processes, spontaneous emission, occurs when an electron and hole spontaneously recombine to produce a photon, as shown in Figure 2.2(a). The energy of this photon is given by the difference of the energy of the electron in the conduction band (CB) and a hole in the valence band (VB).

This spontaneously produced photon will have a random direction, polarisation and phase. The rate of spontaneous emission is proportional to both the electron density in the higher energy band and the hole density in the lower band, and is given by equation (2.5)

\[ R_{\text{spem}} = A_{\text{se}} f_e(E) \rho_{\text{CB}}(E)(1 - f_v(E)) \rho_{\text{VB}}(E) \] (2.5)

where \( \rho_{\text{CB}}(E) \) and \( \rho_{\text{VB}}(E) \) are the densities of states in the conduction and valence bands respectively and \( A_{\text{se}} \) is the Einstein coefficient governing this transition.

Stimulated emission is the creation of a second photon from the recombination of an electron and a hole which has been stimulated by an incident photon; this interaction is shown in Figure 2.2(b). This is a resonant effect caused by the incident photon, consequently the second photon is identical to the first in energy, direction, polarisation and phase. This results in a large number of identical coherent photons being produced. This stimulated emission is the mechanism by which lasing occurs, the conditions required for stimulated emission to build up to allow lasing will be discussed shortly.

The rate of the stimulated emission process is proportional to the density of electrons in the conduction band, the density of holes in the valence band and the density of photons present, as given by equation (2.6)
Chapter 2 - Background Theory

\[ R_{\text{sim}} = B_{21} P(hv) f_c(E) \rho_{CB}(E)(1 - f_c(E)) \rho_{PB}(E) \]  \hspace{1cm} (2.6)

where \( P(hv) \) is the density photons with energy \((hv)\) where, \( h \) is Planck's constant and \( \nu \) is the photon frequency and \( B_{21} \) is the Einstein coefficient governing this transition.

The third basic transition, absorption, is shown in Figure 2.2(c). The process of absorption occurs when a photon is absorbed by the active material, resulting in the excitation of an electron from a state in the (VB) to a state in the (CB). This results in the creation of an electron–hole pair. For this process to occur, the incident photon must have energy greater than the energy difference between these two states. The probability of this occurring is dependent on the density of electrons in the valence band, the availability of free states in the conduction band and the density of photons as given by equation (2.7)

\[ R_{\text{abs}} = B_{12} P(hv) \rho_{CB}(1 - f_c(E)) \rho_{PB}(E) f_c(E) \]  \hspace{1cm} (2.7)

where \( B_{12} \) is the Einstein coefficient governing this transition.

2.4 Population inversion and gain

Initially for an undoped semiconductor at room temperature the density of electrons will be higher in the valence band than in the conduction band and thus from the above equations it will be more probable that there will be absorption rather than gain for a photon travelling within the material. Here the net gain is determined by the change in photon density and is given by \( R_{\text{sim}} - R_{\text{abs}} \).

\[ R_{\text{gain}} - R_{\text{abs}} = \frac{B_{21} P(hv) f_c(E) \rho_{CB}(E)(1 - f_c(E)) \rho_{PB}(E)}{B_{12} P(hv) \rho_{CB}(1 - f_c(E)) \rho_{PB}(E) f_c(E)} - \frac{B_{12} P(hv) \rho_{CB}(1 - f_c(E)) \rho_{PB}(E) f_c(E)}{B_{21} P(hv) f_c(E) \rho_{CB}(E)(1 - f_c(E)) \rho_{PB}(E)} \]  \hspace{1cm} (2.8)

Therefore it is necessary for the population of electrons to be inverted from its original state in order for gain to occur. As the semiconductor is pumped the quasi Fermi levels move to higher energies in their respective bands, and the density of electrons in the conduction band and holes in the valence band will increase. As the Fermi levels separate with pumping, the semiconductor will reach a transparency point at which there will be equal probability of absorption and of gain. This transparency condition is given by equation (2.9). The transparency point was first defined by Bernard and Duraffourg as [8].
As the quasi-Fermi levels in the conduction and valence bands move further apart in energy, population inversion is achieved and gain is possible.

### 2.5 Optical feedback

In order to take advantage of this gain and produce lasing, the gain needs to equal all of the losses in a device. To achieve this there must be a population inversion and a high photon density. The high photon density required for stimulated emission and lasing is more easily achieved by placing the active gain region within a cavity. The cavity serves to retain light, which would otherwise have been lost, by reflecting a fraction of it off mirrors at either end of a cavity. This reflection builds up the photon density and as a result maintains the stimulated emission rate; the cavity effectively increases the opportunity for gain, making sustained lasing possible.

The devices in this study are all edge emitting lasers and have their cavity formed by separating the wafer into individual devices; this forms facets (which are cleaved along crystallographic planes), that typically have a reflectivity of $\sim30\%$ due to the refractive index step between the semiconductor material and air. Individual lasers are scribed with roughened edges at the sides of the device, which serve suppresses transverse modes. The basic edge emitting laser device structure is shown in Figure 2.3.

![Figure 2.3](image)

Figure 2.3 The basic Fabry-Perot device structure used for the laser devices within this work, where R1 and R2 are the reflectivities of the mirrors formed at the semiconductor-air interface.

The mirrors formed by the as-cleaved facets form a Fabry-Perot cavity. This cavity acts as a resonator and defines a number of modes that will establish standing waves within it. The wavelengths of these modes are defined by equation (2.10).
\[ \frac{m\lambda}{2} = \mu L_{\text{cav}} \]  

(2.10)

Where \( m \) is an integer, \( \lambda \) is the lasing wavelength, \( L_{\text{cav}} \) is the cavity length and \( \mu \) is the effective refractive index of the layers supporting the lasing mode.

2.6 Round trip Gain and laser threshold

When these devices are subjected to (optical or electrical) pumping the material of the active region will produce gain. The shape of the gain curve will be specific to the material. The shape of a typical gain curve as a function of carrier density for GalnNAs/GaAs is shown in Figure 2.4.

![Figure 2.4: Gain Curve of GalnNAs material calculated at carrier densities of 1.0, 2.0, 3.0, 4.0, 5.0, 6.0 and $7.0 \times 10^{12}\text{cm}^{-2}$ from[68].](image)

We can clearly see the energy of the peak gain increasing as the carrier density is increased and the Fermi levels move further apart due to additional pumping.

Figure 2.4 can be used to measure the band gap of the device. If the device is unpumped then an absorption edge corresponding to the band gap will be seen. The Fermi level splitting can also be measured using this figure; where the Fermi level splitting is the point on the short wavelength side where the gain is equal to zero. This point also corresponds to the transparency point.

The overlap of the material gain curve with the cavity modes described by equation (2.10) determines which mode within the device will see the most gain. The main lasing mode of a laser device will be the mode that is closest to the peak gain of the material, this is illustrated in Figure 2.5. Other side modes, close to this main mode...
may also lase. However, these side modes are suppressed (albeit not perfectly) as the pump power to the device is increased.

This gain / cavity mode alignment is used within DFB and VCSEL structures (with a much reduced number of cavity modes) to provide relatively temperature instable performance, so as such this is a very important feature of semiconductor laser systems.

The material can be pumped sufficiently that the device becomes transparent, this is not the pump level at which it starts to lase. This is a result of the fact that there are other losses within the cavity apart from absorption. These include optical and carrier scattering out of the active region and mirror losses (since not all the light is reflected back). Therefore, there exists a threshold above the transparency point, where this round trip criterion will be satisfied. The threshold gain per unit length of the device is given by equation (2.11)

$$g_{th} = \frac{1}{r} \left[ \frac{1}{2 \lambda_{mw}} \ln \left( \frac{1}{R_1 R_2} \right) + \alpha_i \right]$$  \hspace{1cm} (2.11)

Where $r$ is the optical confinement factor (this is the overlap of the active material and the optical mode within the device), $R_1$ and $R_2$ are the facet reflectivities and $\alpha_i$ is the internal loss per unit length.

This threshold gain value gives rise to a pumping threshold for the device. For electrical pumping, this corresponds to a threshold current as can be seen on a plot of light emission versus current shown later in Figure 2.10.
2.7 Density of states

As can be seen in equation (2.8) the gain within the material is highly dependent upon the density of states within both the conduction and valence bands of the material. The density of states of a 3D bulk semiconductor where the carriers are free to move in all dimensions is given by equations (2.12) and (2.13) from [67]

\[ \rho_{CB}(E) = 4\pi \left( \frac{2m_e^*}{\hbar^2} \right)^{3/2} \sqrt{E} \]  
(2.12)

\[ \rho_{VB}(E) = 4\pi \left( \frac{2m_v^*}{\hbar^2} \right)^{3/2} \sqrt{E} \]  
(2.13)

Where \( \rho_{CB}(E) \) and \( \rho_{VB}(E) \) are the densities of states for the conduction band and the valence band respectively.

However, in a quantum well, the system may be considered as quasi 2-D where the carriers are effectively confined in the direction of the growth of the quantum well. The density of states for this “2-D quantum well” system are given by equation (2.14) for the conduction band and equation (2.15) for the valence band from [67].

\[ \rho_{CB} = \frac{4\pi m_e^*}{\hbar^2 L_z} n \]  
(2.14)

\[ \rho_{VB} = \frac{4\pi m_v^*}{\hbar^2 L_z} n \]  
(2.15)

Where \( L_z \) is the thickness of the quantum well and \( n \) is the energy level.

Illustrations of these densities of states for the two systems are shown in Figure 2.6 in these illustrations it is clear that the density of states in the 2-D system is independent of energy, for each energy level.
In moving from 3-D to 2-D the change in the density of states results in a relative abundance of states at the band edge of the 2-D devices, this results in the Fermi level remaining closer to the band edge at transparency. The result of the Fermi level remaining at the band edge is that a larger number of the occupied states can usefully contribute to gain, resulting in a narrower output spectrum in comparison to the 3-D system.

2.8 Strain

The use of strain within laser devices was first proposed in 1986, it was thought that incorporation of strain could reduce the threshold current of the lasers incorporating it [20, 21], this has been proven by many groups [69, 70]. Since then the growth techniques have been improved and it is now possible to grow high quality strained layers. The use of strain has resulted in many more material systems becoming available for the growth of semiconductor laser devices.

Strain is introduced into the lattice by growing thin layers that have slightly different lattice constants to the bulk substrate. The growth of a compressively strained layer is illustrated in Figure 2.7.
This leads to energy being stored within the lattice. Providing the energy stored is lower than the critical energy for a dislocation no defects will be formed as a result of this stored energy, this leads to the concept of critical thickness \((h_c)\), this condition can be seen in Figure 2.8.

The addition of strain can also lead to reliability problems with the lifetime of devices being shortened when the incorporated strain is too high. However, provided the strain-thickness product is kept within acceptable limits the incorporation of strain is in general beneficial.
The incorporation of strain into the lattice has the effect of distorting it. There are two components of strain: hydrostatic and uniaxial. The effect of hydrostatic strain is similar to the application of external hydrostatic pressure, where compressive strain will increase the band gap and tensile strain will reduce the band gap.

Uniaxial strain however, alters the symmetry of the lattice which has an effect mainly on the valence band [71] and to a lesser extent on the conduction band at the X point. The effects of tensile and compressive strain are shown in Figure 2.9.

![Figure 2.9](image)

The effect of the compressive strain is that it leads to a reduction in the density of states at the top of the valence band, this in turn reduces the threshold current [20, 21]. This reduced threshold current is due to a reduction in the carrier density at threshold \( (n_a) \) and serves to reduce unwanted spontaneous emission, defect related recombination and Auger recombination, following from equation(2.16).

It should also be understood that tensile strain also has positive effects, however, since none of the active regions within the devices in this study are under tensile strain it will not be discussed here. Nevertheless, the interested reader is directed to ref [72]

### 2.9 Threshold current

The threshold current, \( I_{th} \) is defined as the current at which the device achieves threshold gain fulfilling the round trip gain requirements discussed in equation(2.11).
Above this current, the device functions as a laser, where each additional electron hole pair ideally creates an extra photon through stimulated emission.

The threshold current can be expressed in terms of four current paths described by equation (2.16), each of which will be discussed in the following sections.

\[ I_{th} = eV(An + Bn^2 + Cn^3) + I_{leak} \]  \hspace{1cm} (2.16)

The \( An \) term corresponds to the monomolecular recombination, the \( Bn^2 \) term corresponds to radiative recombination (spontaneous emission) and the \( Cn^3 \) term corresponds to Auger recombination. \( A, B \) and \( C \) are the monomolecular, radiative and Auger recombination coefficients, respectively. The \( I_{leak} \) term corresponds to any leakage current present within the device.

The threshold current is determined experimentally by plotting a graph of facet emission (light) versus the injected current, as shown in Figure 2.10.

However, for most of the work within this thesis the threshold current density will be considered. This accounts for the total area being pumped and allows for the comparison of devices with different dimensions.

\[ \text{Figure 2.10 Light current characteristic for a typical semiconductor laser. As can be seen from the graph below } I_{th}, \text{ the light output is low this is the region where spontaneous emission dominates. Above the current } I_{th}, \text{ stimulated emission dominates.} \]
2.10 Slope efficiency

The gradient of the light current characteristic, shown in Figure 2.10 in the region above threshold, can be used as a direct measure of the differential quantum efficiency of the laser, if all or a known fraction of the light has been collected from the facet. The differential quantum efficiency is defined by equation (2.17)

\[ \eta_d = \frac{e}{h} \frac{dL_{\text{eff}}}{dI} \]  

Where \( dL_{\text{eff}}/dI \) is the gradient above threshold, \( e \) is the charge of an electron and \( h \nu \) is the photon energy. This term is used as an indicator of the device performance, where \( L_{\text{eff}} \) is a power.

2.11 Carrier Recombination processes

2.11.1 Radiative recombination

The current associated with the spontaneous emission is known as the radiative current, this process is illustrated in Figure 2.11.

Radiative recombination requires the presence of an electron \( (n) \) and a hole \( (p) \), this is expressed in equation (2.18). For undoped active regions with uniform pumping we can make the assumption \( n = p \), hence

\[ I_{\text{rad}} = eVBn^2 \]  

(2.18)
where $B$ is the radiative recombination coefficient. $I_{\text{rad}}$ is proportional to the integrated pure spontaneous emission emitted from the device, $L_{SE}$. This will be shown to be an important relationship in section 2.15.

$$I_{\text{rad}} \propto L_{SE} \quad (2.19)$$

In order for lasing to occur there must be spontaneous emission to provide the seed photons for stimulated emission. As spontaneous emission is a random process, the photons that are emitted are emitted in all directions with a broad energy range. Only a small fraction of the spontaneously emitted photons can couple to the laser gain. Therefore, for efficient laser operation it is desirable that the amount of spontaneous emission is small.

### 2.11.2 Defect related recombination

Another non-radiative possible recombination path to be discussed is recombination through material defects. Material defects are caused by problems within the crystal lattice such as trap sites or vacancies, these can be the result of issues with the growth of the material, problems with the processing or may be merely intrinsic.

![Figure 2.12 Typical defect recombination path through a trap within the band gap.](image)

This recombination rate is dependent only on the single carrier that is trapped by the defect; because of this the defect related recombination is also known as monomolecular recombination. The defects can have a significant current flowing through them. The relationship governing the defect (monomolecular) recombination path is
where \( e \) is the electron charge, \( V \) is the volume of the active region, \( A \) is the monomolecular recombination coefficient and \( n \) is the carrier density.

The monomolecular recombination coefficient, \( A \), may be written as shown in equation (2.21).

\[
A = \sigma_w \nu_{th} \nu_d
\]

Where \( \nu_d \) is the defect density, \( \nu_{th} \) is the thermal electron velocity and \( \sigma_w \) is the average defect capture cross section in the active region[4].

### 2.11.3 Auger Recombination

The other main type of carrier recombination that may occur is Auger recombination. This occurs when the energy released from a recombining electron-hole pair is used to excite a third carrier higher up within its band, or even into a higher energy sub band. Auger processes are commonly classified by labelling their initial and final states of carriers where (C) is the conduction band (H) is heavy hole band and (S) is spin split off band. Two examples of these mechanisms are shown in Figure 2.13. These two Auger mechanisms have been shown to be the main Auger processes occurring in GaInNAs (Andreev et al. [73]).

![Figure 2.13 A schematic of two different Auger processes, (a) CHCC (b) CHSH](image)

In Figure 2.13 (a) CHCC, the energy and momentum from one electron (1) recombining with hole (1') is transferred to electron (2), which is excited to higher energy in the conduction band. This process is very temperature sensitive, as the
energy and momentum have to be conserved. The rate of this process depends upon the availability of this hole state \((1')\) which increases with temperature. Thus it is easy to see why Auger recombination is strongly dependant on temperature. It also depends upon the band gap of the material, with the rate decreasing with increasing band gap.

In Figure 2.13 (b) CHSH, the energy from the electron hole recombination is transferred to a second hole \((2)\) which is excited from the heavy hole band into an empty state in the spin split off band. This process is again very temperature sensitive. It depends upon the occupation of the electron in the \((1)\) state and the hole in the \((2')\) state. This is a particularly important process in semiconductors which have spin orbit splitting less or equal to their band gap.

Clearly three charge carriers are involved in these electronic transitions. Again assuming \(n = p\), the Auger related current is expressed as in equation (2.22).

\[
I_{\text{Auger}} = eV C n^3
\]  

(2.22)

\(C\), the Auger recombination coefficient, is thermally activated [74, 75], and can further be expressed as in equation (2.23).

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

(2.23)

\(C_0\) is independent of temperature, \(E_a\) is the activation energy of the Auger recombination process (this is specific to the particular type of Auger occurring [4]), \(k\) is the Boltzmann constant and \(T\) is the absolute temperature. Assuming parabolic and isotropic bands, \(E_a\) for the CHCC and CHSH processes are given by.

\[
E_a(CHCC) = \frac{m_e - m_h}{m_e + m_h} E_g
\]  

(2.24)

\[
E_a(CHSH) = \frac{m_e}{2m_e + m_h + m_s} (E_g - \Delta_{so})
\]  

(2.25)

Where \(m_s\) is the mass of the carriers in the split-off band and \(\Delta_{so}\) is the spin-orbit splitting energy, where (2.24) and (2.25) are taken from [72]. These equations are used here as approximations in order to help study the Auger current.

