Mid-infrared Laser Diode Performance and Suppression of Auger Loss

by

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Abstract

High pressure and spontaneous emission analysis techniques have been used to probe the recombination mechanisms in mid-infrared semiconductor lasers for the 2-4 μm wavelength range. Analysis of the spontaneous emission collected through a window in the substrate contact of two type-I GaInAsSb/AlGaAsSb, compressively strained, quantum well lasers emitting at λ ~ 2.11 μm and λ ~ 2.37 μm, reveals that the threshold current of both devices is dominated by Auger recombination at room-temperature. Further analysis shows that approximately 80% of the room-temperature threshold current of the 2.37 μm devices can be attributed to Auger recombination. Comparison with larger band gap near-infrared devices suggests that the CHSH Auger process (involving the generation of hot holes in the spin-orbit split-off band) is suppressed in the 2.37 μm lasers as the spin-orbit splitting energy is greater than the band gap in these structures. However, other types of Auger process, such as CHLH and CHCC, persist and dominate the room-temperature threshold current of these lasers.

Hydrostatic pressure measurements on the 2.37 μm devices indicate that as pressure is applied, the band gap increases and approaches the spin-orbit splitting energy and at pressures above 6 kbar the CHSH process becomes important. This is also evident in the larger band gap 2.11 μm lasers where the pressure dependence indicates that the CHSH process is important at atmospheric pressure.

The loss processes in GaSb-based "W" diode lasers operating at λ ~ 3.25 μm (at T = 80 K) are also investigated through analysis of their spontaneous emission characteristics and the pressure dependence of their threshold currents. Spontaneous emission analysis shows that defect/impurity recombination, which had been of concern in these structures, does not have a significant influence on the threshold current. Results suggest that a substantial contribution from Auger recombination exists at 80 K and increases strongly with increasing temperature. It is estimated that Auger recombination accounts for about 87% of the threshold current at 200 K and is the main cause of the poor temperature performance in these lasers.
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Kevin O’Brien - Conference Presentations


Kevin O’Brien - Publications


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Chapter 1

Introduction

1.1 Motivation & Objectives

The mid-infrared (MIR) spectral region is generally understood to lie between about 2 μm and 15 μm in the electromagnetic spectrum. Light emitters and detectors in this spectral range have not seen the intensity of research that emitters and detectors in the visible and near-infrared (NIR) spectral ranges have, but as the potential for useful instruments and systems using MIR technology has been recognised, interest has grown. Technologies such as CDs, DVDs, and global telecommunications have been hugely successful and it is these lucrative applications which have pushed forward the technology in the visible and NIR regions. This section will now follow on to detail some of the drivers for MIR semiconductor laser research and the requirements that these application put on device performance.

There are a number of features of the MIR, which can be exploited. One notable feature is the atmospheric transmission windows which exist in the MIR, as displayed in Figure 1.1, taken from Wikipedia [1]. Within these wavelength bands, light of the correct wavelength can travel through the atmosphere with minimal absorption and hence can be used for free-space optical communications (FSO) [2,3], laser range finding and infrared countermeasures [4]. Proposals for FSO, include using MIR lasers and detectors to maintain high data transfer rates where fibre connections are not possible. For instance, in built-up city business areas, it may not be possible to obtain high bit-rate connections between buildings using fibre or RF technology, whereas FSO can be used if a clear line-of-sight
between buildings exists (safety constraints permitting) and gigabit per second connectivity may be possible [5, 6].

Another important feature of the MIR is the fact that many gaseous molecules have their fundamental absorption lines in this region. These absorption lines originate from the coupling of light of a specific wavelength to the rotational or vibrational modes of the molecule. Fluctuations in the absorption of a particular wavelength of light can be monitored with a simple laser/detector arrangement and the absorption signal can then be used to measure the quantity of gas present. Gas detectors using MIR lasers and detectors can use the stronger fundamental absorption lines of these molecules, offering greater sensitivity than their NIR counterparts, which use the 1<sup>st</sup> or 2<sup>nd</sup> order modes of the molecule. For instance, methane can be detected at a wavelength of 3.3 μm with a sensitivity of 1.7 ppb (parts per billion), rather than at its NIR absorption line of 1.65 μm where sensitivity is only about 600 ppb [7]. The absorption lines of some typical gaseous molecules of interest are listed in Table 1.1 [4].

Highly sensitive gas detectors would prove useful in a number of different real-world applications. As pollution becomes more and more of a problem in our modern environment, detection instruments are necessary to monitor the pollution from cars, industry, homes etc. Gas detectors containing semiconductor lasers and detectors can be compact and portable, in comparison to the laboratory-based spectroscopic alternative. Sensitive gas detectors could also be useful in chemical engineering.
Some precise chemical processes require in situ detection of small amounts of gases used in industrial processing [4,8].

Another interesting application is the detection of trace gases in the human breath. There are many conditions/diseases of the human body which result in changes in the levels of particular trace gases in the breath. These gases could be detected with the high sensitivity and high resolution offered by MIR lasers and could realise the development of a revolutionary handheld device which allows early, non-invasive diagnosis. For example, patients suffering from asthma have raised levels of nitric oxide in their breath. A laser-based breath analyser could give early indication of an on-coming asthma attack [9]. Other medical applications include laser surgery and non-invasive optical blood glucose monitoring, both of which exploit the absorption spectrum of human tissue [8,10].

In order to fulfill the requirements of the applications outlined above, highly developed semiconductor lasers emitting in the MIR wavelength range are required. Semiconductor laser diodes are ideally suited to such application due to their small size, low power consumption and narrow linewidth. In order to maximise the benefits of these devices in the real-world, lasers need to reach a stage of development where they are highly efficient, have low threshold currents, low temperature sensitivity and in some cases, high power and high spectral purity are important.

As the mid-infrared spans a broad range of energies from approximately 600 meV down to below 100 meV, there are several different material systems competing at different parts of this range. Many of these will be discussed briefly in the next section. The focus of this project was on the 2 - 4 μm region of the MIR, where the antimonide-based material system is a major competitor. Between 2 and 3 μm, Sb-based lasers with GaInAsSb in their active regions and a type-I band alignment between

<table>
<thead>
<tr>
<th>Gas</th>
<th>Absorption λ</th>
</tr>
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<tbody>
<tr>
<td>NH₃</td>
<td>2.1 μm</td>
</tr>
<tr>
<td>HF</td>
<td>2.5 μm</td>
</tr>
<tr>
<td>CH₄</td>
<td>2.35 / 3.3 μm</td>
</tr>
<tr>
<td>HCHO₂</td>
<td>3.5 μm</td>
</tr>
<tr>
<td>N₂O</td>
<td>3.9 / 4.5 μm</td>
</tr>
<tr>
<td>HCL</td>
<td>3.5 μm</td>
</tr>
<tr>
<td>SO₂</td>
<td>4.0 μm</td>
</tr>
<tr>
<td>CO₂</td>
<td>4.25 μm</td>
</tr>
<tr>
<td>CO</td>
<td>2.3 / 4.6 μm</td>
</tr>
</tbody>
</table>

Table 1.1: Wavelengths of fundamental absorption lines for some common gaseous molecules of interest.
the quantum wells (QWs) and barrier layers were studied. In the 3 - 4 μm range it is necessary to use alternating InAs and Ga(In)Sb layers to form a type-II band alignment and these devices are also studied in this work. The objective of this project was to analyse the primary loss mechanisms of lasers in the 2 - 4 μm range, with the aim of providing knowledge which will aid the future development of these devices. High pressure and spontaneous emission techniques were the main investigative tools used to gain insight into the physics behind the operation of these devices. All devices studied in this work were grown elsewhere, while the characterisation and analysis presented in this thesis was carried out at Surrey.