These Auger processes become more important when moving to longer wavelength devices, as the conditions for conservation of energy and momentum are more easily
met due to the closer spacing of the conduction and valence bands and the reduction in the threshold energy for the Auger processes.

2.12 Further loss mechanisms

There are a number of additional loss mechanisms which can be present within a typical laser device, these include carrier leakage and Inter-Valence Band Absorption (IVBA) these will now be defined.

2.12.1 Carrier leakage

Carrier leakage can be a problem within semiconductor lasers. Carrier leakage is a thermally activated process; if the carriers can gain enough energy to escape from the quantum well of the device, they will be removing energy from the active region as illustrated in Figure 2.14.

Carriers can escape from the well into the barrier material or even the cladding regions. Once there they may recombine non-radiatively emitting phonons resulting in a heating of the lattice, or they may recombine radiatively, but as the band gap of the cladding and barrier materials is different to that of the quantum well, the photon emitted will not contribute to gain, and thus it acts as a loss process. The probability of carrier leakage depends upon the height of the potential barriers and the thermal spread of the carriers.

2.12.2 Inter-Valence Band Absorption (IVBA)

Inter-valence band absorption occurs when a photon propagating along the laser cavity is re-absorbed by an electron in the spin split-off band, exciting it towards the
valence band maximum, as illustrated in Figure 2.15, this mechanism was first proposed by Adams et al. [77].

The magnitude of IVBA depends upon the band structure of the material, in particular the spin-orbit splitting energy, in cases where the band gap far exceeds the spin orbit splitting there is a negligible probability of IVBA occurring, however as the magnitude of the spin orbit splitting approaches that of the band gap IVBA rapidly becomes a problem. IVBA is directly proportional to the hole density in the heavy hole band. IVBA is also highly dependent on temperature as the spreading of carriers will determine how far in $k$ space that this can occur. For a full treatment of this mechanism see [77].

![Figure 2.15 Schematic illustrating Inter-valence band absorption (the photon emitted from the recombination of electron 1 and hole 2 is used to excite an electron 1' to 2')](image)

The presence of IVBA results an increase in the internal losses $\alpha$, which results in an increase in the threshold gain, and thus in $n_\text{th}$. This has the effect of increasing the threshold current of the device, particularly of Auger recombination ($\propto n^3$) is occurring.

### 2.13 The characteristic temperature ($T_0$)

As briefly described in the introduction, the characteristic temperature is a measure of the sensitivity of the threshold current to variations in temperature. $T_0$ is given by equation (2.26)
where \( T_0 \) is expressed in units of Kelvin.

If \( T_0 \) is constant over a given temperature range, the solution of (2.26) is an exponential as given by equation (2.27)

\[
I_{th} = I_o \exp \left( \frac{T}{T_0(I_{th})} \right)
\]

where \( I_o \) is a constant. From this, it is clear that a high \( T_0 \) corresponds to low temperature sensitivity and vice-versa. Therefore, a high \( T_0 \) is a desired characteristic.

The \( T_0 \) of a device can be determined experimentally using equation (2.28)

\[
T_0(I_{th}) = \frac{T_2 - T_1}{\ln \left( \frac{I_{th}(T_2)}{I_{th}(T_1)} \right)}
\]

where \( I_{th}(T_1) \) and \( I_{th}(T_2) \) are the threshold currents at temperatures \( T_1 \) and \( T_2 \) respectively, and \( T_2 > T_1 \).

### 2.14 Temperature dependence of carrier recombination paths

#### 2.14.1 Temperature dependence of monomolecular recombination

To calculate the characteristic temperature of the monomolecular current, \( I_{mono} \), we use the assumption shown in equation (2.29) for quantum well devices for the temperature dependence of the threshold carrier density, \( n_{th} \), [74, 78, 79].

\[
n_{th} = n_o T
\]

Where \( n_o \) is temperature independent. Using this form of \( n_{th} \) and the monomolecular recombination coefficient, \( A \) from (2.21), assuming a two dimensional electron gas, the characteristic temperature of the monomolecular current \( T_0(I_{mono}) \) at threshold is now given by equation (2.30).

\[
T_0(I_{mono}) = \frac{2}{3} T
\]

From this it can be deduce that the maximum \( T_0(I_{mono}) \) at 300K for an ideal quantum well laser dominated by recombination through defects is limited to 200 K.
2.14.2 Temperature dependence of radiative recombination

The characteristic temperature of the radiative current, $T_0(I_{rad})$, can also be determined, using an expression for the radiative recombination coefficient, $B$, developed by O’Reilly and Silver [74], and shown in equation (2.31),

$$B = \frac{P_0}{T}$$  \hspace{1cm} (2.31)

Where $P_0$ is temperature independent. Using equations (2.31), (2.29) and (2.18) the characteristic temperature of the radiative current $T_0(I_{rad})$ can be shown as

$$T_0(I_{rad}) = T.$$  \hspace{1cm} (2.32)

This shows that the maximum $T_0(I_{rad})$ for an ideal quantum well device at 300K will be 300K.

2.14.3 Temperature dependence of Auger recombination

In the same way the characteristic temperature of the Auger current is determined by the substitution of equation (2.29) and equation (2.23) into equation (2.22), which gives the following expression for the Auger related current.

$$I_{Auger} = C_0 n_0 T^3 \exp \left( \frac{E_a}{kT} \right)$$  \hspace{1cm} (2.33)

Substituting $I_{Auger}$ for $I_{th}$ in equation (2.26) yields equation (2.34)

$$T_0(I_{Auger}) = \frac{T}{3 + \frac{E_a}{kT}}.$$  \hspace{1cm} (2.34)

This shows that the maximum possible characteristic temperature at 300K for the Auger contribution to the total current ($E_a = 0$) is $T_0(I_{Auger}) = 100K$. This can be used to show that where the $T_0$ of a device is low ($\leq 100K$) then Auger recombination must dominate.

2.15 Carrier density dependence of the threshold current

The current flowing through a laser is described by equation (2.16). The ability to determine which of these components are present within the devices being studied is an essential technique. This can be achieved by analysing the spontaneous emission...
from the device. If one of the recombination current paths in equation (2.16) is dominant over a small current range, we can write that

\[ I \propto n^Z \]  

(2.35)

where \( Z \) is the power law dependence. \( Z = 1 \) if defect recombination is dominant, \( Z = 2 \) if radiative recombination is dominant or \( Z = 3 \) if Auger recombination is dominant. It follows that as the radiative current is proportional to the pure spontaneous emission rate given by \( L_{SE} \) shown in equation (2.19), substituting \( L_{SE} \) for \( I_{rad} \) in equation (2.18) and then rearranging for \( n \) gives equation (2.36).

\[ n \propto L_{SE}^{\frac{1}{Z}} \]  

(2.36)

Substituting into equation (2.35) gives equation (2.37).

\[ I \propto \left( L_{SE}^{\frac{1}{Z}} \right)^{2Z} \]  

(2.37)

By taking the logarithm of both sides we obtain equation (2.38)

\[ \ln(I) = Z \ln \left( L_{SE}^{\frac{1}{Z}} \right) + K \]  

(2.38)

where \( K \) is a constant. Therefore, if \( L_{SE} \) is measured as a function of current and \( \ln(I) \) is plotted as a function of \( \ln \left( L_{SE}^{\frac{1}{Z}} \right) \) a value for \( Z \) can be obtained directly from the gradient of the plot, thus deducing which of the recombination paths dominates. This is particularly useful when the gradient is studied close to the threshold, the value of \( Z \) at threshold \( Z_{th} \) can be used to determine directly which in the dominant recombination mechanism within the device at threshold.

Using this technique further regions can be fitted where \( Z = 1 \), \( Z = 2 \) and \( Z = 3 \), to find over which current range the different recombination paths are dominant. When these regions are extrapolated to threshold the contributions of the different components can be calculated.

This method is the most accurate method available for the determination of the monomolecular component. It is important however that only the pure spontaneous emission is studied. Pure spontaneous emission can be obtained through a window in the substrate of the device as will be described in chapter 4.
2.16 Hydrostatic pressure

Hydrostatic pressure is a useful technique for studying semiconductor devices. By applying hydrostatic pressure to a III-V semiconductor the direct band gap can be increased.

The effect of the hydrostatic pressure is that it reduces the atomic spacing and hence the lattice constant of the crystal (Figure 2.16). The effect this has is to increase the band gap of the material, mainly by causing the conduction band to move towards higher energies, with respect to the valence band [80]. The rate of change is typically $80-100 \text{meV/GPa}$ [81] for III-V materials.

The conventional approach to studying energy gap dependent processes in a semiconductor laser is to grow a series of wafers differing slightly in active region composition. This is a very costly procedure and has the additional difficulty that all the remaining structural details, for instance layer thicknesses and doping profiles have to be kept constant, which is virtually impossible. Using hydrostatic pressure it is possible to perform band gap dependence studies on a single device.

As the various recombination processes occurring in semiconductor lasers have different dependencies on band gap, the band gap variation provided by the application of hydrostatic pressure is a powerful tool to investigate the corresponding
current contributions present at threshold. The effect of the hydrostatic pressure on the lasing wavelength along with the lasing threshold current can be studied. Assuming $I_{rad} = E_g^2$ for a quantum well laser [80], with the application of pressure the radiative current is expected to increase with pressure. The Auger current however is expected to decrease, as the band gap is increasing from (2.23), (2.24) and (2.25). Thus, for simple lasers where the radiative current is dominant, the threshold current would be expected to increase with pressure. However, if Auger recombination were dominant the threshold current would fall. This model is much too simple to describe the effect of pressure on the GaInNAs material system, which will be dealt with thoroughly in chapter 6. The details of the hydrostatic pressure experimental technique are outlined in chapter 4.

2.17 The band anticrossing (BAC) model

As outlined in chapter 1 dilute nitride materials are unusual, because of the band bowing which is present with small amounts of incorporated nitrogen. This behaviour is caused by the presence of a localised nitrogen level caused by the large electronegativity of the N atom and the local perturbation it causes to the lattice. The first complete review of this band structure was published by Shan et al. [82] in 2004. Within this paper the BAC model is described by the following equation.

$$E_z(k) = \frac{1}{2} \left[ (E_M(k) + E_N) \pm \sqrt{(E_M(k) - E_N)^2 + xC_{MN}} \right]$$

(2.39)

Where $E_M(k)$ is the energy level of the unperturbed local conduction band and $E_N$ is the energy level of the localised nitrogen level and $C_{MN}$ is a coupling factor and $x$ is the nitrogen concentration. The interaction of the conduction band edge with the non dispersive nitrogen level results in a splitting of the conduction band into a $E_+$ and $E_-$ sub bands these bands can be seen in Figure 2.17.
This interaction between the conduction band edge and the nitrogen level, causes a change in the shape of the conduction band, those states away from the $E_N$ level retain their $E_M$ character, however the states close to the $E_N$ level take on a $E_N$ character that enhances the effective mass and the density of states of this band. This interaction is changed as the $E_M$ level is moved, for example by changing the indium fraction in a GaInNAs device. When the $E_N$ and $E_M$ levels are closer, the $E_s$ sub band will have a much enhanced effective mass and density of states. This band anticrossing is the cause of the large bowing that is seen in the dilute nitride materials, as a result it plays a large part in analysis of the characteristics of these materials.
Chapter 3

A review of GaInNAs based edge emitting laser devices

3.1 Introduction
In 1996 Kondow et al. [37] proposed that incorporating a dilute amount of nitrogen (~2%) into InGaAs, grown lattice-matched on GaAs substrates, could provide a new material for laser diodes operating in the 1.3–1.55μm emission range. They predicted excellent high-temperature performance due to the large type-I conduction band (CB) offset. This material also has the unique feature that its strain can be controlled, as the addition of indium increases the compressive strain and the addition of nitrogen increases the tensile strain, as a result the material can be grown with the desired strain at the desired emission wavelength. This made the material system the ideal candidate for the active region of long wavelength telecommunications lasers, and in particular for VCSELs, due to the fact that these active regions could be grown monolithically on GaAs substrates utilising the well developed GaAs/AlAs Bragg reflector system. As a result of this potential, much work has since been carried out on this material system, as will now be reviewed.

3.2 1.3μm devices
Following this proposal, utilising gas source molecular beam epitaxy (MBE) growth techniques Kondow et al. quickly produced GaInNAs devices emitting at 1.2μm [83, 84], these devices consisted of a single 7nm thick quantum well (SQW) with 30% indium and 0.4% nitrogen sandwiched between GaAs barriers. The first 1.3μm edge emitting lasers operating at room temperature were driven by pulsed current, as demonstrated by Sato et al. in 1997 [85]. Sato et al. had used metal-organic chemical vapour deposition (MOCVD) to grow these devices. Soon after, the first continuous
wave (CW) laser operation at this wavelength was demonstrated by Nakahara et al. using MBE [86]. However, the threshold current density of these devices was ~6.75kA/cm² at room temperature.

The Sato group significantly reduced the threshold currents of their devices in 1999 [87-89]. These devices were MOCVD grown double quantum well (DQW) lasers which had threshold current densities of 660 A/cm² [87], 1000A/cm² [88], and 1200 A/cm² [89] and emission wavelengths of 1.25, 1.29 and 1.3|μm respectively. This reduced threshold current was achieved by optimisation of the growth temperature which resulted in using low growth temperatures of ~550°C. Höhnsdorf et al. again using MOCVD held the record in 1999 for a GaInNAs device emitting around 1.3|μm with a SQW device emitting at 1280nm with a threshold current of 800 A/cm² [90].

The GaInNAs lasers grown around this time showed very promising high-temperature performance. In February 2000 Kitatani et al. [91] reported a 1.3|μm GaInNAs/GaAs laser diode with a characteristic temperature, \( T_0 \), ~215K above RT. This was achieved using highly strained active layers and the extremely low growth temperatures of 460°C with post growth annealing at 550°C. However, these lasers had a quite large threshold current density of \( J_t \), ~2.8 kA/cm² thus it is likely that non-radiative defect related current paths were affecting the measured \( T_0 \), as shall be discussed later in the chapter where MOCVD growth will be studied.

To try to improve the crystal quality of the material, some groups investigated the addition of dilute amounts of antimony during MBE growth of GaInNAs. This was initially carried out by Yang et al.[55]. At this time it was thought that antimony acted as a surfactant and increased the critical thickness of the strained layers, allowing the incorporation of larger amounts of indium into the active regions (~40%) without experiencing any lattice dislocations.

The first 1.3|μm GaInNAsSb/GaAs lasers were reported by Yang et al. early in 2000 [92]. These devices were grown by MBE and had a threshold current of 1 kA/cm². However these devices had poor temperature stability with a \( T_0 \) of ~65K. Since then GaInNAsSb/GaAs devices have been reported with similar threshold current densities (600-1000 A/cm²) and higher \( T_0 \) s ~150K[51, 93]. The Stanford group amongst others have continued to develop this material system with devices grown in 2002 emitting at 1.39|μm and 1.46|μm with threshold densities of 1.8 kA/cm² and 2.8 kA/cm².
respectively [52, 94]. Their contribution will be further considered in the 1.5μm device section of this chapter.

In 2000 Riechert et al. reported devices with record low threshold densities for 1.3μm SQW and triple quantum well (TQW) devices of 500 A/cm² and 650 A/cm² at RT [61, 95]. These devices were also shown to have Tₜₛ of between 70K and 100K. Additionally the group fabricated long cavity length devices Lc = 3200μm; these devices were shown to have Jₜₙ = 270 A/cm² (from a SQW device), a record at the time. Broad area lasers from this group maintained at 10°C were reported to produce 8W of CW output power [96]. The devices produced by this group were grown by solid source MBE, with the nitrogen produced by an RF plasma source.

Also in the year 2000, Sato et al. reported improvements on their previous design with highly compressively strained DQW structures. These devices had a room temperature Jₜₙ = 920 A/cm² pulsed and a Tₜₒ of ~200K the highest at that time for a device with a threshold below 1.1kA/cm² [97].

MBE had initially been setting the standard for low threshold operation at this wavelength, however Kawaguchi et al. reported the first low threshold 1.3μm MOCVD GaInNAs/GaAs devices in October 2000 [62, 98]. These devices utilised GaAs barriers and showed Jₜₙ as low as 340 A/cm² comparable with the ~ 500 A/cm² of the MBE devices of the time. In 2001 Infineon reported lasing at 1.27μm with a threshold current of 350 A/cm² from a SQW GaInNAs active region with a GaNAs barrier this was again the record for a standard sized MBE grown device at the time.

In April 2002 another breakthrough in threshold current was made, when Tansu and Mawst reported Jₜₙ of 290 A/cm² with SQW devices grown by MOCVD. These devices utilised a strain compensating layer of InGaP/GaAsP and GaAsP barriers [99]. Further optimisation of their design produced a new record low threshold of 210A/cm² at 1295nm [63].

The threshold current of the MBE grown devices from other groups has also been decreasing towards the record value set by the Tansu group. In 2004 the Wang et al. in Chalmers produced 1.3μm MBE grown devices with a threshold current of 299A/cm² [100] using a GaInNAs SQW with GaNAs barriers. Recent developments (2006) at the University of Sheffield have shown GaInNAs/GaAs devices with
threshold current densities of 178 A/cm² emitting at 1336nm [49]. This emission, at a longer wavelength that the of the Tansu and Mawst group, was a new record within the 1.3μm range. These devices also returned the record for low threshold current devices to the MBE growers.

The longevity of the Tansu et al. record at 1.3μm serves to illustrate that the focus of the development of this material has shifted to that of long wavelength growth in the 1.55μm region.

The literature has shown that many groups have produced emission in the 1.3μm wavelength range. There was however a slight delay in the MBE growers (excluding Infineon) reaching the record low thresholds set by the MOCVD growers. The literature does however show that low threshold growth has now been achieved by many groups including Chalmers and Sheffield. Clearly the technology is available to commercialise this material at this wavelength. In fact, 1.3μm VCSELs were already commercially available from Infineon in 2002 [64, 101]. The main challenge for the growth of GaInNAs material now rests at the longer wavelengths.

3.3 1.5μm devices

The first emission beyond 1.5μm with the GaInNAs/GaAs based devices was at 1.52μm reported in July 2000 by Fischer et al. using a 5%N and 38% In DQW structure [102]. However, the threshold current density of these devices was very large with \( J_{th} \sim 60kA/cm² \) at \( \lambda=1.51μm \). They have since reported improvements in their growth reducing the threshold to 34 kA/cm² at \( \lambda=1.51μm \) [103] in 2001. Further reductions were shown in 2002 when GaNAs barriers were used to achieve a \( J_{th} = 7 kA/cm² \) at 1.49μm [104]. The Stanford group using GaInNAsSb reported a threshold current of 2.7kA/cm² at \( \lambda=1.46μm \) in 2002 [52]. In 2003 the CNRS group reported emission at 1500nm with a threshold current density of 3500 A/cm², this development was again aided by the use of antimony to form a GaInNAsSb active region [105].

The development of 1.5μm devices and the reduction in the reported threshold current has been rapid with both the GaInNAs and the GaInNAsSb material systems. The development of the GaInNAs material system was driven by Infineon, Germany. In 2004 they reported a number of long wavelength devices at \( \lambda=1.4μm \) with \( J_{th} = 690A/cm² \) and \( \lambda=1.43μm \) with \( J_{th} = 1090 A/cm² \) [106]. At the time, these values
where the lowest values for Sb free devices emitting beyond 1.3μm. By 2005 they had extended the emission to 1.51μm with a GaInNAs SQW and GaAs barriers [48]. This device had a record low threshold current density for any GaAs based device at this wavelength with $J_{th} = 780 \text{ A/cm}^2$.

The development of the GaInNAsSb system has been largely driven by the Harris group at Stanford. Their initial report of GaInNAsSb growth contained devices with emission at wavelengths as long as 1.49μm with $J_{ih} \approx 80\text{kA/cm}^2$[52]. By 2003 the Stanford group had reduced the threshold current density to $J_{th} = 910 \text{ A/cm}^2$ at $\lambda=1.49\mu\text{m}$ through refined growth conditions [107]. In 2004 Gupta et al. in Ottawa extended the record emission wavelength to 1.532μm using the GaInNAsSb material system and GaNAs barriers [108]. These devices had a reported threshold current of 194 kA/cm². The emission wavelength was further extended to 1.55μm by the Stanford group in 2005 [109]. With further developments of their device design and optimisation of their growth the Stanford group produced devices with a record low threshold current density at 1.55μm of 579 A/cm² [110] using GaInNAsSb and GaNAs barriers in 2006. These devices are the current benchmark for 1.55μm emission using the GaInNAs material system.

The Harris group in Stanford have concentrated on the use of antimony in their growth of GaInNAs active regions. As a result of this they have published much work on the effect of antimony [111-113]. There has been much discussion on the effect of antimony e.g. whether it acts as a surfactant improving growth quality or actually being incorporated in the lattice. The current theory is that antimony acts as a reactive surfactant; and that it modifies the surface kinetics during growth by participating in bonding and enhancing reactive incorporation of adatoms [114, 115]. This reduces the surface mobility and suppresses phase segregation and roughening, allowing growth at higher temperatures. This is in contrast to the previous view that it was a surface surfactant that did not incorporate in the material [112]. It is suggested that the higher growth temperatures provided by the use of antimony enable superior optical quality material because of fewer point defects [116].
A summary of reported threshold currents densities versus wavelength is shown in Figure 3.1. It is notable that $J_{th}$ tends to increase with increasing wavelength. This will be discussed further in chapter 5. From this figure it is also clear there is difficulty producing long wavelength GaInNAs devices using MOCVD growth techniques. From the literature it appears that the cause of this problem is found to be the nitrogen precursors used. Many groups are currently trying to improve this technology. Hopefully with more development of these precursors there will soon be a low threshold current device reported at long wavelengths by MOCVD. This issue will be further discussed in chapter 8 of this thesis.
3.4 Temperature dependence

A summary of the $T_0$ s reported for devices considered previously within this chapter is shown versus wavelength in Figure 3.2 and versus device type (ridge waveguide versus broad area) in Figure 3.5. From Figure 3.2 it appears that there is no clear trend in the behaviour of the $T_0$ of these devices, however we note that for the lowest $J_{th}$ devices at longer wavelengths, the $T_0$ values are significantly lower than those reported at ~1.3μm. However we do observe that the MOCVD grown devices appear to have higher $T_0$ values than the MBE devices, although these devices have similar $J_{th}$ s.

![Figure 3.2](image-url)
Chapter 3 A review of GalnNAs based edge emitting laser devices

It is also interesting to study $T_0$ as a function of $J_{th}$ at 1.5$\mu$m and 1.3$\mu$m. This data has been plotted separately for the 1.3$\mu$m and the 1.5$\mu$m devices in Figure 3.3 and Figure 3.4 respectively. These plots have then been split into quadrants corresponding to low $J_{th}$ and low $T_0$, high $J_{th}$ and low $T_0$ etc. From these figures it is clear statistically that the majority of the devices at both wavelengths with a low $J_{th}$ also have a low $T_0$ (i.e. the majority of the devices are in the lower left quadrants). This outlines the difficulty in simultaneously achieving a low $J_{th}$ and a high $T_0$. The physical causes of this will be discussed in chapter 5.

![Figure 3.3](image)

**Figure 3.3** The variation of $T_0$ versus threshold current per quantum well for the 1.3$\mu$m devices where the reference letters are as follows Hitachi A [84] B [83], Ricoh C [85], Hitachi D [86], Ricoh E [87] F [89] G [88], Marburg H [90], Hitachi J [117], Infineon K, L, M [95], Ricoh N [97], TIT O [62] P [118], Wisconsin Q [99] R [63], Sheffield S [49], Chalmers T [100], Wurzburg U [102] V [103] W X Y Z AA [106], Infineon AB [48], Surrey AC [47], Hitachi AD [119], Wisconsin AE, AF [120], Stanford AG [121], Madrid AH [122], Sony AI [123], Chalmers AJ [124], Sony AK [125], TIT AL AM AN [126], CNRS AO [127], Infineon AP AQ AR [128], Ottawa AS [129], CNRS AT [130], Tampere AU [131] AV [132]

It is interesting therefore to consider why there are some high $T_0$ low $J_{th}$ devices apparent in the literature. When we consider the $T_0$ data for the GalnNAs devices as a function of device structure type as shown in Figure 3.5 we observe that the majority
of the high $T_\text{O}$ devices are reported from devices which are fabricated into ridge waveguide devices. These $T_\text{O}$ values may be artificially high due to the current spreading effects around the ridge which introduce a less temperature sensitive parallel current path [137]. The majority of these broad area devices are also MOCVD grown so this explains the apparent difference in the $T_\text{O}$s of the different growth techniques seen in Figure 3.2. This clearly illustrates the importance of measuring broad area devices for an unbiased quantitative analysis of device performance, as has been the case for the measurements presented with this thesis.

![Figure 3.4 The variation of $T_\text{O}$ versus threshold current per quantum well for the 1.5µm devices where the letters correspond to GaInNAs Hitachi A [84] B [83], Ricoh C [85], Hitachi D [86], Ricoh E [87] F [89] G [88], Marburg H, I [90], Hitachi J [117], Infineon K, L, M [95], Ricoh N [97], TIT O [62] P 118], Wisconsin Q [99] R [63], Sheffield S [49], Chalmers T [100], Wurzburg U [102] V [103] W [104] X, Y, Z, AA [106], Infineon AB [48], Surrey AC [47], Hitachi AD [119], Wisconsin AE, AF [120], Stanford AG [121], Madrid AH [122], Sony AI [123], Chalmers AJ [124], Sony AK [125], TIT AL, AM, AN [126], CNRS AO [127], Infineon AP AQ AR [128], Ottawa AS [129], CNRS AT [130], Tampere Au [131] AV [132] and for the GaInNAsSb Columbia A [55] B [92], Tsukuba C [133], Princeton D [93], Stanford E [134], CNRS F [103], Stanford G [107], H [110], Ottawa I [108], Beijing J [135]
The highest $T_0$ reported for a broad area device was $\sim T/3$, the significance of this will be shown in chapter 5.

### 3.5 Summary

This review of the literature has shown a clear trend of increasing threshold current densities with increasing wavelength. It can also be seen that on average the $T_0$'s reported in the 1.5$\mu$m range are much lower than those reported around 1.3$\mu$m. It is also clear that when the $T_0$'s are studied for over a given wavelength range the devices with the lowest threshold currents also have the lowest $T_0$ values.

This review shows the use of different barrier materials with different growers and a variation of the reported threshold currents as a result. From this review it is unclear what the effects of the different barriers are, as there are devices reported with similar...
thresholds and wavelength with different barriers. It did appear that the devices with GaAsP barriers had lower thresholds at 1.3µm from those reported by the Tansu Group. However the Sheffield group has since reported lower $J_\text{th}$ using a simple GaAs barrier. As a result of this ambiguity the effect of the barrier will be investigated in chapter 7.

There also appears to be a clear difference in the quality of the devices produced around 1.5µm depending upon the growth technology. At the longer wavelengths the devices grown by MBE appear to be significantly better with their reported threshold currents being much lower that the MOCVD. However this is not the case at 1.3µm where the quality of the devices appears to be very similar between the two growth techniques.

This may in fact be due to the greater effort to date on the MBE growth of 1.5µm devices and we expect to see improvements in the long wavelength MOCVD grown devices in the future.
Chapter 4

Experimental Techniques

4.1 Introduction

The following chapter will describe the experimental techniques used to characterise the laser devices studied within this thesis. These techniques will be described and any important issues will be highlighted.

The instrumentation and experiments described within this chapter are controlled using the National Instruments LabVIEW programming environment, with Virtual instruments (VIs), which have been written specifically for these experimental setups by the author. The VIs written are now in everyday use by other members of the group.

4.2 Experimental considerations

4.2.1 Current regime choice

The type of current to be injected into the device (be it continuous wave [CW] or pulsed) is the first important variable to be discussed. The majority of the lasers investigated within this study have been studied using pulsed current. Pulsed current was used in order to reduce the heating within the laser. It has been seen that some of the broad area GaInNAS lasers studied here would not lase under CW current, they simply heated up and their L-I characteristics “roll-over” as illustrated in figure 4.1.

This roll over in the L-I characteristic is caused by the current flowing through the device, this current causes joule heating which reduces the efficiency of the device. The effect of joule heating can be decreased by operating the device in pulsed mode.
The pulsed duty cycle determined to be most suitable for the devices in this study was a 500 ns pulse width with a repetition rate of 10 kHz. This optimum value for the duty cycle was reached by conducting experiments to find the highest duty cycle (to collect the most light) which had no significant effect on the threshold current of the devices around room temperature and 40°C above RT. Unless otherwise stated, all the experiments within this thesis were performed using this duty cycle.

Where pulsed current is used, the pulse is applied to the devices from a voltage source. The current of this voltage pulse is then measured inductively with a Tektronix CT1 current probe and a Tektronix oscilloscope.

In order to prevent any impedance mismatching problems with the 50Ω coaxial cables used, a 47Ω resistor is placed in series with the laser device when using pulsed current. This is needed because a typical laser device has a resistance of only ~3Ω under forward bias. If the pulse was applied without the 47Ω resistor there would be significant ringing within the circuit which may damage the device.

### 4.2.2 Electrical contact with the laser

The electrical contacting to the devices is achieved in a number of ways. Initial measurements are carried out on the samples in the form of bars of devices, utilising a probe station designed and constructed by the author. Here one contact is made using a large highly polished brass base plate, this acts as a stable platform to operate the device on and additionally provides an electrical contact, usually to the n-contact on the laser. The other contact is made with one or more probe tips, (7μm tungsten probe tips are typically used) positioned with Karl Suss micro-positioners which are applied to the p-contact of the devices.
Three probe tips are commonly used as it was found that with some samples the threshold current varied, when repeated measurements were carried out using only a single probe tip. This variation was believed to have been caused by poor quality point contacts to the devices. This variation was eliminated by using multiple probe tips.

Once the bars have been cleaved into individual devices (the cleaving technique is described in Appendix 1) there are a number of alternative contact methods. The first contact method is to use a laser clip as shown in Figure 4.2. With this method the bottom contact is again made using the large plate upon which the device sits. The top spring contact can be levered and is used to hold the laser in position. This method can be used on devices which have been processed to a standard such that slight changes in the position of the contact point on the laser will not result in a significant change in the quality of the electrical contact.

![Figure 4.2 schematic showing the design of a typical laser clip from [137]](image)

Alternative contact methods are used on devices which are more sensitive to the position of the contacts i.e. devices with poorly insulating oxide layers. On these devices a polished probe tip can be used to make the top contact. Here the probe tip is polished in such a way as to increase the surface area in contact with the device. Typical polished probe tips make contacts with the devices which are of the order of 200μm by 30μm wide. The use of these tips has been seen to reduce the contact problems encountered with selected devices.

It is also possible to attach gold wires directly to the devices using a gold wire bonder. This can be achieved either by using standard ball and wedge bonds, or for more sensitive devices, and those to be used in pressure experiments, the gold wire bond is made using a gold wire micro soldering technique adapted from that described in [138].
4.2.3 Thermal contact with the devices

In all of the thermal contact cases the temperature is controlled via the bottom electrical contact. These are typically large brass plates which act as heat sinks to the devices. The temperature of these heat sinks can be maintained in a number of different ways. The first is using a peltier heater-cooler element. This peltier element is in thermal contact with the laser through the brass plate, and is also in contact with a heat sink. The heat sink in this system can be maintained at a steady temperature within the range of -5°C and 35°C using a closed cycle cooler utilising antifreeze, as the coolant. This allows the laser to be studied over an operating temperature range from -5°C to 85°C. When operating below the dew point of the air in the lab the system has dry nitrogen gas blown over it, in order to prevent condensation on the facets of the devices.

The other main technique used to control the temperature of the heat sink of the laser is described in the following section on the closed cycle cryostat.

4.2.4 Closed cycle cryostat

The limit of the peltier system discussed above is that the temperature window is quite small from -5°C to 85°C. However for the spontaneous emission techniques (to be described in section 4.3.2), it is necessary to study the threshold current in a region where the probability of Auger recombination is effectively zero. For the devices within this study this is typically a temperature below 100K.

Therefore a closed cycle helium cryostat is used to extend the available temperature window to below this 100K limit. A schematic of the system that is used is shown in Figure 4.3.

The system consists of a helium compressor which highly compresses helium gas, this compressed helium gas is pumped via high pressure tubes into the cooling head unit where it expands and cools the cold finger. The low pressure helium then returns to the compressor unit to be recompressed. The accumulating heat generated is removed in the compressor by means of a closed cycle water cooling system.

In operation, the cold finger cools to a temperature of approximately 10K. At the end of the cold finger the laser clip is mounted on a brass bush within a copper plate, which is separated from the cold finger by a heating element. Utilising computer
control the current flowing through the heating coil is adjusted via a temperature controller unit, the temperature of the laser clip can be set in a range of approximately 10K to 300K.

The temperature in the cryostat is measured with a calibrated silicon diode, which is mounted on the copper plate next to the laser clip. A constant current of 100μA is set to flow through the diode and the temperature is determined by measuring the voltage across the diode and comparing it with the voltage-temperature calibration curve provided by the diode manufacturer, this is again carried out with the aid of a computer monitored temperature controller.

4.2.5 Light collection

The light is collected from the facet of the laser either using a detector incorporating an integrating sphere or a silica optical fibre. Using the detector directly at the facet allows for the collection of all the light from that facet and thus this method can be
used to measure the slope efficiency and hence the external quantum efficiency of the device.

With optical fibre coupling, the light output can be made available to a number of different pieces of test and measurement equipment. The instruments available are extensive and include optical spectrum analysers, wavemeters, and power meters. These instruments can each be used in turn to measure the characteristics of light output from the devices.

The use of a fibre coupled system has some additional elements which need to be considered over the detector arrangement; the first of these is the alignment of the fibre, this is typically achieved using an X-Y-Z positioner on the probe station allowing the fibre to be moved to collect the maximum light. However, within the spontaneous emission setups the fibre is fixed and the laser must be positioned in order to achieve maximum light collection. An additional problem with the use of fibres is that, the ends of the fibre must be carefully maintained, as a result they require constant polishing, cleaving and replacing within the systems.

4.3 Experimental techniques

4.3.1 Basic Measurements

The first characteristic of a laser to be measured for all the devices is the light - current (L-I) characteristic. This L-I can then used to determine the threshold current of the device as described in chapter 2.

The gradient of this L-I curve above threshold can be used to measure the external quantum efficiency of the device. This can only be achieved if the light is collected using an optical power meter at the facet or a calibrated detector incorporating an integrating sphere, so that the true power can be measured.

The emission wavelength of the laser can be measured using an optical spectrum analyser or a wavemeter. The optical spectrum analyser gives more information about the structure of the output spectrum, whereas the wavemeter will only give the peak wavelengths of the emission (usually wavemeters only work when the lasers are driven CW).
All of these measurements can be repeated over the different temperature ranges using the setups described above, allowing the temperature dependent characteristics of the devices to be measured.

4.3.2 Collection of spontaneous emission

The measurement of the pure spontaneous emission from a device is necessary in order to carry out the $Z$ analysis as described in section 2.15. The emission from the facet of the device below threshold will have undergone the effects of gain and loss along the cavity. In order to avoid such effects the light is collected from a window milled into the n-contact of the devices.

![Simple schematic of spontaneous emission collection diagram](image)

This windowing process allows some of the spontaneous emission to escape from the cavity, perpendicular to the optical axis. This light having escaped perpendicular to the cavity through a very small thickness of active material (~10nm) will have seen negligible gain or loss. Therefore, there will be no stimulated emission through the milled window.

The window is positioned at the centre of the cavity, and as such will be far from any stray stimulated emission reflecting from the facets. Thus, from this window pure spontaneous emission can be collected. The "windowing" technique involves the removal of a small 50μm diameter circular section of the metallisation from one contact of the device, typically the n-contact to avoid damage to the active region. The
details of this windowing process are described in Appendix 1. An illustration of this method is shown in Figure 4.4.

The light is collected by an optical fibre and fed into an optical spectrum analyser which is used to analyse the spontaneous emission spectrum. This can only be carried out if the cavity is long enough so that none of the light scattered at the facets is able to reach the window. If scattering occurs, a clear lasing peak can be seen on the collected spontaneous emission spectrum. This can be removed in the data analysis stage.

![Figure 4.5 Spontaneous emission collected from a 1.24μm Marburg device both below and above threshold.](image)

An example of the lasing emission in the spectra can be seen in Figure 4.5. It is clear from Figure 4.5 that any stray lasing emission collected in the SE will seriously affect the integrated spontaneous emission spectra and as such this must be carefully checked for and removed if possible. Note that since the peak of the SE spectrum is at a different $\lambda$ to the lasing peak we can be sure that we are not observing any amplified spontaneous emission.