1.2 MIR emitters

In an ideal situation, one material system would be used to manufacture semiconductor lasers operating in continuous-wave (CW) mode at room temperature (RT), to cover the entire MIR range. In reality, this is not possible and there is effectively a team of different technologies attempting to provide for this broad wavelength range. Although much progress has been made in the last decade, it is still not possible to grow semiconductor lasers operating in CW at RT over the entire MIR region of the spectrum. Coverage of this range is somewhat patchy and different material systems excel in different wavelength bands with overlap and competition in certain areas. Some of the material systems currently being explored include Pb-salt devices, quantum cascade lasers, GaSb-based type-I structures, GaSb-based “W” structures and III-V materials incorporating dilute amounts of nitrogen. The devices considered here are III-V lasers, using type-I and “W” structures. In the following sections, the advantages and disadvantages of these materials and competing technologies will be described.

Until recent years, IV-VI lead-salt lasers of (Pb,Eu)(S,SeTe,Sn) were the only commercially available MIR semiconductor lasers. Most of these devices were restricted to operation at cryogenic temperatures but covered a wide range from 3 - 30 μm [4]. Some advances were made with the advent of advanced growth techniques such as liquid phase epitaxy (LPE) and molecular beam epitaxy (MBE) and through the use of double-heterostructure and QW designs but advances in III-V devices quickly began to overtake the performance of the lead-salt materials. However there is some hope for Pb-salt devices. Researchers at Linz in Austria have been working on optically pumped lead-salt vertical
cavity surface emitting lasers (VCSELs) on BaF$_2$ substrates, which emit between 3 µm and 8 µm. Some devices operating in CW-mode at RT have been realised at the shorter wavelength end of this range and research is ongoing to develop a full range of devices. As these devices are optically pumped, the aim is to develop a range of VCSELs emitting at different wavelengths which can be pumped by a single, inexpensive, electrically pumped, semiconductor laser with a view to developing a compact, highly sensitive, multiple-gas detector. The VCSEL structure also offers distinct advantages over edge emitting devices in particular, an improved beam profile and a narrower linewidth. Also, the high refractive index contrast possible using this material system lends itself to the growth of highly reflective bragg mirrors with only a few layers [11,12]. The difficulty of producing efficient electrically-pumped lead-salt devices and the relatively low power output of these VCSELs are the major technological drawbacks for this material system.

Quantum cascade lasers (QCLs) are a fast-growing technology with devices being developed for emission in the MIR region, through to the far-infrared. QCLs use inter-subband transitions between excited states in the conduction band (or valence band for the Si/Ge system) and a cascade arrangement to achieve lasing at a wide range of wavelengths. Injected carriers make a transition from one excited state to an excited state of lower energy in the conduction band to produce a photon and then tunnel into the next layer of the cascade, where they can undergo another transition to produce another photon. GaAs- and InP-based QCLs perform well at MIR wavelengths [13-16]. The GaAs-based system takes advantage of being one of the most highly developed semiconductor technologies, making it easier to achieve the high growth quality, layer thickness and compositional control which is a requirement for QCLs. GaAs-based devices perform well in the above-12 µm wavelength region. However, InP-based devices out perform GaAs-based QCLs in the 5-12 µm range, owing to their superior waveguiding, larger conduction band discontinuity and better thermal conductivity.

QCLs at shorter wavelength, in the 3-5 µm range, are showing good potential in recent years. The important parameter in the development of short wavelength QCLs is the depth of the QW, i.e. the conduction band offset $\Delta E_c$. Typically, a $\Delta E_c$-value of twice the photon energy is required to accommodate all the necessary energy levels of a QCL [17-19]. The GaAs/(Al)GaAs system has difficulty in this respect, as to achieve high $\Delta E_c$-values it is necessary to use Al$_x$Ga$_{1-x}$As with $x \geq 0.45$ where the AlGaAs material becomes indirect. Control of the separation of the lowest lying
conduction band level in the barrier layers (the X-valley) and the injector and upper lasing level, along with the introduction of InAs monolayers to the active region has led to lasing emission at 7.2 \(\mu m\), with the possibility of further reduction in the emission wavelength [20]. The InGaAs-AlInAs system grown on InP substrates has been used to achieve shorter wavelength emission as it can be grown with a \(\Delta E_c\) of about 0.72 eV using strain balancing [19,21]. This sets an approximate lower wavelength limit for this system of 3.5 \(\mu m\). Also grown on InP, the InGaAs-AlAsSb system can achieve a \(\Delta E_c\) of \(\sim\)1.6 eV but the \(\Gamma\)-X splitting energy is small. This can lead to a small energy difference between the upper lasing state and the X-valleys and hence electron leakage to the X-valleys can be significant [19]. A system which in the early stages of development and has a substantial \(\Delta E_c\) of \(\sim\)2.1 eV and larger intervalley separation energies is the InAs-AlSb system grown on either InAs or GaSb [15,19].

Currently, InGaAs-AlInAs/InP QCLs operating at RT and in CW mode have reached a wavelength of 3.8 \(\mu m\) [22] with a \(J_{th} \sim\)1.4 kAcm\(^{-2}\). CW output powers were as high as 143 mW. In pulsed operation, laser emission at around 3.3 \(\mu m\) at 80 K has been realised using a InGaAs/AlInAs/AlAs on InP system although above 160 K performance degrades rapidly, indicating that carrier leakage to indirect valleys is becoming a problem [23]. Within the InGaAs-AlAsSb/InP system, electroluminescence has been observed at wavelengths as short as 3.1 \(\mu m\) [24] to a temperature of 240 K, while lasers based on this system operating at 4.4 \(\mu m\) have been demonstrated [18]. Although a relatively young technology, the InAs-based system has already achieved pulsed lasing at RT at a wavelength of 4.5 \(\mu m\) [25] and lasing up to 240 K has recently been realised at approximately 3.3 \(\mu m\) and 3.1 \(\mu m\) [19]. QCL performance at shorter wavelengths is continually improving and there is the potential to cover a very broad range of wavelengths. As mentioned, the InP-based systems do hold some key advantages over their competitors, in that, a high refractive index contrast is achievable and the fact that InP growth technology of already wide-spread in the photonic industry [19,23]. Also, InP may be used as a waveguide material in this system and has thermal conductivity of \(\sim\)0.7 W/cm/K which is 10 times higher than the waveguide materials used in the GaAs-, InAs- and GaSb-based QCL material systems [15]. In general, QCLs hold some distinct advantages over non-cascade interband devices such as high quantum efficiency, reduced impact of series resistance on device performance and the avoidance of non-radiative Auger recombination. However, disadvantages of QCLs include the depletion of electrons from the upper lasing state by phonon scattering, possible leakage paths
to indirect satellite valleys and continuum states and the need for precise control of the thickness, composition and quality of a high number of growth layers [16].