### 4.3.3 Determination of the monomolecular current

The spontaneous emission can be used in many ways including the determination of the magnitude of the recombination rates as outlined in chapter 2. An example
showing how the magnitude of the monomolecular recombination rate is determined is shown in Figure 4.6. To study the monomolecular current the integrated spontaneous emission is plotted on a graph of \( \ln(I) \) versus \( \ln \left( L_{\mathrm{SE}}^{1/2} \right) \) as outlined in section 2.15. On this plot a line with a gradient equal to one is fitted to the low current data where the monomolecular current will dominate the device. This line with a gradient of 1 is extrapolated to threshold where it can be used to determine in absolute terms the amount of current flowing through monomolecular recombination in the device at threshold.

![Graph showing fitting of Z=1 line to plot of the device](image)

Figure 4.6 Example of the fitting of \( Z=1 \) line to plot of the device shown here is the 0.45%N MOCVD grown sample at 300K. From the fit of \( Z=1 \) it can be seen that the monomolecular current measured for this device is \( 370 \pm 8 \, \text{A/cm}^2 \) (the error is taken from the standard error of the slope).

### 4.3.4 Determination of the radiative current

The spontaneous emission collected from the window shown in Figure 4.4 can also be used to determine the radiative current at threshold in the device. The level of the integrated spontaneous emission in a typical semiconductor laser device is seen to pin at threshold. The variation of the pinning level with temperature is used to determine the variation of the radiative current with temperature. This variation can be converted into absolute units by normalising it at low temperatures as follows [139]. At low temperatures the threshold current of the devices is made up purely by
monomolecular and radiative recombination since the Auger recombination is negligible. The absolute value of $J_{mono}$ can be measured (as described in the previous section) and since, at low temperatures the remainder of the threshold current is due to radiative current, thus the value of the radiative current is determined at low temperature, together with its temperature variation (measured from the change in pinning level) a measure of the actual magnitude of the radiative current can be determined.

In cases where the temperature variation of the pinning level can not be normalised at low temperatures it is possible to alternatively estimate the value of the radiative current by fitting a line $Z=2$. This is achieved by using the fitting method described for the determination of the monomolecular current. However the calculation of radiative current from the pinning level is however more accurate.

### 4.4 Hydrostatic Pressure Techniques

The application of hydrostatic pressure can be carried out in a number of ways, the two methods considered here are the application of pressure using a piston in cylinder system, and a compressed helium gas system.

#### 4.4.1 Piston in cylinder system

Initially for these investigations it was planned to use a piston in cylinder pressure system. However when initial measurements of the pressure dependence of the GaInNAs devices using this system where carried out it appeared that the pressure transmitting medium, undergoing a reaction with the GaInNAs devices, which was resulting in their performance deterioration. As a result the no further pressure studies were carried out using this system.

#### 4.4.2 Helium gas pressure system

As a result of the degraded performance of the GaInNAs laser devices observed after being placed in the pressure transmitting medium in the liquid system, the pressure results reported in the body of this thesis were all carried out using a helium gas compressor system. This pressure system uses helium gas as the pressure transmitting medium.
The helium is compressed in 3 stages reaching pressures of up to 15 kbar. The operation of this gas compressor is a very complex process and further details of its operation can be found in [140].

The helium gas transmission medium has a higher thermal conductivity and a smaller volume in comparison to that of the liquid pressure system[141], and as such requires less settling time between pressure changes. The helium gas has little affect on the laser performance as there is no absorption in helium within the near infrared, the helium gas also has no effect on the facet reflectivities. The main benefit and reason for the use of this system is that, there are no solvent effects, from the helium gas, and thus there was no damage to the devices.

This system consists mainly of a Cu-Be cell. Attached to this cell is a capillary which is used to inject the compressed helium gas to the sample cell. A schematic of the sample chamber of the system is shown in Figure 4.7.

The two ends of this cell are closed with pistons. One of these pistons has a sapphire window attached to it which allows the light to be collected and acts as an unsupported seal. The piston at the other end has a laser mount attached to it similar
that shown in Figure 4.2 this bung also incorporates the electrical feed-throughs to the devices.

The external compression of the He gas allows for the pressure of the gas within the system to be measured in the compressor (again using a manganin coil) saving space in the sample cell.
Chapter 5

Wavelength dependence of the threshold current of MBE grown GaInNAs lasers

5.1 Introduction

The literature review in chapter 3 shows that there is a large variation in the values of threshold current density and $T_0$ values reported for MBE grown GaInNAs devices. These results vary greatly as a function of many variables, these include but are not limited to the emission wavelength [7, 48], the growth temperature [47, 109, 142] and the annealing conditions [132, 143, 144]. As a result of this great variation in the reported values there is major activity within the community to try and produce devices operating with the lowest threshold currents at the important wavelengths for optical fibre communications.

The current records at the time of writing for devices grown using GaInNAs as the active region currently belong to single quantum well devices grown in Sheffield for $\lambda$=1.3μm devices with $J_n$~180 A/cm² [49], and Infineon at $\lambda$=1.5μm for which $J_n$~800 A/cm² [48]. The Harris group at Stanford have produced 1.5μm devices with lower threshold current densities using the GaInNAs(Sb) material system where $J_n$~500 A/cm² [110].

Within this chapter the variation of the threshold current as a function of the emission wavelength will be investigated. In order to try to make this a study of the effect of wavelength with as few as possible other variables to consider we have obtained a set of lasers grown under similar conditions, and using the same techniques to fabricate
the devices. These devices have been optimised for growth at their specific emission wavelengths.

To study the effect of the change in emission wavelength, the threshold current, its temperature sensitivity and the variation of its constituent recombination paths will be investigated as a function of emission wavelength.

**5.2 Devices studied**

Within this chapter we will investigate a set of samples produced by Infineon, the full details of these samples are given in Appendix 2. Where a specific sample is being investigated its details will be more fully discussed, and a sample number will be given corresponding to the sample in Appendix 2.

The samples investigated here are all MBE grown single quantum well devices processed into 1200μm cavity length devices with 100μm wide contact stripes. In order to achieve the variation in the emission wavelength, the nitrogen and indium contents within the quantum well were varied from 1.3% to 4.5% for the nitrogen and from 30% to 40% for the indium, this resulted in devices emitting over the wavelength range 1.27μm to 1.6μm.

**5.3 Threshold current of MBE devices**

Initial investigations of the threshold current as a function of wavelength were carried out on the full range of Infineon samples, this study was performed at room temperature, using the probe station and the results of this study are shown in Figure 5.1. The devices were maintained at RT and were driven by pulsed current.

To determine the threshold current density of the devices the threshold current was measured from the experimentally obtained light current characteristic, this value was then divided by the area of the contact (the stripe width x the cavity length). This assumes that there is negligible current spreading from under the contact stripe in these 100μm wide broad area devices. The assumption of negligible current spreading is in agreement with the Hu et al. model of current spreading [145]. (Typical current spreading would result in the pumped region being 3μm larger, with a 100μm width contact stripe this would only amount to an error of 3%.[145])

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Chapter 5- Wavelength dependence of the threshold current of MBE grown GaInNAs lasers

From Figure 5.1 it is clear that the threshold current density increases with increasing wavelength. This increase in the threshold current density at long wavelengths is a significant issue as GaInNAs VCSELs grown by MBE have been commercially available at 1.3μm [101] for some time but as yet they are still unavailable at 1.55μm. This is because the active region of 1.55μm devices needs to incorporate relatively large amounts of both indium and nitrogen in order to reduce the band gap to reach this operating wavelength [58]. The growth of GaInNAs with the high concentrations of indium and nitrogen needed to emit at 1.55μm is not easy, however growth of devices emitting at these wavelengths is possible and has been reported by several groups [48, 105, 123, 135, 146, 147].

The 1.5μm devices reported in the literature tend to have high threshold current densities, this is thought to be brought about by an increase in the fraction of the current flowing through defect related pathways[148], resulting from the large amount of nitrogen incorporated into the lattice. Thus, we have carried out an investigation of the variation of the threshold current and of the modification of its constituent components as a function of both temperature and wavelength. This study will aid our understanding of the processes that are preventing the commercialisation of 1.55μm GaInNAs devices.
Chapter 5- Wavelength dependence of the threshold current of MBE grown GaInNAs lasers

We have studied the threshold current of two selected Infineon devices at the ends of the wavelength range available; a 1.28\(\mu\)m device (sample number 24269) and a 1.51\(\mu\)m device (sample number 24448). The temperature dependence of the threshold current density of these devices is shown in Figure 5.2. From Figure 5.2 it can be seen that as the wavelength is increased there is an increase in both, the threshold current density, and the temperature sensitivity of this threshold current density. This suggests that the increase in the threshold current is due to a relative increase in a current path which is highly temperature sensitive.

![Temperature dependence of the threshold current densities of 1.28\(\mu\)m and 1.51\(\mu\)m MBE grown devices](image)

The characteristic temperature, the \(T_0\), was investigated for a selection of the devices over this wavelength range, and is shown in Figure 5.3. From Figure 5.3 we can see that the \(T_0\) of these devices decreases as the emission wavelength is increased, as expected from the variation of \(J_{th}\) seen in Figure 5.2. There does however appear to be a slight increase in the \(T_0\) as the emission wavelength although this is small within scatter.
Chapter 5- Wavelength dependence of the threshold current of MBE grown GaInNAS lasers

Figure 5.3 $T_0$ around room temperature for a number of the MBE grown devices where the emission was within the wavelength range 1270-1510nm

To aid in the understanding of this change in $T_0$, a simple calculation of the $T_0$ for a laser was calculated. The variation of the $T_0$ can was calculated at 300K as the percentage of the threshold current from each constituent recombination path is changed from 0% to 100%, the resulting plot can be seen in Figure 5.4.

Figure 5.4 The variation of $T_0$ as the percentages of each of the components in the threshold current is changed, where the temperature is set at 300K
Here we assume that $T_0(Auger) = 100K$, $T_0(red) = 300K$ and $T_0(nano) = 200K$ from equations (2.30), (2.32) and (2.34), we also argued that
\[
\frac{1}{T_0} = \frac{\alpha}{T_0(Auger)} + \frac{\beta}{T_0(nano)} + \frac{\gamma}{T_0(red)}
\]
where
\[
\alpha = \frac{I_{Auger}}{I_{th}}, \quad \beta = \frac{I_{nano}}{I_{th}} \quad \text{and} \quad \gamma = \frac{I_{red}}{I_{th}} \quad \text{and clearly} \quad \alpha + \beta + \gamma = 1.
\]

From Figure 5.4 it is clear that a reduction in the $T_0$ with increasing wavelength is consistent with an increase in the Auger component since $T_0 \leq 100K$.

Further study of the components of the threshold current, will shed light on the interplay between the recombination paths and what is causing the wavelength dependencies observed.

### 5.4 Analysis of threshold current components

By investigating the carrier density dependence of the current at threshold ($Z_{th}$) for a number of these devices, information on which are the dominant recombination mechanisms within these devices can be gathered. The carrier dependence at threshold is measured by studying the plot of $\ln(I)$ versus $\ln\left(\frac{I_{th}^2}{Z_{th}}\right)$ specifically by investigating the gradient at threshold as discussed in chapters 2 and 4. The $Z_{th}$ values measured over the temperature range 70K-350K are shown for the 1.28µm and the 1.51µm devices in Figure 5.5.

We can see from Figure 5.5 that there is little variation in the trend of $Z_{th}$ between the two devices. It appears that the $Z_{th}$ values for the 1.3µm devices are offset from those of the 1.5µm devices by approximately 25K. This leads to the $Z_{th}$ value of the 1.5µm devices saturating at a value ~3 at a lower temperature than the 1.3µm devices. The fact that $Z < 2$ at low temperature is strong evidence that defect related recombination is important. Further more, the saturation of $Z$ to 3 at high temperature is consistent with the devices being dominated by Auger recombination.
This lower saturation temperature indicates an increased Auger rate at lower temperatures for these long wavelength devices. The saturation of these $Z_m$ values at 3 is also good supporting evidence for the argument that there is negligible carrier leakage present within these devices, as any carrier leakage would have caused a corresponding increase in the $Z_m$ to a value above 3.

The $Z_m$ value gives us insight into which is the dominant recombination mechanism within the device however, it shows us little about the magnitude of the individual recombination mechanisms. It is therefore beneficial to study the magnitude of the current flowing through each of the recombination pathways separately. The method used to determine the magnitudes of the current flowing through these paths was outlined in chapters 2 and 4. The results of the analysis of the individual current components are shown for the 1.28µm and the 1.51µm devices in Figure 5.6-5.9.

From these figures it is clear that there is an increase in the magnitude of current flowing through each of the recombination paths as the operating wavelength is increased.
Figure 5.6 The variation of the current flowing through the monomolecular path over the temperature range 70K to 300K for the 1.51µm and 1.28µm devices.

Figure 5.7 The variation of the radiative current path over the temperature range 70K to 300K for the 1.51µm and 1.28µm devices.
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Figure 5.8  The variation of the current flowing through Auger recombination over the temperature range 70K to 300K for the 1.51μm and 1.28μm devices.

Figure 5.9  The variation of all the current paths over the temperature range 70K to 300K for the 1.51μm and 1.28μm devices.
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From Figure 5.6 it is clear that there is a higher monomolecular current in the 1.5μm devices; this difference is initially small at low temperatures however it rapidly increases as the temperature is increased. The cause of this increase in the monomolecular current within the 1.5μm devices must be due to either a more rapidly increasing $A$ or $n_n$ or possibly a combination of both. It is possible that the 1.5μm device may have more loss processes present such as IVBA (which is highly temperature sensitive), if this were the case it would increase the variation of $n_n$ with temperature. From equation (2.21) it is unclear whether there is a variable which would allow for a more rapid increase in the $A$ coefficient with temperature and requires a more sophisticated model. However the increased nitrogen fraction in the 1.5μm devices must have resulted in an increase in the $A$ coefficient with increased wavelength. As this nitrogen level is only weakly temperature dependent and the CB edge of the host GaInNAs moves with temperature, the effective mass will also vary with temperature. This variation would allow for a change in $n_n$ with temperature. Thus it is unclear from Figure 5.6 whether $A$ or $n_n$ is varying more significantly with temperature in the 1.5μm devices.

A study of the variation of the radiative current with temperature from Figure 5.7 shows us that the radiative current is higher in the 1.5μm device, however from our simple model of $I_{rad} \propto E_g^2$ this appears contradictory. However a variation from $I_{rad} \propto E_g^2$ is supported by previous work [149] which showed that the BAC interaction between the conduction band minimum plays a significant part in this variation. In order for $I_{rad} \propto Bn^2$ to be larger in the 1.5μm devices either or a combination of both of $B$ and $n_n$ within this devices must have increased in comparison to the 1.28μm devices. An increase in $B$ may be possible because of the difference in the device structure since the 1.5μm devices have a 15% deeper quantum well, the $B$ coefficient may be increased as a result of improved wave function overlap. This change in the quantum well width was the result of optimisation of the structure of the 1.51μm device for operation at this longer wavelength.

A comparison of the Auger currents from Figure 5.8 also shows that the magnitude of this current path has increased in the 1.5μm device, this however is to be expected as result of the smaller band gap and higher $C$ coefficient (see equations 2.23-2.25). Additionally $n_n$ could be also be increased by the presence of the additional nitrogen...
as may be suggested by the variation of the monomolecular and radiative currents. An increase in $n_a$ would have further increased the difference in the magnitude of the Auger components between the two wavelengths.

When the 1.3μm and 1.5μm devices are compared in Figure 5.9 it can be seen that the largest changes in the component magnitudes are in the monomolecular and Auger recombination paths. It therefore appears that the cause of the increased in threshold current with increasing wavelength is due to an increase in both the monomolecular and Auger recombination rates.

To fully validate this hypothesis, it is useful to study this variation of the magnitudes of the different current paths for further wavelengths. Spontaneous emission analysis was carried therefore carried out on four more of the devices, and the contribution of each of the current paths in the threshold current was determined. The break-down of the threshold current is shown in Figure 5.10 for the original devices and the additional devices.

![Figure 5.10 Break-down of recombination paths for devices in the 1280nm to 1510nm range](image)

It is clear that the increase in the threshold current is due to an increase in both the monomolecular and the Auger currents, with little change in the radiative current over the wavelength range.
From Figure 5.10 it is clear that Auger recombination is the dominant current path in these devices over the entire wavelength range investigated. The apparent flattening of the Auger current of the devices with wavelength is most likely due to an increase in the amount of strain incorporated in the 1.51μm device, as will be further discussed in chapter 7.

The source of the temperature instability of these devices as the wavelength is increased has yet to be explained. In order to study the temperature sensitivity of the threshold current of these devices, we have investigated the temperature dependence of the constituent recombination paths. From Figure 5.9 it appears that the Auger recombination path is the most temperature sensitive. If we carry out an analysis similar to the $T_0$ analysis used on the threshold current we can measure the temperature sensitivity of the individual current components. The results of this analysis are shown in Figure 5.11.

The high $T_0$ value of monomolecular current seen in Figure 5.11 can be used to explain the high $T_0$ s reported for a number of the devices in chapter 3. These devices reported with high $T_0$ s in the literature also tended to have associated high $J_{th}$ s. These higher $J_{th}$ values most likely correspond to an increased monomolecular current.
component, and as the $T_0$ of the monomolecular current is three times higher than that of the Auger current, an increase in the monomolecular current would clearly result in improved temperature stability of the device, albeit at the expense of a larger $J_{th}$.

From Figure 5.11 it can be seen that the $T_0$ for the radiative current is slightly higher than the expected value of 300K. It is believed that this increased value of the $T_0$ is due to the presence of carrier localisation effects, which are common within the GaInNAs material system [150-153].

Figure 5.11 clearly shows that the Auger current path is the most sensitive to temperature variations with the lowest $T_0$ of around 50K. Thus, it is likely that the increased Auger current component, of the threshold current of the long wavelength devices is causing the increased temperature sensitivity of these devices. Figure 5.12 shows the percentage of each current path as a function of wavelength.

![Figure 5.12 Percentage of the threshold current that each recombination path is making up, here the broken lines are a guide to the eye](image)

From Figure 5.12 it is clear that the Auger recombination path is the dominant path over the entire wavelength range, never falling below 55% of the total threshold current and reaching as high as 70% of the threshold current. The contribution of the monomolecular current path is approximately constant with wavelength tending to keep the $T_0$ value higher than would be the case with just Auger recombination.
The radiative current within these devices makes up between ~5%-10% of the threshold current indicating that it has little effect on the threshold current and the temperature dependence of the devices.

5.5 Carrier recombination coefficients

Previously we investigated the variation of monomolecular, radiative and Auger currents versus wavelength and temperature. It would be useful to study the purely material dependent part of these terms as this should remove the impact that the device design is having on these recombination currents. We therefore must extract the monomolecular recombination coefficient \( A \), the radiative recombination coefficient \( B \) and the Auger recombination coefficient \( C \) separately. In order to study the variation of these coefficients we will again study the 1.28\( \mu \)m device (sample number 24269) and the 1.51\( \mu \)m device (sample number 24448). These devices were chosen because they were good representative devices which emitted at both ends of the telecoms window. The break-down of the current paths in these devices was shown in Figure 5.9

In order to estimate the values of the recombination coefficients a realistic 10 band \( k.p \) Hamiltonian has been used to determine \( n_{th} \). This model incorporated the Band Anti-Crossing (BAC) model. The basis states (which were each doubly spin-degenerate) of the model, include the highest valence bands (i.e., heavy hole, light hole, and spin split off) and the lowest \( CB \) of the InGaAs host material, and two additional spin degenerated basis states representing the nitrogen resonant level. With these the band-structure of the devices was determined. This was used to model the gain and the spontaneous emission from the devices which allowed us to determine the threshold carrier density, \( n_{th} \) for these devices assuming 1200\( \mu \)m (e.g. the cavity lengths studied experimentally). More detail on the application of this theory can be found in [154-156]. The modelling was undertaken by Dr Stanko Tomic [157].

The suitability of this model has been tested by comparing the predicted values of the radiative current within the temperature range 50K - 300K to the values measured from experiments, this is comparison is shown in Figure 5.13.
Chapter 5 - Wavelength dependence of the threshold current of MBE grown GaInNAs lasers

Figure 5.13 Comparison of experimentally measured radiative current and theoretically calculated values

Figure 5.14 Theoretical calculation of the threshold carrier density for the 1.51μm Infineon MBE grown device
In order to calculate these values, the internal losses of the devices were set at values taken from the literature, using this data the threshold gain was calculated for the devices. The model was then used to calculate the spontaneous emission spectra increasing the carrier density until threshold gain was reached. This resulted in the values for the threshold carrier density that were used.

Figure 5.13 shows the theoretical and the experimental radiative currents. The overlap of the data sets shows that the theory is a good fit to the experimental data. The model has been primarily used to calculate the threshold carrier density for the two samples, an example of the calculated values of $n_{th}$ for the 1.51μm device can be seen in Figure 5.14. This calculation of the threshold carrier density was repeated for the 1.3μm device giving the threshold carrier density for both the 1.3μm and the 1.5μm devices. These calculated values of threshold carrier density ($n_{th}$) have been used along with experimentally measured values of $J_{\text{mono}}$, $J_{\text{rad}}$, and $J_{\text{Aug}}$ to calculate the values of the recombination coefficients. The recombination coefficients are given by $A = J_{\text{mono}}/eL_{th}$, $B = J_{\text{rad}}/eL_{th}^2$ and $C = J_{\text{Aug}}/eL_{th}^3$ where $L$ is the thickness of the active region. The values of these recombination coefficients have been calculated over the temperature range 100-300K and are shown in Figure 5.15.

It is noted that the monomolecular recombination coefficient, $A$, at room temperature has increased by a factor ~2 when the nitrogen composition was only increased by slightly more than 50%. This result indicates that the number of defects per N atom must be increasing as the N fraction is increased.

We see that the $A$ coefficient in the 1.3μm device is lower than that previously reported by Fehse in 2002 where the $A$ coefficient was reported as $1 \times 10^9$ s$^{-1}$ from measurements on a similar device [158]. We believe that this decrease in $A$ is due to improved growth between the devices. This quantifiable improvement in the growth of GaInNAs reducing the $A$ coefficient between the growth of the different devices, shows that the growth of the GaInNAs material system is very complicated, and that even with careful growth there remains a significant level of defects within the material.
Figure 5.15 Recombination coefficients of both the 1.3μm and the 1.5μm devices as a function of temperature.
Chapter 5- Wavelength dependence of the threshold current of MBE grown GaInNAs lasers

When we study the variation of the $B$ coefficient between the two wavelengths we can see that $B$ has been increased in moving from 1.3$\mu$m to 1.5$\mu$m. The magnitude of this change is however quite small. It is thought that it may possibly be due to an increased wave function overlap provided by the thicker quantum well in the 1.5$\mu$m devices, it has been shown in the literature that a change in quantum well depth can cause a large change in the in the $B$ coefficient \[159\]. Alternatively it may possibly be due to the difference in the strain incorporated in the two devices, since the strain in the 1.5$\mu$m device is higher than that in the 1.3$\mu$m device.

In Figure 5.9 it can be seen that Auger recombination makes up a much more significant proportion of the threshold current in the longer wavelength device. This is also seen in Figure 5.15 where the Auger coefficient also shows a significant increase, where $C$ (1.5$\mu$m) $\approx$ 3$C$ (1.3$\mu$m). This increase in the Auger coefficient is primarily responsible for the increased Auger current seen in the threshold current break-down and thus the increase in threshold current of the 1.5$\mu$m devices. This increase in the Auger recombination coefficient is a result of the decreased band gap as discussed in chapter 2.

The values of the recombination coefficients measured here are now compared to values for other common material systems used for telecommunications lasers such as AlGaInAs and InGaAsP. The values taken from the literature are shown in Table 5.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Wavelength</th>
<th>A (s$^{-1}$)</th>
<th>B(cm$^3$s$^{-1}$)</th>
<th>C (cm$^3$s$^{-1}$)</th>
<th>Reference, Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaInNAs</td>
<td>1.3$\mu$m</td>
<td>4x10$^8$</td>
<td>3x10$^{-11}$</td>
<td>6x10$^{-29}$</td>
<td>This work</td>
</tr>
<tr>
<td>GaInNAs</td>
<td>1.5$\mu$m</td>
<td>8x10$^8$</td>
<td>6x10$^{-11}$</td>
<td>1x10$^{-28}$</td>
<td>This work</td>
</tr>
<tr>
<td>GaInNAs</td>
<td>1.3$\mu$m</td>
<td>1x10$^9$</td>
<td>1.0x10$^{-10}$</td>
<td>4x10$^{-29}$</td>
<td>[158], 2002</td>
</tr>
<tr>
<td>InGaAsP</td>
<td>1.3</td>
<td>4.5x10$^7$</td>
<td>7.2x10$^{-11}$</td>
<td>5.1x10$^{-29}$</td>
<td>[160], 1999</td>
</tr>
<tr>
<td>InGaAsP</td>
<td>1.3</td>
<td>-</td>
<td>1.5x10$^{-10}$</td>
<td>5x10$^{-30}$</td>
<td>[161], 1997</td>
</tr>
<tr>
<td>AlGaInAs</td>
<td>1.3</td>
<td>2.5x10$^8$</td>
<td>4x10$^{-10}$</td>
<td>5x10$^{-28}$</td>
<td>[162], 2002</td>
</tr>
<tr>
<td>InGaAsP</td>
<td>1.5</td>
<td>2.2x10$^8$</td>
<td>8x10$^{-11}$</td>
<td>1.3x10$^{-29}$</td>
<td>[163], 1993</td>
</tr>
<tr>
<td>InGaAsP</td>
<td>1.55</td>
<td>1.1x10$^4$</td>
<td>-</td>
<td>1.1x10$^{-27}$</td>
<td>[164], 1999</td>
</tr>
<tr>
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<td>7x10$^7$</td>
<td>-</td>
<td>1.4x10$^{-28}$</td>
<td>[164], 1999</td>
</tr>
<tr>
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<td>6.7x10$^7$</td>
<td>-</td>
<td>3x10$^{-24}$</td>
<td>[164], 1999</td>
</tr>
<tr>
<td>InGaAs</td>
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<td>-</td>
<td>-</td>
<td>1.57x10$^{-29}$</td>
<td>[165], 2007</td>
</tr>
</tbody>
</table>

Table 5.1 Recombination coefficients for GaInNAs, InGaAsP AlGaInAs, and InGaAs at room temperature for 1.3$\mu$m and 1.5$\mu$m, data taken from the literature. The error in the values obtained in this work have the following order of magnitude $C>B>A$ where the error in $C$ may be as large as 50% and the error in $A$ may be as large as 20%.

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From Table 5.1 we can see that the large Auger recombination coefficient seen from this study for GaInNAs devices is a common problem for semiconductor laser devices emitting within this wavelength range based on different material systems. The comparison of this data shows that the Auger coefficient at 1.5\textmu m is of a similar magnitude for the different materials. This shows that Auger recombination is a generic problem at the telecoms wavelengths.

The $A$ coefficient is higher in the GaInNAs devices reported here but there appears to have been a measurable improvement in this over recent years, when comparing the 1.3\textmu m device reported here and the previous work of the group. This shows promise for the future development of this material system.

In spite of the high defect and Auger currents is should be stated that GaInNAs offers several advantages over conventional InP based materials, the GaInNAs devices are grown on GaAs and the superior wave guiding provided by Al(GaAs) more than compensates. This growth Allows for SQW lasers to work at RT which is not possible for InP based devices which typically require $>4$QWs. The growth on GaAs additionally allows for the routine growth of VCSELs at important telecommunications wavelengths, which would have significant benefits over the InGaAsP devices in terms of cost effective laser production.

### 5.6 The use of antimony

It has been suggested that the incorporation of antimony into GaInNAs should reduce the threshold current [7]. To investigate this further a device emitting at 1.49\textmu m was obtained from Stanford University, the details of the devices can be found in [107].

This device was compared to the 1.51\textmu m Infineon device. The GaInNAsSb device was initially studied utilising the same techniques as the GaInNAs device, with its threshold current being broken down into the current flowing through each constituent recombination path. The comparison of the magnitudes of the recombination paths for these two long wavelength devices is shown in Figure 5.16.
It can be seen that the threshold current densities of the GaInNAs and GaInNAsSb devices are comparable. The GaInNAs device has a slightly lower threshold current density in comparison to the GaInNAsSb device. This is due mainly to a reduced monomolecular current component in the GaInNAs device. It was expected that the use of Sb as a surfactant during the growth would have reduced the monomolecular current within these devices. However as reported in the literature, the growth of GaInNAsSb has been improved.

The Stanford group has since produced better devices which have threshold currents approximately half of those reported in this work [110]. Their progress appears to be the result of optimisation of the device annealing.

With Infineon no longer participating in the growth of GaInNAs, the long wavelength window has become dominated by the low threshold devices grown by the Harris group at Stanford with devices reported in 2006 operating at $\lambda=1.55\mu m$ with $J_\text{th}=550A/cm^2$ in comparison the next best Infineon at $\lambda=1.51\mu m$ with $J_\text{th}=780A/cm^2$ in 2005. It is unclear if further developments will be made with GaInNAs lasers.
5.7 Conclusion

An investigation of a number of MBE grown GaInNAs devices within the wavelength range 1.3μm to 1.5μm has shown that at room temperature the threshold current of these devices increases as the emission moves to longer wavelengths. This increase in $J_{th}$ with wavelength is caused by the presence of both Auger and monomolecular recombination in the devices, where Auger dominates both $J_{th}$ and $T_0$ over the entire wavelength range.

An investigation of the $Z_{th}$ values for a number of devices showed that the carrier density dependence of the threshold current pins at a value of 3 at high temperatures indicating that Auger recombination is the dominant current path in these devices at room temperature. This result is also a good indication that there is no significant carrier leakage present in these structures.

Measurements of the temperature dependence of the individual current paths around room temperature showed that the $T_0$ of the Auger current is only ~50K, this shows that the large Auger current in these devices is also the primary cause of the low $T_0$ of GaInNAs lasers in this wavelength region. This investigation also showed that the $T_0$ of the monomolecular recombination path is relatively high (~150K), and that its presence increases the $T_0$ of the devices. As a result it was suggested that the presence of monomolecular recombination was the cause of the high $T_0$ seen for a number of the literature results devices reported in chapter 3 which also exhibited a high $J_{th}$.

From the measurements of the room temperature ratios of the current components at threshold it is clear that over the 1.28μm - 1.51μm wavelength range studied the Auger current is never less than ~60% of the threshold current. The monomolecular current always makes the next largest contribution to the threshold current with a value of between 25% and 40% of the threshold current over this wavelength range. The radiative current barely rises above 10% of $J_{th}$ over the 1.28μm - 1.51μm wavelength range and as such has no significant effect on device performance.

It was also seen that the large magnitude of the Auger component in the 1.5μm lasers is caused by a large $C$ coefficient, this however, is of similar magnitude to that of InGaAsP and AlGaInAs devices at the same wavelength. In spite of this, we note that the GaInNAs devices work well with a SQW suggesting that MQW devices may, in
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fact, be better than the standard MQW InP based lasers. These similar Auger components along with the superior wave-guiding provided by the GaAs/AlGaAs/ system makes GaInNAs devices very promising over this wavelength range.

We also found that the $A$ coefficient can vary significantly from sample to sample and that careful control of the growth is needed to reduce it, if GaInNAs is to be a commercially viable material. These results are promising for this material system.
Chapter 6

Pressure Dependence of the lasing wavelength and threshold current of GaInNAs devices

6.1 Introduction

The application of hydrostatic pressure is used to increase the direct band gap of III–V semiconductors in a way very similar to alloying. The use of high pressure methods with semiconductor lasers enables continuous tuning of the band gap, in an easily controlled way. Since carrier recombination mechanisms, such as radiative and Auger, have a strong band gap dependence, the application of high pressure is a powerful tool when used to investigate the importance of these processes within devices. Within this investigation, hydrostatic pressure will be applied using the helium gas compressor system described previously in chapter 4.

6.2 Hydrostatic pressure dependence of the lasing energy

For this study hydrostatic pressure has been applied to three of the MBE grown single quantum well GaInNAs lasers. These samples were a 1.3μm device (sample number 24269), a 1.4μm device (sample number 24316–m1) and a 1.5μm device (sample number 24888-1). Information on the device structure and composition can be found in Appendix 2.

The lasing energy of these devices was measured at room temperature at a pulsed current equal to 1.2 times $J_{th}$ at each pressure. The variation of $E_{Laser}$ with pressure was then studied as shown in Figure 6.1.
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From Figure 6.1 it can be seen that the measurements are reversible and hence that the effect of hydrostatic pressure is not damaging the devices. This reversibility was also confirmed by studying $J_{th}$ of these devices and it again was seen to be unchanged after the pressure studies were completed.

Figure 6.1 shows calculations using the BAC model to predict the change in the lasing energy with pressure (where $\text{d}E/\text{d}P$ was taken to be 7.5meV/kbar for the GaInAs host and 3meV/kbar for the N – level[155]), it can be seen that these calculations are a good fit to the experimental data. For these calculations the value of $C_{MN}$ was set at 3.05eV for the devices with 2.5% nitrogen, this was increased to ~4.5eV for the devices with 3.91% nitrogen.

From Figure 6.1 it can also be seen that the rate of change is different for the different emission wavelengths, the rate of change is largest for the 1.5μm device at 8.5meV/kbar, the rates for the 1.3μm and 1.4μm devices are 7.6meV/kbar and 7.4meV/kbar respectively. These different rates of change are already showing the interesting effects of the nitrogen level – conduction band interaction present within this material.

This exercise clearly illustrates that pressure can be used to change the band gap of these devices in a controlled manner.
6.3 The effect of pressure on 1.3μm devices

In order to further investigate the recombination rates within the GaInNAs material system, the effect of hydrostatic pressure on the threshold current density of the devices has been studied. This effect has initially been investigated with the 1.3μm devices (sample number 24269). The variation of the threshold current density of these devices versus the applied pressure is plotted in Figure 6.2.

![Figure 6.2 The change in the threshold current density with changing pressure for the 1.3μm GaInNAs devices at room temperature](image)

From Figure 6.2 it can be seen that the change in $E_g$ caused by the application of pressure has resulted in a rapid rise in $J_{th}$. The rate of increase of $J_{th}$ with pressure is $\sim 15$ A/cm²/kbar. In a linear approximation this equates to an increase in $J_{th}$ of $\sim 2.5$ kA/cm²/eV. In order to understand the change in $J_{th}$ of these devices, the variation of $E_g^2$ is compared with $J_{th}$ as can be seen in Figure 6.3. It is assumed that the radiative current $I_{rad}$ is proportional to $E_g^2$. In previous work on 1.3μm GaInNAs lasers this was found to be valid up to pressures of 6 kbar [149]. To calculate the value of $E_g^2$ it is assumed that the lasing energy of the device corresponds to the band gap to of the device.
From Figure 6.2 and Figure 6.3, it can be seen that threshold current of these devices is increasing rapidly with pressure, and that the rate of this increase is in excess of $E_g^2$. This result indicates that if the radiative current is following $E_g^2$ then the rapid rise in the threshold current must be due to a change in either one or both of the monomolecular and Auger currents.

To understand this variation of the threshold current work previously carried out on a similar 1.3µm device must be considered [149, 166]. Within this work the observed increase in the threshold current with pressure, was explained by studying the variation of the monomolecular, radiative and Auger components with pressure, this result is shown in Figure 6.4.

From Figure 6.4 it is clear that the increase in the threshold current is primarily brought about by an unusual increase in the Auger current and to a much lesser extent the radiative current. Here it can be seen that the monomolecular current appears to be pressure insensitive, this indicates that the defects associated with the monomolecular current are deep level defects. The increased Auger current in the 1.3µm devices must be caused by an overall increase in the $Cn_a$ term.
It is known that as pressure is applied to a semiconductor material the increase in $E_g$ is primarily caused by the movement of the conduction band to higher energy. Initial measurements on GaInNAs carried out here suggest that the conduction and valence bands move apart at a rate of $\sim 7.5\text{meV/kbar}$. Reports in the literature suggest that the nitrogen band moves at a rate of at most $3\text{meV/kbar}$ [167, 168]. This will result in the CBE and nitrogen level coming closer together when pressure is applied. This trend can be seen if the variation of the bands is plotted as a function of pressure. This is shown in Figure 6.5. Clearly from this figure it can be seen that the nitrogen level and the conduction band edge/host band gap become closer as hydrostatic pressure is applied.