Working with III-V compounds has always been an attractive option for MIR devices as growth technologies are well-developed in comparison with IV-VI and II-VI materials and a wide range of quaternary alloys are possible with the nearly lattice-matched compounds of InAs, GaSb and AlSb as shown in Figure 1.2. III-V materials also tend to have superior mechanical strength and thermal conductivity. Devices with type-I band alignment as shown in Figure 1.3, with GaInAsSb as the active material and barriers formed of AlGaAsSb have been most successful at the shorter wavelength end of the MIR. Lasers have been developed which operate well at RT up to about 3 μm and will be discussed in more detail in the following section. Emission from about 3 μm to over 4 μm can be achieved with a type-II “W” structure, so-called because of the shape of its conduction band, shown in Figure 1.4, taken from Meyer et al [26]. This design allows for a strong probability amplitude of the electron wavefunction in the central Ga(In)Sb layer. Hence the wavefunction overlap for electrons and holes is far greater than for a standard type-II design as can be seen by the sketched wavefunctions for electrons (continuous line) and holes (broken line) shown at the top of Figure 1.4 [26]. The devices studied in this thesis are type-I GaInAsSb and GaSb-based type-II “W” structure lasers and we are interested in how different loss mechanisms affect their performance.

### 1.3 Type-I Sb-based lasers

The most successful material system in the 2-3 μm wavelength region is the GaSb-based system with type-I band alignment. Structures usually consist of GaInAsSb QWs separated by AlGaAsSb barriers and with AlGaAsSb waveguide/cladding layers, on GaSb substrates. The choice of substrate is governed by a number of factors. Firstly, the lattice constant of the substrate material must be suitable, in that there must be a range of III-V alloys with similar lattice constant which can be grown on the substrate to form cladding, waveguide and active layers. The three binary alloys of InAs, AlSb and GaSb meet this condition, as shown in Figure 1.2. They all have a lattice constant of approximately 6.1 Å and III-V ternary or quaternary alloys of these 6 elements, with suitable lattice constant and band gap, can be grown epitaxially to form the required device layers. Another issue which needs to be addressed is the ease with which good quality substrate material can be grown.
InAs substrate material grows with unintentional n-type doping, which is not easily controlled and hence it is not a particularly suitable substrate material. AlSb meets the two previous conditions but is susceptible to oxidation, which makes it a difficult substrate to work with. GaSb however, proves to be the most suitable of these three alloys for this type of device, since many ternary and quaternary alloys can be grown on it epitaxially, high quality substrates are easily obtainable, and there are no problems of oxidation.

As mentioned above, the 3 binary compounds with similar lattice constants, offer 6 elements from which III-V ternary and quaternary alloys can be grown. This gives flexibility in the choice of material composition for each layer to give the band gap, band offsets and strain desired. The devices studied here are compressively strained and employ GaInAsSb QWs, with barrier, waveguide and cladding layers comprised of different compositions of AlGaAsSb. A schematic of the typical band alignment of these devices is shown in Figure 1.3. High performance devices operating at RT in CW mode have already been realised using this system and researchers continue to make improvements, with some of the lowest threshold currents for any quantum well laser being demonstrated. In this thesis, the basis for these low thresholds will be explored and the origin of their temperature sensitivity will...
be investigated.

Early devices of this type showed good performance at RT in the wavelength range of 2.0 - 2.5 μm, using a double-heterostructure (DH) design. Threshold current densities were high by modern standards though, at ~7 kAcm$^{-2}$ [27] and 3 kAcm$^{-2}$ [28]. In the early 90's the concept of using strained QWs in the active region was introduced to the GaSb-based type-I laser system. Significant advances were seen through the use of strained QWs, in the form of lower threshold currents, higher output powers and enhanced temperature performance. Choi and co-workers used a QW active region in their devices which had a comparatively low RT threshold current density of 260 Acm$^{-2}$ and CW output power of 190 mW per facet [29]. Later, lasers with pulsed threshold current densities of 143 Acm$^{-2}$ and total output power of 1.3 W developed [30].

GaSb-based lasers with GaInAsSb strained QWs separated by AlGaAsSb barrier layers became the standard for this material system and continued development of the design has led to impressive performance figures for lasers the λ ~2 - 2.6 μm range. For instance, CW threshold current densities as low as of 34 Acm$^{-2}$ per QW for a λ ~2.38 μm device, 50 Acm$^{-2}$ for a λ ~2.05 μm device and
58 $\text{Acm}^{-2}$ per QW at 2.24 $\mu\text{m}$ have been recorded at RT [31–33]. These low threshold figures have been attributed to several different improvements. For example, the use of broadened waveguide structures have helped to decrease internal losses in these devices to as low as $4 \text{ cm}^{-1}$ [3, 31, 34].

Several of the applications mentioned in Section 1.1 require high output powers and this material system looks quite promising in this respect. Output powers of over 500 mW have been achieved with the application of AR (anti-reflection) coatings on one facet of the devices and through the minimisation of heating effects [3, 35]. In pulsed operation, (where internal heating is not as significant) output power of almost 5 W at a heatsink temperature of 20°C was measured at a wavelength of 2.5 $\mu\text{m}$ [36]. At 2 $\mu\text{m}$, through the use of AR and HR (high-reflectivity) coatings, 1.7 W of output power was attained in CW mode and a peak power of 9 W was measured in pulsed operation [8].

In spite of these impressive figures, performance of these devices degrades greatly at wavelengths longer than 2.7 $\mu\text{m}$ and RT. CW emission at around 3 $\mu\text{m}$ has proven difficult to accomplish. At wavelengths longer than 2.7 $\mu\text{m}$, threshold current densities increase to several hundred $\text{Acm}^{-2}$ per quantum well [37–39] and the characteristic temperature $T_0$ is reduced from around 90-100 K (at 2.3 $\mu\text{m}$) to 30-40 K at 2.7 $\mu\text{m}$ [39]. It seems there are a host of issues to consider when attempting to develop type-I Sb-based lasers at wavelengths longer than 2.7 $\mu\text{m}$. Not least, the increased contributions from Auger recombination and FCA which are difficult to avoid at these longer wavelengths [4].

Also, there appears to be a delicate balance to be met for growth of structures in this region. Firstly, the compressive strain in the QWs must be sufficient to avoid the miscibility gap of the quaternary alloy. Working too close to the miscibility gap will compromise the quality of the material and promote SRH non-radiative recombination. Secondly, to maintain a reasonable valence band offset ($\Delta E_v$), it is necessary to increase the As-content in the QWs, while increasing the In-content to decrease the band gap. A guideline to maintain a $\Delta E_v$-value of about 130 meV and avoid leakage of holes from the QW, is to keep $y = 0.32x$. However, in trying meet this condition close to 3 $\mu\text{m}$ when In-content is high, the compressive strain necessary becomes too great and there is the risk of strain relaxation (as layer thickness is also high to minimise quantisation energy) which leads to the formation of dislocations and high SRH currents. Maintaining a low As-content with respect to In-content at 2.7 $\mu\text{m}$ does seem to give rise to very high threshold current densities, possibly due to
the formation of dislocations as a result of the high compressive strain of 2.3 % in these devices [39].