As a result of the increased proximity of the CB edge and the N – level there is a strengthened interaction between them. This strengthened interaction results in the conduction band of the GaInNAs taking on more N-level like characteristics resulting in an increase in the conduction band effective mass, the density of states, and thus the threshold carrier density of the device.
Chapter 6 Pressure Dependence of the lasing wavelength and threshold current of GaInNAs devices

1.75 -
1.50 -
1.25 -
1.00 -

Host Band Gap
Nitrogen Level
E Level
E+ Level
Measured E

Pressure (kbar)

Figure 6.5 Plot of calculated energy levels within 1.3μm GaInNAs laser device as a function of pressure

Figure 6.6 Theoretical calculation of the variation of $n_{th}$ as a function of pressure [149]

From calculations carried out using the 10 band $k.p$ Hamiltonian model introduced in the previous chapter, it was seen that as the pressure was increased $n_{th}$ was also seen to increase, this variation can be seen in Figure 6.6. From Figure 6.6 it is clear that this is

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a significant increase in \( n_{lh} \), as \( n_{lh} \) increases by \(-15\%\) over 10kbar. In contrast previous work on GaInAs heterostructures showed \( n_{lh} \) to be reduced by the application of pressure [169], however for GaInAs lasers \( n_{lh} \) is generally pressure independent [170].

Clearly as the Auger term is given by \( Cn_{lh}^4 \) then the change in \( n_{lh} \) must be greater than the pressure induced reduction in \( C \) in order for \( J_{Auger} \) to increase with pressure. This change in \( n_{lh} \) must therefore be responsible for the increase in the Auger term and thus the threshold current. This explains the high pressure sensitivity of the threshold current in the 1.3\( \mu \)m devices.

6.4 The effect of pressure on 1.5\( \mu \)m devices

Following this initial study into the effect of pressure on the 1.3\( \mu \)m devices and the study of the work by Jin et al. [149, 166], the effect of hydrostatic pressure on the 1.5\( \mu \)m devices (sample number 24888-1) was investigated. From Figure 6.1 it can be seen that the application of pressure was clearly changing the lasing energy of the devices, and thus the band gap. However, when the threshold current density of the 1.5\( \mu \)m devices was studied, pressure appeared to have no significant effect. This pressure insensitive threshold current can be seen in Figure 6.7.

![Figure 6.7](image.png)  
Figure 6.7 The change in threshold current density with changing pressure for the 1.5\( \mu \)m GaInNAs devices at room temperature.
In order to confirm this result the measurement was repeated several times with several devices, a number of these experiment runs can be seen in Figure 6.7. Consequently, it is clear that the applied pressure does not result in a significant change in $J_{\text{th}}$ for the 1.5\(\mu\)m devices. In comparison the 1.3\(\mu\)m devices showed an increase in $J_{\text{th}}$ of ~20% over ~10 kbar.

The study of the recombination paths in the 1.3\(\mu\)m [149] devices showed that the monomolecular current in the devices was pressure insensitive. It was also shown that the radiative current increased at rate approximately equally to $E_g^2$ up to 6 kbar, above 6 kbar the rate was in slightly in excess of the change in $E_g^2$.

We will assume again that this is the case that the radiative current in the 1.5\(\mu\)m devices, is following the variation of $E_g^2$ as may be expected due to the weaker CB-N-level interaction in the 1.5\(\mu\)m devices. The normalised $J_{\text{th}}$ and normalised $E_g^2$ have been plotted for the 1.5\(\mu\)m devices in Figure 6.8, clearly $E_g^2$ increases much more than the variation of $J_{\text{th}}$ with pressure.

From chapter 5 we know that at room temperature and pressure, $J_{\text{th}}$ for the 1.5\(\mu\)m device is composed of ~60% Auger recombination, ~30% monomolecular
recombination and ~10% radiative recombination. As it has been previously shown the monomolecular current is pressure insensitive in the GaInNAs devices, therefore the increase in the radiative current must be balanced out by Auger current.

Simple calculations of the change in the Auger current needed to balance this increase in the radiative current were carried out, the results of these calculations can be seen in Figure 6.9. Figure 6.9 shows that the Auger current must decrease with pressure at a rate of ~5% over 8 kbar.

The cause of the major change in $J_{\mu}$ for the 1.3µm devices with pressure was a change in the Auger current. In the 1.3µm devices, the Auger current unusually increased with pressure due to the large increase in $n_{\mu}$ with increasing pressure. This was due to the pressure-induced increase in the conduction band effective mass as a result of an increased interaction between the conduction band edge and the nitrogen level. The resulting increase in $n_{\mu}$ was greater than the decrease in the Auger coefficient, $C$, and since the Auger current is proportional to $Cn_{\mu}^2$, this meant that $J_{\mu}$ increased with pressure in the 1.3µm devices.

In contrast, for the 1.5µm devices the nitrogen level – conduction band separation is initially ~100 meV greater. Thus the interaction is smaller and less pressure dependent for the 1.5µm devices. This results in a smaller increase in $n_{\mu}$ with pressure.
The weaker repulsion from the nitrogen level for the 1.5μm device is confirmed by band structure calculations [171] of the conduction band effective mass for the two samples which show that the effective mass in the 1.3μm device \( m_e^* = 1.21m_i \), where \( m_i \) is the effective mass of GaInAs of that indium fraction) is higher than the 1.5μm device \( m_e^* = 1.11m_i \) illustrating that there is a larger interaction with the nitrogen level in the 1.3μm samples. This reduced interaction can also be seen in the variation of the lasing energy, as shown in Figure 6.10, where it can be seen that the rate of change in the lasing energy in the 1.3μm devices is sub-linear indicating a strong interaction, whereas in the 1.5μm devices the change in lasing energy is linear indicating that there is a smaller interaction between the nitrogen level and the conduction band.

![Figure 6.10](image)

Figure 6.10 The variation of the normalised lasing energy versus pressure for the 1.3μm and 1.5μm devices

The result of this reduced interaction is that the increase in \( n_L \) with pressure should be smaller for the 1.5μm devices, as the conduction band edge in these devices will not have as much N-level character.

### 6.5 The effect of pressure on 1.4μm devices

When the effect of pressure on the 1.4μm lasers (sample number 24316–m1) is studied another trend is seen. In the case of the 1.4μm devices the threshold current is seen to be initially slowly decreasing with pressure this rate of change increases, then
about 4 kbar threshold current levels out, and then at 7 kbar begins to increase. This trend can be seen in Figure 6.11.

As seen previously for the 1.3μm and 1.5μm devices the radiative current approximately follows the variation of $E_g^2$ and the monomolecular current is pressure insensitive. Therefore the observed variation of the threshold current with pressure must be due to the variation of the Auger current in addition to the increase in the radiative current within the device.

From Figure 6.11 it is clear that $E_g^2$ increases thus there is an increase in the radiative current. The threshold current of this device is dominated by the variation of the Auger current.

The Auger current variation needed to balance the increase in the radiative current and produce the trend measured for the threshold current was calculated and is shown in Figure 6.11. It is believed that this unusual variation of the Auger current is again due to the variation of the nitrogen level conduction band interaction.

However, upon investigation of the band structure of these 1.4μm devices the splitting of the nitrogen level and the conduction band is initially the same as in the 1.3μm devices as the indium fraction is the same, however because of the increased amount
of nitrogen incorporated in these devices the $E_-$ level has been pushed to a ~100meV lower energy level.

If we return to the variation of the lasing energy with pressure shown in Figure 6.1, we see that the lasing energy changes at the same rate for both the 1.3µm and 1.4µm devices, as a consequence it may be assumed that the variation of $n_n$ versus pressure will be identical for these two devices. In order to produce the variation in the Auger current seen in Figure 6.11 the Auger coefficient $C$ must be changing much quicker for these 1.4µm devices in comparison to the 1.3µm devices, this may be possible due to the smaller band gap of these devices and larger variation of the Auger coefficient which will result.

These changes in the $C$ coefficient along with the rapid increase in $n_n$ are responsible for the unusual behaviour of the calculated Auger current within these devices, and thus the unusual behaviour of $J_{th}$ for these devices.

### 6.6 Investigation of the Auger coefficient

Using the information about the variation of the Auger current of the 1.4µm device, the variation of the Auger coefficient $C$ was calculated assuming that the pressure dependence of $n_n$ for the 1.4µm was approximately equal to the behaviour of $n_n$ in the 1.3µm device. The variation of the normalised $C$ coefficient was determined to have the shape shown in Figure 6.12 for the 1.4µm device. This variation of the Auger coefficient is of similar shape to those seen for other materials within this wavelength range [172].

Calculations of the splitting of the $E_-$ and the $E_+$ levels as a function of emission wavelength for these devices show that as the wavelength is increased, the magnitude of this splitting becomes of the same order as the band gap. This variation can be seen in Figure 6.13. This splitting of the $E_-$ and the $E_+$ levels may allow a higher proportion of recombination through the CHCC Auger mechanism. This is thought as when the separation of the $E_-$ and the $E_+$ levels becomes close to $E_g$ the levels will supply many more states for the transition of an excited electron as needed for a CHCC process.
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Figure 6.12 Variation of the normalised C coefficient for the 1.4μm device.

The dominant Auger mechanism was calculated to be CHSH for the short wavelength 1.3μm devices studied in reference [149] by Andreev in [73] this has also been observed in other material systems over this wavelength range [173]. This highlights that it maybe possible that there is transition between the two Auger mechanisms as the emission wavelength of the GaInNAs material is increased.

Figure 6.13 Comparison of the variation of $E_g$ versus $\Delta E_+ - E_-$ as a function of emission wavelength.
By repeating this analysis of the Auger coefficient for the 3 devices, normalising these together, and including the values of $C$ measured in chapter 5 ($1.2 \times 10^{-28} \text{ cm}^6 \text{s}^{-1}$ for 1.5$\mu$m and $6 \times 10^{-29} \text{ cm}^6 \text{s}^{-1}$ for 1.3$\mu$m) the plot of the variation of the Auger coefficient can be extended to the entire wavelength range studied as shown in Figure 6.14.

![Figure 6.14](image)

Figure 6.14 Variation of the $C$ coefficient as a function of $E_g$ with the calculated variation of $C$ taken from each device.

The results for these three devices show that the interaction of the nitrogen level and the conduction band is a hugely important factor when considering the threshold carrier density and thus the threshold current of these GaInNAs devices. As at certain wavelengths its increase and the resulting increase in $n_a$ dominates the reduction of the Auger coefficient.

**6.7 Comparison of the pressure dependence of the 1.49$\mu$m GaInNAsSb device and the 1.5$\mu$m GaInNAs device**

If we return to the comparison of the GaInNAs and GaInNAsSb material systems we can compare the pressure dependence of the threshold current for the two devices. The variation of the threshold current of the 1.49$\mu$m GaInNAsSb device as a function of pressure can be seen in Figure 6.15 together with the previously discussed data for the 1.5$\mu$m GaInNAs devices.
Figure 6.15 The pressure dependence of the normalised threshold current for the 1.49µm GaInNAsSb devices and 1.5µm GaInNAs devices

From Figure 6.15 it can be seen that the pressure dependence of $J_m$ in the 1.49µm devices appears to flat within some small scatter.

This stability of $J_m$ for these GaInNAsSb devices appears to indicate that the threshold current in these devices is also pressure insensitive, as it was for the 1.5µm GaInNAs device. The pressure insensitivity of the $J_m$ in the GaInNAsSb devices shows us that there must be very little difference in the processes occurring in the two active regions based on the two different materials. This similarity in both the pressure and temperature dependence of the 1.5µm devices measured in chapter 5 shows us that the active regions of the devices grown with the two different material systems behave fundamentally the same with almost identical performance.

This reinforces the findings in chapter 5 where the break-down of the recombination paths in both of these long wavelength devices was found to be almost identical even though the indium and nitrogen fractions have been slightly changed between the two devices. This indicates the wavelength of the device must play a large part in determining the recombination rates, once material quality is removed as an issue.
6.8 Conclusions

In this chapter the effect of hydrostatic pressure on the emission wavelength and threshold current of GaInNAs lasers was investigated. It has highlighted the unusual nature of this material. Here we find that the nitrogen level – conduction band interaction has a significant impact on the performance of the devices.

In the 1.3μm devices, the interaction was large enough that it caused a large increase in the threshold carrier density of the devices when pressure was applied. This increased $n_{th}$ resulted in an increase in the Auger current within the devices. The magnitude of this increase in Auger current was enough to cause a 20% increase in the threshold current over 10 kbar.

For the 1.5μm devices, the nitrogen level – conduction band interaction was smaller and as such did not result in an increase in the Auger current within this device. In fact for the 1.5μm devices the strength of the interaction was such that the threshold current appeared to be pressure insensitive. There was no significant change in $J_{th}$ observed over 8 kbar. This pressure insensitivity was due to the opposing changes in $C$ and $n_{th}$ with pressure.

When the threshold current of a similar long wavelength GaInNAsSb device was studied, it too was found to have a similar pressure independent $J_{th}$. This again reinforced the findings in chapter 5, that the GaInNAsSb and GaInNAs devices being studied here are almost identical in terms of performance.

The 1.4μm device showed an unusual decrease in its threshold current followed by an increase, reaching a minimum at ~5 kbar corresponding to a lasing wavelength of 1340nm. This variation of $J_{th}$ is very unusual over such a small pressure range of just 9 kbar. The behaviour of $J_{th}$ in this device was also closely attributed to the nitrogen level – conduction band interaction. The magnitude of the increase of this interaction was seen to increase at the same rate for the 1.4μm and 1.3μm devices, indicating that $n_{th}$ in the 1.4μm device should vary in a similar way to that of the 1.3μm device. It was also seen that the variation of the Auger coefficient played a part in the variation of $J_{th}$ for these devices.
The variation of the Auger current for these devices was calculated. These calculated values along with the calculated variation of $n_0$ were used to determine the variation of the Auger coefficient with band gap, $C$ was seen to vary as expected from 1.1 eV to 0.88 eV at this energy the $C$ coefficient was seen to jump by $\sim 30\%$ in 0.02 eV indicating there may be an unusual effect occurring.

Calculations of the splitting of the $E_-$ and the $E_+$ levels seemed to suggest that it was possible that the dominant Auger mechanism could change from CHSH at short wavelengths to CHCC at longer wavelengths. However we do not observe an abrupt increase in $J_{th}$ for the 1.5 $\mu$m devices.

This investigation showed that the effect of the nitrogen level – conduction band interaction is well simulated by the BAC model. Using this model the $C_{\text{AV}}$ was determined for the devices, it was found to be $\sim 3$ eV for the devices with 2.5% nitrogen and $\sim 4.5$ eV for the devices with 3.91% nitrogen.

It has also been highlighted that this interaction is a very important factor for consideration when attempting to grow GaInNAs active regions. As such it will need to be investigated and utilised when attempts are made to reduce the Auger recombination component of the threshold current of these devices to allow commercialisation of this material at longer wavelengths.
Chapter 7

MBE Device optimisation

7.1 Introduction

It is possible to optimise GaInNAs devices by changing a number of parameters as outlined in the literature review provided in chapter 3. There are many variables which can be considered, such as the annealing conditions, the incorporated QW strain or the barrier material composition. Within this chapter, two important device parameters will be investigated; firstly the choice of barrier material (composition and band gap) will be studied and secondly the influence of the quantum well strain on the device performance will be investigated.

7.2 Barrier structure variation

7.2.1 Introduction to Barrier structure variation

A change of the band gap of the barrier will result in a change of the offset between the conduction and valence bands of the quantum well and those of the barrier, resulting in a change to the carrier confinement within the quantum well, this will directly affect any carrier leakage.

The main concern with GaInNAs, in respect to carrier leakage is principally the leakage of holes. The conduction band offset is believed to be too large to allow electron escape [37], however the valence band offset in a device with a GaAs barrier is only of the order of 150meV [120, 174, 175]. Whilst this is still ~6kT at RT, it has been suggested that holes may be able to escape from the valence band in the quantum well into the valence band of the barrier layers[120].

Within the literature there are three types of barrier that are commonly used with GaInNAs quantum wells, these are; GaAs, GaNAs and GaAsP. As outlined in chapter
3 the \( J_{\text{th}} \) reported with each of these barriers has been seen to vary greatly. It was suggested that GaAsP barriers have the highest hole confinement potential [120, 176] due to the larger band gap. This was believed to be the reason the devices grown by the Tansu group had the lowest \( J_{\text{th}} \) [63]. However, these devices have recently been surpassed in terms of \( J_{\text{th}} \) by devices with GaAs barriers [49]. These results however do not resolve the debate on which material is the best barrier material. They in fact give little insight into the affect of the barrier on carrier leakage, as several studies trying to determine the best barrier material through growth and comparison of multiple devices introduce problems associated with reproducibility of the growth. Therefore it is useful to study theoretical literature on the subject.

The effect of the barrier band gap has been studied theoretically by Healey et al. [175]. Healy et al. studied the effect of using GaAsP barriers instead of the usual GaAs barriers, here they used a P concentration of 0.15. This is the same barrier composition that was used by Tansu et al.. Healy et al. used a 10 band \( \mathbf{k.p} \) Hamiltonian and a Poisson solver to calculate the effect of electrostatic confinement in GaInNAs lasers.

It was found that the inclusion of the electrostatic forces within the model significantly reduced the hole leakage within the material. The electrostatic attraction of the highly confined electrons in the conduction band significantly increased binding to the holes within the quantum well. They observed that using GaAsP barriers with larger band gap, instead of GaAs barriers had little effect on the calculated device performance. The columbic attraction between the electrons in the conduction band and the holes in the valence band greatly outweighs any small benefit from the increased valence band offset provided by the change in barrier material from GaAs to GaAsP. Healy et al. stated that the low threshold currents achieved by the Tansu group with the use of GaAsP barriers [46, 63, 99, 177-179] were most likely due to a reduced monomolecular current as these devices also have a reduced amount of nitrogen incorporated within the quantum well. This is in agreement with work shown in previous chapters where the increase in the nitrogen content appears to result in an increase in the monomolecular recombination. This is also consistent with the results shown in chapter 5 where the \( Z_{\text{sh}} \) of the devices was
seen to pin at a value of 3 indicating that there was no significant carrier leakage within these devices around room temperature.