Increasing the As-content at the risk of not achieving sufficient hole confinement seems to be a more successful approach. Kim et al, have managed to reach wavelengths of 2.7 and 2.8 µm by maintaining a conservative level of strain. Threshold current densities per QW were 175 Acm⁻² and 600 Acm⁻² and output powers were as high as 500 mW and 160 mW for the 2.7 and 2.8 µm lasers respectively, at 16°C in CW mode. At even longer wavelength, lower threshold current densities per QW of 102 Acm⁻² and 172 Acm⁻² for CW operation at RT have been achieved at wavelengths of 2.81 µm and 3.04 µm, respectively [33,37]. The valence band offset of the 3.04 µm device is estimated to be 83 meV. Although low, this seems to be sufficient and less of a problem than the high defect-related recombination associated with very highly strained material. Some experimental analysis of spontaneous emission characteristics and internal efficiency has suggested that it is indeed leakage of holes from the valence band and increased SRH current that are the cause of performance degradation at wavelengths approaching 3 µm [40]. Recently, a novel technique using quaternary AlGaInAsSb in the barrier/waveguide layers has allowed extension of the maximum operation wavelength of these laser to 3.26 µm. The quaternary barriers increase the achievable valence band offset, allowing these devices to operate up to 50°C [41].

Another possibility for realising λ > 3.3µm emission with type-I Sb-based devices is to develop Sb-based dilute-nitride materials. A strong band gap bowing is observed in III-V materials with the addition of a small amount of nitrogen and very narrow band gaps can be achieved while maintaining substantial band offsets with the barrier materials [40]. Furthermore, suppression of the Auger recombination mechanism is possible with the III-V-nitride system. The introduction of nitrogen increases the non-parabolicity of the conduction band and the effective mass of the conduction band becomes more like that of the heavy-hole valence band, increasing the Auger activation energy. Although the concept of using III-V nitrides for long wavelength emission in the MIR is in the early stages of development, it has already been shown experimentally that suppression of the Auger process is possible [42].

In summary, the type-I GaInAsSb system grown on GaSb is the material of choice for the 2-2.7 µm wavelength region. While threshold current densities of lasers in this range are low, they are still temperature sensitive and it is not clear from the literature what the origin of this temperature
CHAPTER 1. INTRODUCTION

sensitivity is. Much research is needed to improve performance of devices in the 2.7-3.0 μm range and if the growth of structures containing quaternary barriers can be optimised, emission up to 3.3 μm may be possible. For emission beyond 3.3 μm it looks as if other device structures such as cascade lasers and "W" structure devices will need to be advanced. However, the possibility of moving to a dilute nitride device with this material system is open, as addition of small amounts of nitrogen to GaInAs material has proven to decrease the band gap significantly, while maintaining a type-I band alignment [43].

1.4 "W" diode lasers - Type-II Sb-based lasers

As discussed in the preceding section, the CW operation of type-I Sb-based laser diodes at RT is possible up to ~ 3 μm [33] and recent work has shown the possibility of pushing the operation wavelength of type-I devices to 3.3 μm [41]. Quantum cascade lasers have good characteristics at longer wavelengths [13-15] and continual improvements have meant that CW lasing at RT has been achieved at wavelengths as short as 3.8 μm [17,22]. In the spectral niche between these two technologies, about 3.3 to 3.8 μm, type-II "W" structure lasers display very good performance using both single stage and interband cascade designs. Although not yet realised, continued improvements show the potential for CW, RT operation across this range. CW emission has been achieved up to a temperature of 218 K for a single stage device with a wide-stripe geometry at an emission wavelength of 3.2 μm [44], while similar, narrow ridge devices have reached a CW operation temperature of 230 K due to better lateral heat dissipation [45].

Interband cascade lasers (ICLs) containing "W" active regions currently show slightly better performance than single period devices. In CW mode, operation temperatures up to 257 K at 3.7 μm emission wavelength [46] and 264 K at 3.3 μm [47] have been accomplished. These figures bring the ICLs into the critical range of thermoelectric coolers, which greatly increases the scope for practical application of these lasers. The high efficiency of the cascade structure and lower series resistance are cited as the main reasons for this superior performance. In this project we study single stage "W" diode lasers with the aim of identifying the primary loss mechanism which is responsible for their strong temperature sensitivity. As ICLs with "W" active periods are subject to some of the same loss mechanisms as single-stage devices, this work will be useful in their development also.
The structure of a typical "W" diode laser with three active periods is shown in Figure 1.4 [26]. The term, "W" diode laser, refers to the "W" shape of the conduction band profile as can be seen in Figure 1.4. In general, the "W" active periods consist of a central Ga(In)Sb hole confining QW, bounded by two electron confining InAs QWs which in-turn are bounded by two AlGa(As)Sb barriers (the barriers depicted in Figure 1.4 are for earlier versions of the structure), forming a type-II band alignment with a low and thin central barrier for electrons. The main waveguide and cladding layers are usually formed of AlGaAsSb and, like the type-I lasers, these devices are grown on GaSb substrates for the general reasons discussed in the previous section. This configuration offers several advantages over type-I, conventional type-II and superlattice (SL) structures in this wavelength band [26,48,49]. Firstly, as the central hole confining Ga(In)Sb layer is only of the order of 20-30 Å-thick, the electron wavefunctions in the InAs layers on either side can tunnel into the Ga(In)Sb layer and couple to each other, creating a substantial probability amplitude for electrons in the conduction band of the hole-confining QW. This gives an overlap of the wavefunction for electrons and the wavefunction for holes which is estimated to yield optical matrix elements about 70% as large as that in a typical type-I structure. Calculations showing the large wavefunction overlap are detailed in [26]. Since Sb-based devices are difficult to grow with a type-I band alignment, the "W" lasers are a good alternative. The "W" structure also provides a 2D-dispersion for both electrons and holes which is not possible in SLs, which increases the density of states at the band edge, making it easier to achieve population inversion [26,50].

Another advantage of the "W" laser design is the potential for suppression of Auger recombination, which is always of major concern in narrow band gap diode lasers [4,51]. The suppression of Auger recombination is achieved since the resonance between the spin-orbit splitting energy and the band gap energy, which is present in bulk GaSb and InAs, is removed by the use of a type-II band alignment. Suppression of CHCC-type Auger processes is also achieved through the reduction of the in-plane effective mass of holes in the uppermost heavy hole band [26].

A steady improvement in electrical and optical characteristics has been observed over the course of development of "W" laser diodes and much has been learned about their principles of operation. Many design modifications are now incorporated as standard. For instance, the incorporation of a hole-blocking layer consisting of a InAs/AlSb SL which serves to prevent injected holes from escaping
Figure 1.4: The band alignment of typical "W" laser structure with three "W" periods, reproduced from Meyer et al [26]

from the active region [48]. Another important development has been the use of transition InAs/AlSb SL layers in order to smooth abrupt steps in the conduction and valence band profiles. Substantial improvements in the V-I characteristics were realised through the use of SL transition regions and may be partly responsible for improvements in the temperature performance of these devices [49,52].

Re-absorption of emitted photons by free carriers is often a problem in MIR diode lasers, as it increases as $\lambda^2$. In order to avoid excessive loss in this way, it is necessary to increase the overall width of the waveguide and to reduce the doping and hence the number of free carriers in the cladding layers next to the active region, where there is some overlap with the optical mode. Internal loss figures of recent devices are about $7 \text{ cm}^{-1}$ and constant over the 78 K - 190 K range studied [49], in comparison to early figures of $19 \text{ cm}^{-1}$ [53].

Inter-period transport of holes has also been of concern during the evolution of these lasers. Researchers were concerned that holes injected into the heavy hole lasing state would not be injected uniformly across all "W" periods of the device. Typical devices contain 5 or 10 "W" periods. For this reason, quaternary AlGaAsSb barriers were employed in place of the AlAs or AlSb barriers used previously. This brought the first excited light-hole state to within 100 meV of the heavy-hole lasing
state to allow some holes to be thermally excited to the light hole band where they can tunnel through
the barriers to adjacent wells, while maintaining a reasonable population of holes in the heavy hole
state [48,50].

Their improvements along with the optimisation of the MBE growth conditions [54, 55] have led to
the steady advancement of this technology. The latest single stage devices have threshold current
densities as low as 30-40 Acm$^{-2}$, operate above RT in pulsed operation and up to 218 K in CW
mode with low internal loss and wallplug efficiencies of up to 10% [45]. The incorporation of “W”
periods into ICLs has seen some of the best performance figures so far in this spectral range with
CW lasing having been achieved up to higher temperatures than for single stage devices and with
lower threshold current densities at 78 K. The work presented in this thesis is based on single stage
devices but the results are also relevant to ICLs with “W” active regions.

In short, the Sb-based “W” lasers system achieves good results for lasers in this wavelength range
using strong coupling between the InAs QWs to achieve a better overlap between the electron and
hole wavefunctions (for a type-II structure). Steady advances have been made to improve operation
at higher temperatures. ICL’s using “W” active periods, take advantage of the their cascade structure
and have shown promising results at what is an early stage of development. ICLs however, are still
subject to non-radiative Auger recombination as they use interband transitions. QCLs avoid this
problem using only transitions between excited states of the conduction band. On the other hand,
QCLs have the difficulty of engineering a suitable system for short wavelength operation and the
non-radiative mechanism of fast phonon scattering from the upper to lower lasing states.
Chapter 2

Laser operation and analysis techniques

2.1 Introduction

Presented in this chapter is some basic semiconductor laser theory and some discussion on the analyses used in this project. The aim of this chapter is to provide the reader with the necessary background to understand the results and interpretation presented in subsequent chapters. Some basic laser diode principles will be introduced first, followed by an outline of the developments in semiconductor lasers which have had the most impact on laser performance. As the focus of this work is on the loss mechanisms in MIR laser diodes, the main loss mechanisms relevant to MIR lasers will be discussed in detail. This will be followed by an explanation of the theoretical background for the analysis techniques used in this work. For further reading on these subject areas, see refs. [56–60]

2.2 Spontaneous and stimulated optical transitions

Using a simplified two-level model, where the upper level represents the conduction band edge and the lower level represents the valence band edge, three important optical transitions are considered in Figure 2.1, where filled circles represent electrons (filled states) and open circles represent holes (empty states). In thermal equilibrium, the majority of states in the conduction band of an intrin-
sic semiconductor will be empty and the majority of states in the valence band will be filled by electrons. However, the conduction band may contain some electrons when at thermal equilibrium at temperatures greater than 0 K or electrons may be excited/transported to the conduction band under external stimulation. There exists a finite probability that these electrons can de-excite into an empty state (also known as the recombination of an electron and a hole) in the valence band. This process is represented in Figure 2.1(a) where an electron makes a transition from the upper level to the lower level. The energy dissipated by this de-excitation may be released as a photon. This is known as spontaneous emission. Photons emitted spontaneously have no phase and direction relationship to other spontaneously emitted photons in the same material.

Figure 2.1: Optical transitions in a semiconductor material, shown for a simple two-level model. (a) spontaneous emission, where an electron makes a downward transition to the valence band and releases its energy as a photon, (b) absorption, where a photon is absorbed by an electron which is excited to the conduction band and (c) stimulated emission, where an incident photon stimulates the de-excitation of an electron accompanied by the emission of another photon of the same phase, energy and direction.

Figure 2.1(b) shows an absorption transition, where the energy of an incident photon excites an electron in a state in the lower level across the forbidden energy gap into a state in the upper level. In order for this transition to occur, the incident photon must have an energy equal to or greater than the band gap. The final transition illustrated in Figure 2.1(c) provides the necessary amplification for lasing to occur. Here, an incident photon perturbs an excited electron in the conduction band, de-excitation it and stimulating the emission of second photon which has the same energy, phase and direction as the incident photon. This mechanism, coupled with a suitable optical cavity allows a coherent optical field to be built-up. The necessary conditions for stimulated emission and lasing will be discussed in the following section.
2.3 Population inversion

In thermal equilibrium at a temperature of 0 K, it can be assumed that all of the available states in the valence band are filled with electrons and all conduction band states are empty. As temperature is increased, the probability of states in the conduction band being occupied increases. In order to achieve population inversion, the concentration of electrons at the conduction band edge must be higher than the equilibrium level, so an external pumping mechanism is required. In the case of laser diodes, an electrically pumped pn-junction is used to inject electrons into the conduction band and holes into the valence band.

In order to achieve net gain, where the probability of stimulated emission is greater than the probability of absorption, population inversion is required. A material is said to have reached population inversion when the population of electrons in the upper state (conduction band) is greater than the population of electrons in the lower state (valence band). Both bands have a density of states associated with them, which can be multiplied by the probability of occupation of these states to estimate the carrier population. As carrier-carrier (e-e, e-h, h-h) scattering times are generally in the sub-picosecond range, which is much faster than typical electron-hole recombination times (~ns), one can assume electrons and holes are all at the same temperature. On the other hand, the two bands may have different quasi-Fermi energies and hence Fermi-Dirac statistics are employed to describe the carrier populations in the bands. The occupation probability, $f_c$, of a conduction band state at energy $E_c$ can be described by:

$$ f_c(E) = \frac{1}{1 + \exp \left( \frac{E_c - F_c}{k_B T} \right)} $$

(2.1)

where $k_B$ is the Boltzmann constant, $T$ is the temperature and $F_c$ is the quasi-Fermi level for electrons in the conduction band, which corresponds to the energy at which the state has a 50% occupation probability. Similarly, the probability of occupation for a state of energy $E_v$ in the valence band is:

$$ f_v(E) = \frac{1}{1 + \exp \left( \frac{E_v - F_v}{k_B T} \right)} $$

(2.2)

where $F_v$ is the quasi-Fermi level for electrons in the valence band.
For a semiconductor in thermal equilibrium at RT, the number of electrons in the conduction band is much smaller than the number of electrons in the valence band and hence absorption is much more likely than emission. Under external pumping, the separation between the quasi-Fermi levels is increased. The transparency point, when the probability of absorption is the same as the probability of stimulated emission is given by the Bernard-Duraffourg condition:

\[ F_c - F_v = E_g \]  \hspace{1cm} (2.3)

Once this condition is satisfied, further separation of the quasi-Fermi levels brings about population inversion, where positive gain is achieved.