Within this study, we will look at another common barrier material system used in the growth of GaInNAs QW lasers, namely GaNAs. The use of GaNAs barriers is common when growing GaInNAs devices [120, 129, 180-184]. GaNAs is used as initially it is easy to grow as there are no additional sources required for its growth in comparison to GaAsP barriers which require an additional P source. Another reason for the use of GaNAs barriers is that when they are used there is a reduction in the blue shift seen after the thermal annealing of devices, this is believed to be the result of reduced out diffusion of nitrogen from the quantum well [120, 134].

7.2.2 Devices used to study the effect of barrier variation

The devices studied are single quantum well broad area 100μm oxide stripe lasers, with cavity lengths of 1200μm. These devices were grown by Infineon and further sample information is given in appendix 2. Sample 24888-1 is the device with nitrogen free GaAs barriers and sample 24555-1 is the sample with GaNAs barriers, (N=2.5%). The device with GaNAs barriers had a lasing wavelength of 1.47μm and the device with GaAs barriers had a lasing wavelength of 1.51μm, at room temperature. The device with the GaNAs barrier has a 320 meV smaller barrier band gap, this results in a 50 meV reduction in the valence band offset [120].

It has been suggested that the incorporation of nitrogen into the barrier around the quantum well of a device should improve the device performance by reducing the defect density at the quantum well barrier interface [121, 185]. This reduction in the number of defects is thought to be caused by a number of effects; the tensile strain incorporated in the GaNAs barriers reduces the strain at the interface, additionally the presence of nitrogen in the barrier reduces the diffusion of nitrogen during annealing resulting in improved material quality.

An investigation of the threshold current and its constituent parts, should give an indication if this is the case. In spite of the improved performance in terms of a reduced monomolecular current the reduced barrier height of the GaNAs barrier devices should also increase any leakage present. However according to the theory of the Healy et al. [175] this will be negated by coulombic effects.
7.2.3 Measured effect of barrier variation

In order to investigate the outlined possibilities we have studied the temperature dependence of the threshold current for the two devices, the results of this investigation can be seen in Figure 7.1.

![Graph showing the variation of the threshold current density with temperature.](image)

**Figure 7.1** The variation of the threshold current density of the devices (GaAs barrier closed symbols and GaNAs barrier open symbols)

Figure 7.1, shows that there is a reduction in the threshold current for the GaNAs barrier devices, however the magnitude of this reduction decreases at higher temperature. Clearly within this temperature range the use of GaNAs as the barrier material appears to have decreased the threshold current density of the devices.

When the $T_0$ of the devices is studied (shown in Figure 7.2 ) using the technique described earlier, it is observed that the $T_0$ of the devices has been reduced with the change to GaNAs barriers.

In chapter 5 it was shown that the presence of monomolecular current has the effect of artificially improving the temperature stability of the devices increasing the $T_0$. Therefore it is plausible that the change in barrier material has had the effect of reducing both $J_m$ and $T_0$ through a reduction of the monomolecular current.
Temperature (K)

Figure 7.2 $T_0$ of the threshold current of the GalnNAs devices with GaAs and GaNAs barriers over the 50K -300K temperature range.

The investigation of the spontaneous emission from these devices will give further insight into the magnitude of the change in the monomolecular current. The study of the spontaneous emission will also indicate if the other recombination paths have been affected by this change in barrier material. To analyse the spontaneous emission we have again used the technique described in chapters 2 and 4 to determine the monomolecular current component within these GaNAs barrier devices, this is then compared to that obtained from the GaAs barrier devices and is shown in Figure 7.3.

From Figure 7.3 it can be clearly seen that the monomolecular current is reduced by $\sim 15\%$ in the device with GaNAs barriers. This reduction in the monomolecular current clearly explains the reduction in the threshold current seen in the initial measurements of $J_{th}$ it would also explain the reduction in $T_0$ observed.
Further to this study of the monomolecular current an investigation was carried out to study what, if any, other effects the changing of the barrier material has had on device performance. To do this we have investigated the value of $Z$ at threshold ($Z_{th}$) for the devices, this data can be seen in Figure 7.4.

From the investigation of $Z_{th}$ we see that there has been little change in the value within experimental error at low temperature. However, for temperatures above 150K, $Z_{th}$ has in fact decreased in the GaNAs barrier devices. This change suggests that the change in barrier must have affected the other processes within the device. $Z_{th}$ is however similar at room temperature, indicating that this effect may only be prevalent at low temperatures. To further explore this variation the threshold current with the monomolecular current removed has been studied, as can be seen in Figure 7.5.
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Figure 7.4 The temperature dependence of the $Z_{th}$ for the devices (GaAs barrier closed symbols and GaNAs barrier open symbols)

Figure 7.5 The threshold current variation with the monomolecular current subtracted

From Figure 7.5 it is clear that there is a region from ~150K to 200K where the increase in this current is significantly lower in the devices with GaNAs barriers, this region can also be identified on the $Z_{th}$ plot. In order to understand these unusual
changes in the temperature dependence, the break-down of the threshold current of the 
device was studied for the additional current paths, as can be seen in Figure 7.6.

From Figure 7.6 it is clear that Auger current does not start to become dominant in the 
GaNAs barrier device until slightly higher temperatures. This reduction in the Auger 
current is consistent with the slightly shorter wavelength. When the study of the 
pressure dependence of the 1.51μm device carried out in chapter 6 is considered it can 
see that in order to achieve a change in lasing wavelength from 1.51μm to 1.47μm an 
applied pressure of 3.4 kbar would be required. From the calculations of the change in 
the Auger current of these devices it can be seen that the Auger current would be 
reduced to a value of 625 A/cm² if 3.4 kbar where applied, this value is very close to 
the measured value of 615 A/cm². Taking into account the experimental error of ± 50 
A/cm² on these values this calculated variation of the Auger current appears to be 
acceptable, and thus this change in the Auger current is due change in emission 
wavelength.

This reduction in Auger current path explains the reduction seen in the $Z_{th}$ values as 
the barrier material is changed. The range of temperatures were there are large gaps 
differences in the values reported for the GaAs and GaInAs barrier devices seen in 
Figure 7.5 and Figure 7.6 can be attributed to the later switch on of this Auger current.
The change in the Auger current is due primarily to the change in the emission wavelength of the devices with the GaNAs barrier.

This study of the use of GaNAs as a barrier material has shown that it can improve the threshold current through a reduction of the monomolecular current. This agrees with the hypothesis in the literature [121, 185]. This work also supports the work of Healy et al. in confirming that a small change in the valence band offset produced by changing the barrier has little effect on carrier leakage and does not introduce any significant benefits into the device. This change in the barrier band gap must therefore be negligible in comparison to coulombic effects.

7.3 Investigation of the effect of incorporated strain

7.3.1 Introduction

One of the important and unique features of the GaInNAs material system is the ability to produce devices with tailored wavelength and strain as shown previously in Figure 1.3. When the ratio of nitrogen and indium is considered, a ratio of ~3In to 1N is needed for 0% strain growth on GaAs [186]. Any deviation from this ratio results in strain being incorporated in the quantum well.

7.3.2 Effect of strain on ~1.5μm devices

Within this section the effect of strain on two particular ~1.5μm devices will be studied. The two devices are a 1.43μm device, sample number (24317M1) and a 1.51μm device, sample number (24448). The nitrogen composition in both of these devices is 3.9%. The indium content is 34% in the 1.43μm device and 40% in the 1.51μm device. The result of this difference in the indium composition is that there is ~0.05% less compressive strain in the shorter wavelength device (this value was calculated by approximating the GaInAs system as there was no change in the nitrogen composition). A result of the lower strain in the 1.43μm device is that there should be a higher $n_\text{th}$. This in theory will lead to increased Auger and radiative currents and therefore a higher threshold current. As the nitrogen content of the devices has not changed the monomolecular recombination coefficient $A$ of the devices is not expected to have changed. Measurements of the threshold current of the two devices
show that $J_{th}$ is lower in the 1.51\,\mu m device for all temperatures as expected, this variation of $J_{th}$ can be seen in Figure 7.7.

![Figure 7.7 Temperature dependence of the threshold current for the 1.51\,\mu m and 1.43\,\mu m device](image)

However, the magnitude of the difference at low temperatures is unexpected, as we expected little difference in the monomolecular current coefficient $A$ of the devices. This large difference in $J_{th}$ at low temperatures maybe due to a change in the monomolecular current content or a reduction in the radiative current in the device with the higher strain.

The increase in the difference of threshold current as the temperature is increased also indicates that more of the threshold current in the lower strained 1.43\,\mu m devices is going through a highly temperature sensitive current path, this will most likely to be Auger current. This result is perhaps initially unexpected as the emission wavelength of this device is 80nm shorter. In order to understand these variations of the threshold current a full analysis of the composition of the threshold current of the devices was undertaken, the results of this study can be seen in Figure 7.8.

From the break-down of the threshold current into it components, shown in Figure 7.8, it can be seen that the reduction in $J_{th}$ within the 1.51\,\mu m device is caused primarily by changes in the Auger and the monomolecular current components. In the 1.43\,\mu m device the Auger and the monomolecular currents are almost twice that of the
1.51μm device. There is no significant change in the magnitude of the radiative current.

![Break-down of threshold current for the 1.51μm device and the 1.43μm device](image)

The fact that the nitrogen content of the devices has not changed suggests that the $A$ coefficient should not have changed, the increase in the monomolecular current must therefore be due to an increase in the value of $n_{th}$. This increase in $n_{th}$ is to be expected as a result of the lower stain in the 1.43μm device. By assuming that $A$ is unchanged we can calculate the change of $n_{th}$ when the strain is changed, this is shown in Figure 7.9.

This calculation of the ratio of $n_{th}$ in the two devices was carried out by comparing the monomolecular current of the devices assuming that the $A$ coefficient had not changed. From this calculated ratio of $n_{th}$ we can calculate the value of $n_{th}$ in the 1.43μm devices using the values of $n_{th}$ calculated for the 1.5μm device in chapter 5.

If we use these calculated values of $n_{th}$ for the 1.43μm device, and the data for the Auger component of the 1.51μm devices, we can calculate the change in the Auger coefficient when moving from the 1.51μm device to the 1.43μm device. This was achieved by using a least-squares fit to solve for $x$ in the following $C(T)_{1.4} = xC(T)_{1.5}$ allowing the calculated Auger to lie on the measured values. From this $x$ was found to be 0.55 indicating a reduction of the Auger coefficient in the 1.43μm devices to
55% of Auger recombination coefficient the 1.5μm. The resultant calculated Auger current can be seen in Figure 7.10.

Figure 7.9  Threshold carrier density difference of the two devices shown as threshold carrier density (1.5μm/1.43μm)

Figure 7.10  Auger current contributions for the devices and an Auger value calculated for 1.4μm devices using the threshold carrier density variation calculated above and a C coefficient of 0.55 of the 1.5μm value.
A rearrangement of the equation for the threshold current (2.16) gives the following condition, assuming that A is the same for both structures.

$$\frac{J_{\text{Auger}(1.4)}}{J_{\text{Auger}(1.5)}} \times \left[ \frac{C(1.5)}{C(1.4)} \right] = \left[ \frac{J_{\text{mono}(1.4)}}{J_{\text{mono}(1.5)}} \right]^3$$

If we solve this to find a value for $C(1.4)$ using the measured values for the other variables, we find that $C(1.4) = 0.55 \times C(1.5)$ which is within 5% to the value calculated above from the fitting of the variation $C$. This value of $C = 7 \times 10^{-29} \text{cm}^6 \text{s}^{-1}$ was then compared to the plot of calculated $C$ from chapter 6 (Figure 6.14). From this plot it is seen that the value calculated here is close to the measured value for this wavelength.

This reduction in $C$ is as a result of the shorter emission wavelength of the devices and thus the lower probability of Auger in these devices. However, even with the lower Auger coefficient, $C$, these devices still have a higher Auger current, resulting from the higher $n_h$ value. This shows that the main effect of the additional strain is to reduce the Auger current in the GaInNAs material.

This work clearly shows the benefit of the reduction in the $n_h$ given by the additional stain and beneficial effects that it can have on $J_{\text{th}}$. This controllable strain is a characteristic of the GaInNAs material system that can be put to use to reach low threshold, long wavelength emission.

### 7.4 Conclusions

The study of the effect of changing the barrier material shows that small changes in the barrier height have little effect on the device performance in terms of carrier leakage. This was in agreement with the literature and in particular the work of Healy et al.\[175\], confirming that the electrostatic attraction of the highly confined electrons in the conduction band prevents the holes from escaping out of the valence band.

The main consequence of the change from GaAs barriers to GaNAs barriers was seen to be a $\sim 15\%$ reduction in the monomolecular current component, this reduction is most likely due to improved barrier – quantum well interfaces.
Chapter 7 MBE Device optimisation

The study within the second part of this chapter on the effect of the strain incorporated in the quantum well highlights the benefits of strain on the threshold carrier density of the devices, as originally suggested in 1986 [20, 21]. This work on the effect of strain shows that strain can be a useful tool for reducing $n_{th}$ and as a result reducing the threshold current.

In chapter 5 it was shown that the magnitude of the Auger coefficient of the GaInNAs devices was of similar value to that of the other active region materials for emission at this wavelength, however the tunability of the strain in the GaInNAs material may allow for $n_{th}$ to be reduced in comparison to the other materials, resulting in a lower Auger current at threshold for this material.
Chapter 8

Investigation of the threshold current of MOCVD grown GaInNAs

8.1 Introduction

As outlined within the introduction chapter the production of today's quantum well lasers was dependent upon the development of the modern growth techniques that are now used. The two main techniques currently used are MBE and MOCVD (MOVPE). The majority of the GaInNAs samples grown to date by the scientific community have been grown utilising MBE. However, if commercialising this material is an objective, growth utilising MOCVD would be beneficial as it provides a lower cost, high production route.

Within this chapter, the variation of the threshold current within a number of MOCVD grown devices will be investigated. These results will then be compared to the MBE device previously studied and the literature values from chapter 3. This investigation will be carried out with a view to studying any differences in the devices present due to the different growth techniques.

8.2 MOCVD devices

A set of MOCVD grown samples were obtained from the University of Marburg, Germany, these devices were grown within the temperature range 300°C to 550°C. The detailed composition and structural details of these samples is shown within Appendix 3. The samples were all single quantum well devices grown under nominally identical growth conditions, the indium fraction was maintained about 30% and the nitrogen fraction of the devices was varied from 0% to 1.2%, in order to obtain a red shift of the emission wavelength.
Chapter 8 Investigation of the threshold current of MOCVD grown GaInNAs

The study of these samples will allow us to further analyse the effect of adding nitrogen to the active region of a GaInNAs device, and to further investigate the effect of moving from shorter to longer wavelengths within the GaInNAs material system.

These devices will be compared to the MBE samples previously investigated in this thesis, to determine if there any clear differences present in samples grown by the different techniques.

8.3 Threshold current variation of MOCVD samples

Initial investigations of the threshold current of these MOCVD samples were carried out at room temperature and as a function of emission wavelength. The results of this study are shown in Figure 8.1.

From Figure 8.1 it can be observed that the threshold current of these devices increases as the emission wavelength is increased. This trend was also evident in the Infineon grown MBE devices shown in chapter 5. The comparison of the $J_m$ values of the Marburg MOCVD grown lasers to the $J_m$ values of the Infineon MBE grown samples (seen in Figure 5.1), shows that the threshold current densities in the MOCVD grown devices are much higher than in the MBE samples. The threshold current was seen to increase 6 fold over 350nm for the MBE grown devices, the
increase in the MOCVD was ~10 fold over ~150nm, this is a significant rise in the rate of increase in the threshold current.

When these values of $J_{th}$ are compared to the best $J_{th}$ values reported in the literature at 1.3μm for MOCVD grown devices (~210-250A/cm² [63, 99, 126]) it is clear that these values are significantly higher. In the literature, the lowest reported value at 1.3μm for a MOCVD grown device is a mere 210 A/cm² [63], this is lower than any of the $J_{th}$ values of these samples even though they are all at shorter wavelengths, where the dominant mechanism in the 1.3μm devices, Auger recombination, will be much reduced.

The cause of these much larger threshold currents for the MOCVD devices will be investigated, as this may give insight into fundamental problems associated with the MOCVD growth of GaInNAs.

8.4 Analysis of threshold current components

To study the large difference between the obtained threshold currents and the typical reported threshold currents we have considered the constituent components of the threshold current. The threshold current was split into the constituent parts using the fitting of a $Z=1$ region to determine the magnitude of the monomolecular current and a $Z=2$ region to determine the magnitude of the radiative current. This method was necessary as these devices were only studied at room temperature and the variation of the pinning level was not available to quantify the radiative current of the devices.

In order to ensure that the application of this technique was an acceptable measure of the radiative current, the MBE devices previously investigated, were studied again using this $Z=2$ technique. The results obtained for the devices were within 4% of the values initially measured utilising the pinning level technique to determine the radiative current. This was therefore deemed to be an acceptable technique. The break-down of the threshold current obtained using this method is shown for a selection of the MOCVD, the devices in Figure 8.2. The devices chosen were the device with out nitrogen (GaInAs), and two of the GaInNAs devices. These where chosen as the variation of the threshold currents of these samples had the smallest deviation from sample to sample.
From Figure 8.2 it is clear that the current path exhibiting the most variance is the monomolecular current path, once nitrogen is introduced to the lasers. It would therefore be particularly interesting to study the defect density within these devices, in order to determine whether the increased threshold current present in all the MOCVD devices is a result purely of a high defect density.

### 8.5 Study of defect density

The photoluminescence (PL) intensity and spectral width is commonly used as a measure of material quality by growers [126, 187]. However, this can sometimes be influenced by radiative recombination via impurities, thereby making a quantitative determination of the significance of the defects very difficult.

The threshold current density of lasers can also be used to indicate material quality, but again since the threshold current consists of several terms, it cannot uniquely quantify the role of defects. By studying the monomolecular current term \((An)\) within the threshold current one can obtain an accurate indication of defect density and thus the quality of the material. The \(An\) term corresponds to the defect-related current and can be used as a quantitative indicator of the density of defects present within the...
Chapter 8 Investigation of the threshold current of MOCVD grown GaInNAS devices. This measurement of the $A_n$ term is the most accurate measure of defect density available to us.

The variation of the monomolecular current for both the MOCVD samples and the MBE samples is shown in Figure 8.3. From Figure 8.3 it can be seen that the monomolecular current increases more rapidly with wavelength in the MOCVD grown devices. The cause of this accelerated increase in the rate of monomolecular recombination within the MOCVD grown devices requires further investigation.