### 2.4 Fabry-Perot cavity

In order to take advantage of the optical gain in a semiconductor at transparency, some form of feedback mechanism is necessary. In the case of the edge emitting lasers studied here, feedback is provided by a Fabry-Perot (F-P) cavity, shown in Figure 2.2. The F-P cavity is formed by the end facets of a laser which are cleaved along a crystallographic plane of the material. The facets form an optical cavity with partially reflecting mirrors at either end. The end mirrors (facets) reflect a portion of the light incident on them back into the gain medium where it experiences amplification.

The F-P cavity also acts as a resonator, where a discrete set of modes or standing waves resonate and experience gain. The wavelength of these modes is dependent on the length of the cavity:

![Figure 2.2: A Fabry-Perot cavity, which provides the necessary feedback for lasing. Mirrors are simply the cleaved facets of the laser structure and have reflectivities, \( R_1 \) and \( R_2 \), which are about 30% for a semiconductor-air interface.](image-url)
where $m = 1, 2, 3, \ldots$, $L_{\text{cav}}$ is the F-P cavity length and $\mu$ is the effective refractive index of the gain material. It follows from Eqn.(2.4), that the maximum wavelength supported by the cavity is $\lambda_{\text{max}} = 2\mu L_{\text{cav}}$ and the modes will be spaced $\Delta \lambda$ apart, where

$$\Delta \lambda = \frac{\lambda^2}{2\mu L_{\text{cav}}}$$

(2.5)

The mode nearest to the peak of the gain spectrum will experience most amplification and will begin to lase once certain conditions have been met. Once a laser has been pumped to transparency, it is then necessary to supply additional current to compensate for losses in the cavity and sustain lasing. These losses include light allowed to escape from the cavity through the partially reflecting mirrors, scattering losses and losses through re-absorption within the cavity. Lasing is achieved once the level of gain reached is sufficient to overcome the total cavity losses. This is evident in the following equation for the threshold gain per unit length:

$$g_{\text{th}} = \frac{1}{\Gamma} \left[ \alpha_i + \frac{1}{2L_{\text{cav}}} \ln \left( \frac{1}{R_1R_2} \right) \right]$$

(2.6)

$\Gamma$ represents the fraction of the optical mode which overlaps the active region, $\alpha_i$ is the internal loss per unit length and $R_1$ & $R_2$ represent the reflectivity of the end facets. In an electrically pumped laser the point at which sufficient current is supplied to achieve the above condition, i.e. satisfying Eqn.(2.6), is known as the threshold current, $I_{\text{th}}$.

### 2.5 Carrier and optical confinement

Early diode lasers used a simple p-n junction (FIGURE 2.3(a)), where carriers only had a narrow depletion region in which to recombine and could easily be swept across the depletion region without recombination. These devices had extremely high threshold current densities and were limited to pulsed operation at low temperature. The development of the double heterostructure (DH-structure) p-i-n diode laser provided a mechanism for the confinement of carriers in the active region, greatly
increasing the probability of radiative recombination. These devices consist of a thin layer of undoped semiconductor sandwiched between two doped semiconductor layers of larger band gap, as illustrated in Figure 2.3(b) where the junction is under forward bias and at high current. It can be seen that electrons and holes are transported into the active region easily but are prevented from being swept through the junction by the potential barrier formed at the heterointerface. The use of DH-structures helped to decrease threshold current densities of diode lasers by several orders of magnitude, greatly improving their performance.

The DH-structure also presented another useful characteristic, in that it served to confine the optical field to the active region, increasing the photon density in the gain region and hence increasing the rate of stimulated emission. Conveniently, the fact that III-V semiconductor material of larger band gap has smaller refractive index confines photons by total internal reflection at the layer interfaces. The extent of confinement of the optical field in a DH-structure will depend on the width of the active region and the refractive index difference between the layers. Optical confinement is especially important for MIR lasers, as photons travelling in the doped cladding layers can easily be absorbed by free carriers.

The use of DH-structures serves to confine carriers and photons in the growth direction. For a
variety of reasons, including the control of the number of lateral modes supported by the cavity and to reduce the overall threshold current (by reducing the area of the active region), confinement in the lateral direction is also desirable. The lasers studied here use two common types of lateral confinement - stripe contact lasers and ridge waveguide structures. The simple stripe geometry is fabricated using photolithography to define a stripe contact on top of the laser, with two electrically isolated regions either side. The stripe geometry provides current confinement by reducing the contact area of the diode. While this technique can provide adequate confinement for current, photons are only weakly guided through a slight current-induced change in the refractive index of the pumped, gain region (known as gain-guiding). Ridge waveguide structures are formed by masking a narrow ridge along the length of the cavity and then etching through the cladding layers to just above the active region. Either side of the ridge is usually filled with polymer to provide high refractive index contrast and electrical isolation. This structure provides good current confinement and good optical confinement due to the overlap of the optical mode with the ridge/polymer interface (high refractive index contrast). This is known as index-guiding. More complex designs can offer better lateral optical and carrier confinement in the active region but usually require more complex fabrication processes.

2.6 Reduced dimensionality in quantum wells

In a semiconductor, the threshold carrier density required for lasing is strongly dependent on the density of states in the conduction band and valence band. In Figure 2.4(a), it can be seen that the density of states near the band edge for a bulk semiconductor at RT is small. While having few states near the band edge makes it easy to achieve transparency, states of higher energy need to be filled in order to have enough gain to achieve lasing. This results in a broad gain spectrum, whose peak shifts to higher energies with increasing carrier concentration. The shaded region of Figure 2.4(a) shows the density of filled states as a function of energy for a fixed carrier density. This is simply the integral of the density of states function and the Fermi function over energy:

$$N = \int \rho_c(E)f(E)dE$$

If the movement of electrons in the semiconductor is restricted to a 2D-plane, like in a quantum
well, the density of states is altered. The density of states in a QW is step-like as shown in Figure 2.4(b) and the density of filled states for a given carrier density above transparency (shaded region) will have its peak near the band edge (in the growth direction). This means that for a QW, carriers injected above transparency will fill states near the band edge, increasing the gain near the band edge. As the gain spectrum will be narrower for a QW and the peak gain will occur near the band edge, more of the carriers injected above transparency can contribute to useful gain.

Of course, the above discussion assumes symmetric band structure. In a MIR III-V semiconductor the effective mass of the valence band is much greater than that of the conduction band and hence the density of states is much higher in the valence band. This imbalance in the density of states gets more severe with decreasing band gap and hence is an important consideration for MIR devices. The imbalance in the density of states is helped somewhat by the use of QW structures as the degeneracy between the light and heavy hole bands at the band edge is removed, since the confinement energy for the light hole states is much greater than that of the heavy hole states.

2.7 Incorporation of strain in the active region

Another improvement to semiconductor laser design is the incorporation of strain into active layers. Strain is induced simply by growing a thin layer of material on top of a thick bulk-like layer with slightly different lattice constant. Originally, strain was expected to have a negative impact on the
material quality, since it was thought the strain would relax as the layer grows thicker, with the introduction of dislocations. However, for a moderate level of strain, if the thickness of the strained layer is kept below a critical level, dislocations can be avoided. The lattice of the strained layer simply distorts to fit that of the bulk layer. As the band structure of III-V semiconductors is highly dependent on the lattice spacing, it was proposed that the introduction of strain could induce changes in the band structure which could be of significant benefit to laser performance [61,62].

There are two types of strain used in semiconductors, defined by the biaxial strain in the plane of the growth layer. Biaxial tensile strain occurs when the lattice constant of the strained layer is smaller than that of the bulk layer and hence the lattice of the strained layer is stretched in-plane and compressed perpendicular to the plane of the growth layer (assuming the material has a positive Poisson’s ratio), as illustrated in Figure 2.5(a). Figure 2.5(b), shows that if the lattice constant of the strained layer is larger than that of the bulk layer, the lattice is compressively strained in-plane and stretched in the growth direction. Most of the devices studied here incorporate biaxial compressive strain.

There are two components of strain which influence the band structure in different ways. The effect on the bulk band structure (Figure 2.6(a)) shall be considered here for simplicity. Firstly, the hydrostatic component (due to the total volume change) increases the band gap for biaxial compressive strain and decreases the band gap for biaxial tensile strain. Secondly, the uniaxial component of strain increases the separation between the heavy hole (HH) band and the light hole (LH) band at the Γ-point for biaxial compressive strain. Additionally, the valence band dispersion becomes anisotropic, with the in-plane mass of the uppermost valence band becoming lighter than the mass in the growth direction as shown in Figure 2.6(b). It is useful to note a possible point of confusion here - some authors call the uppermost valence band, in Figure 2.6(b) the HH-band because the growth direction mass (important for confined state energies in a QW) is heavy and some call it the LH-band, because the in-plane mass (important for low density of states) is light. In this discussion we shall mainly be concerned with the in-plane effective mass. As mentioned previously, in MIR III-V materials there is a strong asymmetry between the density of states near the conduction band edge and the density of states near the valence band edge, due to the asymmetry of their effective masses. The incorporation of biaxial compressive strain can be employed to reduce
the density of states at the valence band edge, bringing it closer to that of the conduction band edge and hence decreasing the carrier concentration necessary to reach transparency. In the case of a QW where there is already some HH-LH splitting, compressive strain will serve to increase this splitting further and hence further reduce the density of states at the valence band edge.

Figure 2.6(c) shows the effect of tensile strain on the band structure, which is opposite to that of compressive strain. Although, QWs with tensile strain are not studied in this thesis, there are also advantages to be gained through the use of this type of strain [63,64].
2.8 Recombination processes

Radiative recombination in a laser diode, where an electron recombines with a hole producing a photon, can be either spontaneous or stimulated by an incident photon of the correct energy, $\hbar \nu$, as described in Section 2.2. Spontaneous radiative recombination below threshold is necessary to provide photons for the stimulated emission process to take place. The carrier concentration required to reach transparency relies on the band structure of the material, while the current required to maintain this condition in the steady state depends on the total recombination rate. Current must be supplied to account for the radiative recombination rate at transparency and also to account for the non-radiative recombination rate. These non-radiative processes cause the threshold current of the laser to increase and are detrimental to its overall performance. Understanding the primary non-radiative recombination processes in MIR semiconductor lasers and the extent to which they impact laser performance is a major objective of this work.

At threshold, the current flowing through a laser can be approximated by the following expression:

$$I_{th} = eV(An + Bn^2 + Cn^3) + I_{leak}$$ (2.8)
where $e$ is the electronic charge, $V$ is the volume of the active region and $n$ is the carrier concentration (assuming $n = p$ for an intrinsic active region). $A$, $B$ and $C$ are coefficients representing the three main recombination processes of; Shockley-Read-Hall recombination (through defects and impurities), radiative recombination and Auger recombination, respectively. The term $(An + Bn^2 + Cn^3)$ is the number of recombination events per unit volume per second, i.e. the carrier lifetime is given by:

$$\frac{n}{\tau} = (An + Bn^2 + Cn^3)$$  \hfill (2.9)

$I_{\text{leak}}$ represents the contribution from current or carrier leakage out of the QWs. The subsections which follow will describe some examples of these recombination processes in more detail.

### 2.8.1 Radiative recombination

Radiative recombination requires the presence of an electron and a hole in the correct states. If $n$ represents the density of electrons in the conduction band and $p$ represents the density of holes in the valence band, then the radiative recombination rate can be described as follows:

$$R_{\text{rad}} = Bnp$$  \hfill (2.10)

As the active regions of the devices studied are nominally undoped, we make the assumption that $n = p$ and hence from EQN.(2.8) the current necessary to maintain this recombination rate is:

$$I_{\text{th}} = eVBn^2$$  \hfill (2.11)

### 2.8.2 Shockley-Read-Hall recombination

Shockley-Read-Hall (SRH) recombination (through defects and impurities) occurs when a carrier recombines through a defect state or trap within the band gap of the material. These defect or impurity states are usually created during growth and include impurity atoms, vacancies and surface states. The rate of SRH recombination can be described by:
where $A$ is the coefficient relating to the process. SRH recombination is described as being single carrier dependent, since defects usually have a strong affinity for either electrons or for holes. For instance, if a particular defect has a strong affinity for electrons, there is a high probability that it will be occupied by an electron. The recombination process will then be governed by the probability of finding a hole in a suitable state which is needed to complete the recombination from one band to another. The amount of current at threshold which is consumed by this process is highly dependent on the growth quality of the crystal and can be estimated by the expression:

$$I_{SRH} = eVAn$$  \hspace{1cm} (2.13)$$

in an undoped material where it is assumed that $n = p$.

2.8.3 Auger recombination

Auger Recombination is a major non-radiative mechanism of concern for MIR devices as this type of transition becomes much more probable for narrow band gap materials [51,59]. In general, the Auger process involves the energy released during recombination of an electron and a hole being used to excite another electron or hole to a higher energy state and hence it is referred to as a three carrier process. The Auger recombination rate can be approximated by the expression:

$$R_{Aug} = Cn^2p \text{ or } Cp^2n$$  \hspace{1cm} (2.14)$$

depending on which of the main Auger processes, discussed below, is dominant. $C$ is known as the Auger recombination coefficient and again as the material is undoped, we shall make the assumption that the electron and hole concentrations are equal ($n = p$) and the relationship becomes $R_{Aug} = Cn^3$. The additional current required to account for the rate of Auger recombination in a particular laser at threshold is:
\[ I_{th} = eV C n^3 \] (2.15)

Figure 2.7 shows the three main Auger recombination processes which are expected to be significant in III-V QW lasers [56,65] for a simple bulk unstrained band structure. The CHCC process in Figure 2.7(a) results in the excess energy from the recombination of a conduction band electron with a heavy hole being transferred to another conduction band electron, which is then excited to a higher state in the conduction band.

The CHSH process in Figure 2.7(c) excites a heavy hole further into the valence band, into the spin-orbit split off band to be precise, and hence is referred to as a hot-hole producing process. The CHLH process in Figure 2.7(b) is similar to CHSH with the hot-hole being generated deep in the light hole band.