![](image)

Figure 8.3  Comparison of threshold and defect current in MOCVD and MBE samples

It has been suggested in the literature that the nitrogen fraction has the greatest influence on the monomolecular current due to the formation of clusters of nitrogen which act as defect centres within the device [148]. It has been shown that when the nitrogen composition is increased the threshold current of the devices increases [187]. Within chapter 5 it was seen that the monomolecular recombination coefficient ($A$) in the MBE grown devices increased as the nitrogen fraction was increased and this was seen to be a nonlinear effect.

An investigation of the variation of the monomolecular current in the MOCVD grown devices as a function of nitrogen content was therefore carried out. The results of this study can be seen in Figure 8.4.
Further investigation of the literature also suggests that the carbon content of MOCVD grown devices maybe an issue [136]. A study of the carbon concentration was therefore carried out, the carbon content was measured at Philips Universität, Marburg using secondary ion mass spectrometry (SIMS [188]). A comparison of the measured carbon content and the monomolecular current can be seen in Figure 8.5.
From Figure 8.4 and Figure 8.5 it would seem that both the nitrogen content and the carbon concentration could be related to the monomolecular current variation. It is therefore unclear whether the monomolecular current is more strongly dependent on the nitrogen fraction or the carbon concentration.

Further examination of the literature suggests that both the nitrogen content and the carbon content depend upon the growth temperature. Therefore, it is possible that the variation of the nitrogen and the carbon correlate with the growth temperature. The correlation of the carbon content and nitrogen content was therefore investigated and is shown in Figure 8.6.

In Figure 8.6 it appears that the carbon concentration is linked to the nitrogen composition. This correlation allows for the apparent fitting of the monomolecular current to both the carbon concentration and nitrogen content of the devices. It has been found in the literature that some groups have observed that the incorporation of nitrogen into the active region of GaInNAs devices increases as the growth temperature is decreased [189]. This was the drive for the initial low growth temperature. However, it has been found that the incorporation of carbon from nitrogen precursors which have not fully dissociated increases as the growth temperature is reduced [136], this indicates a possible source of the problem.
encountered here. MOCVD samples, grown at higher temperatures should therefore have less carbon incorporated within the active region.

An example of these previously published results of MOCVD grown GaInNAs lasers is given by Kawaguchi et al., Tokyo Institute of Technology (TIT) [126], these were grown at a higher temperature range from 460-550°C. The structures from TIT exhibited lower threshold currents than the Marburg samples, and are reproduced in Figure 8.7.

![Figure 8.7 Threshold current variation for the MOCVD and MBE grown devices along with the samples from * Kawaguchi et al. [126] all plotted as a function of nitrogen concentration.](image)

From Figure 8.7, it can be seen that the threshold current density of the MOVPE devices taken from [126] has a similar dependence on N content as the MBE devices. This indicates that the change in the growth temperature range has resulted in a reduction of the threshold current density. This reduction is most likely due to an improved dissociation of the precursors used in the growth and the resultant decrease in the carbon content from these non-dissociated precursors. Thus the monomolecular current component would be dependent on the carbon content.

### 8.6 Conclusions

This study of MOCVD grown devices shows that the trends seen in the MBE grown devices of increased defect current with increasing wavelength and nitrogen content
are also present in MOCVD grown devices. However the rates of these changes are much higher in the MOCVD grown lasers.

A study the threshold current and its constituent parts shows that monomolecular recombination is the dominant recombination mechanism within these devices. A study of the literature highlighted that carbon contamination may cause this high monomolecular current. Further investigation of the literature suggested that these are both associated with the low growth temperatures of the material, and a resulting non-disassociation of the nitrogen precursor. This resulted in the incorporation of N-C pairs that act as defects.

A review of the literature showed that with the utilisation of higher growth temperatures, the threshold current of MOVPE-grown devices becomes similar to that of the MBE-grown devices previously studied within this work. These MBE devices use atomic nitrogen and as such do not have this N-C problem.

This investigation therefore suggests that carbon contamination can be a problem in MOCVD devices grown at low temperatures. The result of the growth at low temperature is that there is a large increase in the monomolecular current. This is caused by the incorporation of carbon through non-dissociated precursors, most likely resulting in the incorporation of N-C groups within the active region acting as defects.

The literature shows that MOCVD is a viable technique for the growth of GaInNAs devices, with the second best reported devices at 1.3µm being grown by MOCVD. However, this series of measurements shows that MOCVD devices can have a problem with carbon contamination which leads to an increased monomolecular current in the devices. A sensitivity to growth temperature has also been seen by many groups utilising MBE growth techniques devices[47, 109, 142]. From this it follows that careful control of the growth temperature of GaInNAs is vital.
Chapter 9

Thesis Review

9.1 Introduction

Within this thesis we have considered the recombination mechanisms constituting the threshold current of GaInNAs devices emitting over the telecommunications wavelength range. The influence of these recombination mechanisms has also been investigated as a function of temperature.

This study gives insight into the origin of the high threshold currents of long wavelength GaInNAs lasers and the causes of their temperature sensitivity. By studying methods of optimising these devices clear options on the way forward to produce improved GaInNAs devices can be proposed.

9.2 Conclusion

The initial investigations into the variation of the room temperature threshold current of the MBE grown GaInNAs devices carried out in chapter 5 showed that the threshold current density of the devices increased as the wavelength increased. The temperature stability, $T_0$, of these devices was also seen to decrease as the wavelength was increased. Using studies of the spontaneous emission from these devices it was seen that the dominant recombination mechanism within these devices was Auger recombination. This was clear as the $Z_{th}$ values for these devices pinned at a value of 3 at high temperature. This pinning of the $Z_{th}$ values at 3 can also be used to support the argument that there is no significant carrier leakage present within these devices.

When the spontaneous emission from these devices was further studied the threshold current of the devices was broken down into its constituent recombination paths and their individual magnitudes were determined. At 1.5$\mu$m the Auger current was $\sim$60% of the threshold current and the monomolecular current was $\sim$35%. Using
spontaneous emission analysis the variation in the magnitudes of the recombination paths was seen over the entire wavelength range. From this it is clear that the increase in $J_{th}$ seen as the wavelength was increased was caused by an increase in both the Auger and monomolecular recombination currents.

Analysis of the temperature sensitivity of these recombination mechanisms showed that the Auger recombination had the lowest $T_0$ value of just $\sim 50$K. From this it was determined that the temperature sensitivity of the threshold current of these devices was due to the presence of the large amounts of Auger recombination present in the threshold current. The corresponding $T_0$ measurements of the recombination paths also showed that the monomolecular recombination has a relatively high $T_0$, 150K. This high $T_0$ of the monomolecular current can be used to explain why the $T_0$ of $J_{th}$ was seen to be high for a number of the devices mentioned in chapter 3.

In order to study the recombination coefficients governing the recombination paths calculations of the threshold carrier density where carried out. The calculated values of $n_{th}$ allowed the calculation of the $A$, $B$ and $C$ coefficients from the previously measured data. When this was carried out it was found that the $A$ and $C$ coefficients had increased as the wavelength was increased. The increase of the monomolecular current showed that the $A$ coefficient governing it, had increased between the 1.3$\mu$m and the 1.5$\mu$m device, this appears to indicate that the extra nitrogen present within the longer wavelength device had increased the A coefficient. The A coefficient had approximately doubled although the nitrogen content had only been increased by $\sim 50\%$, this is indicative that the defects per nitrogen atom must increases as the nitrogen content is increased.

It was also seen that this large Auger component was caused by a larger $C$ coefficient, which was expected as a result of the increased wavelength. The $C$ coefficient for the 1.5$\mu$m devices is of similar magnitude to that of InGaAsP and AlGaInAs at this wavelength. This indicates that the GaInNAs material system when grown in lasers structures which aid the reduction of $n_{th}$ such as multiple quantum well structures, will have Auger components of similar or lower magnitude to the current industry standard InP based devices.
Within chapter 6 a study of the effect of pressure on GaInNAs devices was carried out. Here it was shown that the nitrogen level – conduction band interaction has a significant impact on the devices. The used of the BAC model also highlighted its ability to model the effect of the nitrogen level – conduction band interaction.

When the variation of the threshold current versus applied pressure was studied, different results were seen for the three structures studied. In the 1.3µm devices the threshold current was seen to increase with pressure. In the 1.4µm device it was seen to decrease level then rise reaching a minimum at ~5 kbar corresponding to a lasing wavelength of 1340nm. For the 1.5µm devices the \( J_{th} \) appeared to be pressure insensitive, remaining constant over the pressure range. The causes of these different behaviours of the devices are a result of both the interaction of the nitrogen level and conduction band edge, and the change of the C coefficient as the band gap was changed. The effect of the pressure on the interaction of the nitrogen level and the conduction band edge in the 1.3µm and the 1.4µm devices resulted in a 6.5% increase in the coupling between the two. This increased coupling resulted in a much increased threshold current with applied pressure. In the case of the 1.3µm device this was the cause of the increase observed in the threshold current. However the effect of the changing the Auger recombination coefficient played a part in the pressure dependence of the 1.4µm device, here there was interplay between the reduction of the C coefficient and the increase in \( n_{th} \) which caused this unusual behaviour of the threshold current. For the 1.5µm devices the nitrogen level – conduction band interaction was smaller and as such did not have as large an effect on \( n_{th} \) this coupled with the decrease in the C coefficient produced a pressure insensitive threshold current over this 8 kbar range. When the threshold current of a similar long wavelength GaInNAsSb device was studied, it too was found to have a similar pressure independent \( J_{th} \).

The variation of Auger coefficient C, was calculated within chapter 6 it was observed that there is an unusual jump in the magnitude of the coefficient at ~0.88eV. Calculations of splitting of the \( E^- \) and the \( E^+ \) levels suggest that the dominant Auger mechanism may change from CHSH at short wavelengths to CHCC at longer wavelengths.
Chapter 9 Thesis Review

In chapter 7 two possible methods to optimise the growth of GaInNAs were investigated. Firstly the effect of changing the barrier material was studied, it was made clear in the introduction to this chapter that theoretical work by Healy et al. shows that the small changes in the barrier height have a negligible impact on device performance. Experimental data showed that the main consequence of the change from GaAs barriers to GaNAs barriers was seen to be a reduction in the monomolecular current component, believed to due to improved barrier - quantum well interfaces. It was shown that the small change in the barrier height had little effect on the device performance. This was in agreement with the literature and in particular the work of Healy et al., confirming that the electrostatic attraction of the highly confined electrons in the conduction band prevents the holes from escaping from the valence band.

Within the second part of chapter 7 the effect of the incorporated strain within the quantum well was studied. This work highlighted the benefits of the incorporation of strain on the threshold carrier density of the devices. It was shown that the addition of extra compressive strain can be a useful tool for reducing $n_n$ and as a result reducing the threshold current density through the effect of the reduced $n_n$ on the monomolecular and Auger current densities.

Within the final experimental chapter of this thesis, chapter 8, a study of MOCVD grown devices was undertaken. Initially this study showed the same trends were present for the MOCVD devices as the MBE devices where the threshold current density increased as the wavelength was increased. However, the threshold current densities of these devices were much higher that the best reported in the literature at much longer wavelengths. Therefore the recombination mechanisms making up the threshold current of these devices was investigated. It was seen that the monomolecular current was the dominant current path within these devices, with the rate of its increase far in excess of that seen in the MBE grown devices.

Upon investigation of the literature it appears that these devices had such high threshold current because of their relatively low growth temperature. The study of the literature showed that with the utilisation of higher growth temperatures, the threshold current of MOVPE-grown devices becomes similar to that of the MBE-grown devices studied here. From this study the possible cause for the increased threshold current
appears to be the non-disassociation of the nitrogen precursor due to the low growth temperature. This is expected to result in the incorporation of N-C pairs which act as defects. With MBE growth atomic nitrogen is used as the N source and as such this problem does not occur. When higher growth temperatures are used for MOCVD devices they have produced results which are comparable to the best MBE devices at 1.3μm.

The literature shows that MOCVD is a viable technique for the growth of GaInNAs devices, with the best reported devices at 1.3μm grown by MOCVD having $J_n$ within 30 A/cm² of the best MBE grown devices. However, this series of measurements shows that MOCVD devices can have a problem with carbon contamination caused by low growth temperatures, which leads to an increased monomolecular current in the devices. From this it follows that careful control of the growth temperature is vital for the MOCVD growth of GaInNAs lasers.

In conclusion this work suggests that GaInNAs is a promising material for the growth of telecommunications lasers. Currently the material grown has a large amount of defects present resulting in a large level of monomolecular recombination present with the threshold current. However it is clear that the used of GaNAs barrier reduces this monomolecular current. Additionally the A coefficient was seen to be reduced by almost an order of magnitude by Infineon at 1.3μm through improved growth. This improved growth also appears to be happening in the Harris group where they have reduced their threshold currents by a factor of 2 just by refining the growth. From a defect perspective GaInNAs growers appear to be making good progress.

From the Auger perspective, in chapter 5 it was shown that the magnitude of the Auger coefficient $C$ of the GaInNAs devices is of similar size to that of the other active region materials for emission at 1.5μm. However the incumbent InP based materials already avail of complex device structures to reduce the effect of Auger through a reduction of $n_h$. If these methods are applied to GaInNAs the magnitude of the Auger component should be substantially reduced. However the tunability of the strain of the GaInNAs material appears to show a method to further reduce $n_h$ and thus the magnitude of the ubiquitous Auger current in GaInNAs devices.
Finally with its growth on GaAs in comparison to InP for conventional telecommunications laser materials, GaInNAs appears to be a solid alternative for the telecommunications market.

9.3 Further work

The investigation within this thesis of the 1.49μm GaInNAsSb device showed that it had similar performance to the GaInNAs device. An interesting study to complete would be the study of the newer GaInNAsSb devices produced by Stanford in order to determine if the reduction in $J_{th}$ that has been achieved is purely due to a reduction in the monomolecular recombination current. Within the literature review chapter another interesting variable that was identified as a possible method for optimising GaInNAs devices, was the effect of annealing in reducing the threshold currents of devices. As such it would be interesting to study the effect of different annealing conditions on the recombination mechanisms present within the devices. In chapter 6 the effect of pressure was shown to push the nitrogen level and conduction bands closer. The use of high pressure techniques such as a diamond anvil cell or a sapphire ball cell to reach pressures where these bands would be much closer would be of considerable interest, to study how this affects the devices.

In addition within chapter 6 there appears to be evidence for unusual changes in the Auger current and the dominant mechanism over the 1.3μm-1.6μm wavelength range, theoretical calculations would further aid the understanding of the data.

The MOCVD devices studied were not the best example of current MOCVD grown GaInNAs lasers and as such did not provide the comparison of the growth techniques hoped for. It would therefore be useful to repeat these investigations on good examples of MOCVD growth.

Finally given the importance of reducing $n_a$ in GaInNAs lasers it would be very interesting to undertake a similar set of studies on MBE and MOCVD grown devices with a variable number of quantum wells.
Appendix 1

Cleaving technique

The method used to cleave laser bars in chips is described below. First the laser bar is placed on a lightly adhesive sheet of plastic commonly referred to as “blue stuff”, this is then aligned on a micro-positioner, where there is full x, y and rotational adjustment of the stage. When the alignment is correct the laser bar is scored between the laser chips with diamond tip this, scoring of the bar is repeated a number of times depending upon the thickness of the substrate layer of the chip. Once all the chips have been separated by a score, the bar can be broken into individual chips, by first covering the chips and the plastic they are on with a layer of further transparent plastic, so as to protect from loss of chips, in the next stage. The bar is then aligned over a razor blade with each of the scores in turn over the blade, slight pressure is then applied, and with this the bar breaks at the score. This is then repeated for each of the different scores on the bar. The next stage is to stretch the lower plastic layer, this separates the laser chips, and allows them to be easily picked up with tweezers, with which they are placed into a labelled box.

Method used to form window by hand

The windowing technique that is used in order to collect the spontaneous emission from the device both above and below threshold, involves the removal of part of one contacts of the device.

In order to “window” a laser chip the following method must be followed. A first Initial L-I has to be carried out so that later, it can be determined whether the windowing process has had any effect on the performance of the chip. The chip is fixed in place (using photoresist) on the centre of a glass microscope cover slip.

The orientation of the chip depends upon the desired location of the window, on the chip, the window side is placed facing up. This has then to be baked for 15 minutes at 90°C. The common side for the window is the n-side, this is the case as when the p-
side is windowed it requires very precise depth control of the window; as the p-side is closer to the active region.

Once the chip is secured in place on the glass slide, the remainder of the laser is covered in photoresist, which is spun on using a centrifuge this is again baked in this case for 45 minutes at 90°C.

This slide is then aligned window side down over an ultra violet light box with a slit of width 50µm, so that the centre of the location desired for the window is centred over the slit. This is then covered and the chip is then exposed to a UV source for 45 minutes.

A developer solution of 1% sodium hydroxide is then used to expose the window created by the UV exposure. If desired the window can then be further defined by using photoresist to define the ends of the window, this needs to be further baked for 15 minutes.

This chip is then placed into an argon ion miller where it is milled at liquid nitrogen temperature, for a time period dependant upon the depth of the window that is desired. The laser chip is then cleaned and separated from the glass slide with acetone. This entire process may be repeated if the window is not deep enough.

L-I's are then carried out at the same temperature as initially; from this resulting L-I the effect if any of the milling can be seen. If there has been a change the device has been damaged, and the process needs to be repeated of a further device.

Further to this technique it is now common for the window in the device to be formed using a focused ion beam system, this allows for a quicker and simpler formation of the window of any shape in the device. However, the cost of this process may be prohibitive on devices with thick layers of metallisation on the contacts.
Appendix 2

Infineon device structure

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Nitrogen %</th>
<th>Indium %</th>
<th>Barrier material</th>
<th>Quantum Well Width (nm)</th>
<th>Emission wavelength (nm)</th>
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<tr>
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<td>7.5</td>
<td>1510</td>
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</table>

- Only the 1200μm cavity length of these devices was investigated
- Only the 100μm broad area devices were studied
Appendices

Appendix 3

Marburg device structure

<table>
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<tr>
<th>Sample number</th>
<th>Emission wavelength (nm)</th>
<th>Indium %</th>
<th>Nitrogen %</th>
<th>Q W width (nm)</th>
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Table of the composition of the Marburg samples.

- All these samples had GaAs barriers.
- These samples had a nominal cavity length of 800μm
- Only broad area 100μm oxide stripe lasers were studied
References


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R.133
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R.136


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