The Auger recombination process is highly sensitive to both temperature and band structure. Temperature affects the Auger process by both increasing \( n_{th}^2 \) and through an increase in \( C \), since a greater thermal spread of carriers increases the number of allowed Auger transitions. The increase in \( C \) with temperature can be expressed as follows:

\[ C = C_0 \exp \left\{ -\frac{E_a}{kT} \right\} \] (2.16)

where \( C_0 \) is temperature independent to a first approximation. \( E_a \) is a phenomenological Auger activation energy, which is specific to the type of Auger process [51]. The dependence of the CHCC and CHSH Auger processes on band gap energy, spin-orbit splitting energy and effective mass, for parabolic bands, can be seen in eqn. (2.17) & (2.18).

\[ E_{a(CHCC)} = \frac{m_c}{m_c + m_h} E_g \] (2.17)

\[ E_{a(CHSH)} = \frac{m_s}{2m_h + m_c - m_s} (E_g - \Delta_{so}) \] (2.18)

where \( m_c, m_h \) and \( m_s \) are the effective mass of carriers in the conduction, heavy hole and split-off band respectively and \( \Delta_{so} \) is the spin-orbit splitting energy [66]. The above equations are based on a simple model assuming parabolic band structure and Boltzmann statistics, which is not the case
Figure 2.7: The three main Auger processes in III-V materials for a simple bulk band structure. (a) The CHCC process where the energy from the recombination of an electron and a hole, excites another electron into an empty state high in the conduction band, (b) CHLH where a heavy hole is excited deep into the light hole band and (c) CHSH where a heavy hole is excited to the spin split-off band.
for MIR III-V materials at high injection. However, EQN. (2.17) & (2.18) are useful to show the general effect that changes in the band structure can have on $E_a$. The effect of a reduced activation energy for the CHCC Auger process in a narrow band gap semiconductor, where both $E_g$ and $m_c$ are reduced can be seen in Figure 2.8 [59].

![Figure 2.8: Schematic energy versus momentum diagram showing the difference in Auger activation energy for the CHCC process in (a) a wide band gap material and (b) a narrow band gap material.](image)

### 2.9 Additional loss mechanisms

Aside from non-radiative recombination processes there are quite a few additional loss mechanisms which can be a problem in semiconductor lasers. The following sub-sections contain discussion on three such mechanisms which should be considered when dealing with interband MIR III-V diode lasers, like the devices studied in this project.

#### 2.9.1 Free carrier absorption

Free carrier absorption (FCA), is a loss process which occurs when the energy of a photon is absorbed by a free carrier, raising it to higher energy. This loss mechanism can make up a significant portion of the internal loss, $\alpha_i$, in EQN.(2.6) increasing the gain necessary to reach threshold. FCA can occur in the conduction band (where the energy is absorbed by an electron) or in the valence band (where the energy is absorbed by a hole). FCA in the active region can be a problem, especially if there is
a resonance between a valence sub-band energy separation and the photon energy. This is known as inter-valence band absorption and will be discussed separately in the next section. Depending on how well the optical mode is confined to the active region, FCA can also be significant in the doped cladding layers as there is a high population of free carriers in these regions. FCA is also more problematic for longer wavelength devices as it is easier to find transitions with less momentum transfer. Its dependence on wavelength is approximately $\propto \lambda^2$ [57].

2.9.2 Inter-valence band absorption

Inter-valence band absorption (IVBA) occurs when the energy of a photon is absorbed by an electron in the light hole band or the spin split-off band. This electron is excited into an empty state in the light or heavy hole band as shown in Figure 2.9, where it can be see that the transition must be almost vertical as there is negligible momentum transfer from the absorbed photon. The magnitude of IVBA in a particular laser structure is highly dependent on the band structure of the material, specifically the spin-orbit splitting energy $\Delta_{so}$. IVBA is also dependent on the hole density in the heavy hole band and on temperature, as the thermal spread of carriers will determine how far out in k-space this absorption can occur [70].

\[ E = E_{\text{laser}} \]

\[ \text{Conduction band} \]

\[ \text{Heavy Hole} \]

\[ \text{Light Hole} \]

\[ \text{Split-off band} \]

\[ \text{Figure 2.9: IVBA absorption which becomes significant when the energy separation of the heavy hole and spin split-off band or energy separation of heavy hole and light hole band are comparable to that of the photon energy.} \]
Like FCA, IVBA will increase the internal loss $\alpha_i$ in EQN. (2.6), increasing the gain necessary to achieve threshold. Therefore, there is an increase in $n_{th}$ which has the effect of increasing the threshold current and increasing the significance of the $n^3$-dependent Auger process [71,72].

### 2.9.3 Leakage

Leakage of carriers out of the QW can be another non-radiative loss mechanism in structures where the potential barriers between adjacent layers are not high enough. FIGURE 2.10 shows how leakage can occur across the heterobarrier between the QW and barrier layers in a laser, should the carriers have sufficient thermal energy to escape. Carrier leakage depends on both the thermal spread of carriers at the operation temperature and the height of the potential barrier. The height of the potential barrier between the conduction band minimum in the QW and that of the barrier layer is known as the conduction band offset ($\Delta E_c$). Similarly, the valence band offset ($\Delta E_v$) is the potential barrier between the valence band maximum of the QW and that of the barrier layer shown in FIGURE 2.10.

Some III-V materials are also susceptible to leakage into satellite minima (which have a high density of states), as shown in FIGURE 2.11, where carriers can find some other recombination path which does not contribute to gain. For instance, leakage to X-minima can be a major loss process for lasers emitting at around 670 nm [73].
Figure 2.11: Energy versus momentum diagram, showing the indirect X and L satellite minima. If the energy separation between these minima and the minimum of the conduction band at the \( \Gamma \)-point is too small, carriers can leak into these valleys.

### 2.9.4 Auger-generated hot carriers

The possibility of an additional leakage current arising from hot carriers, generated as a result of the Auger process, must be considered. These hot carriers, resulting from an Auger event, have an energy \( \geq E_g, \sim 500-600 \text{ meV} \) for the type-I devices studied here. Hence they are not confined in the QW, since the QW-barrier band offsets are smaller than the energy of these hot carriers. The hot carriers quickly relax but will also be subject to drift and diffusion within the structure, as discussed for 1.5 \( \mu \text{m} \) lasers in ref. [67].

For the shortest wavelength devices studied in this thesis, the 2.11 \( \mu \text{m} \) devices, it is estimated that \( \Delta E_c \sim 325 \text{ meV} \) and \( \Delta E_v \sim 140 \text{ meV} \), assuming a band offset ratio of 70/30 [68] and taking the difference between the lasing energy and the band gap of the barrier material [69]. In flat band conditions, one might take a similar band offset ratio between the barrier and cladding material, so that the total offset from the Fermi level in the conduction band of the QW to the minimum of the conduction band in the cladding would be approximately 710 meV. However, this neglects the built-in potential due to the doping in the cladding regions. The simplest picture would be to put all of the offset between the cladding and SCH barrier in the conduction band on the p-type cladding side, making the offset closer to 875 meV. In either approximation, hot Auger electrons (at energies
slightly larger than $E_{\text{lase}} = 588 \text{ meV}$) generated by the CHCC process will not have enough energy to escape into the cladding layers.

In the 70/30 approximation for the holes, the total valence band offset from the valence band maximum in the QW to the valence band maximum in the cladding layers is about 310 meV [69]. Alternatively, assuming that all of the offset between the cladding and SCH barrier is in the valence band presents a potential barrier of $\sim 690 \text{ meV}$. The actual offset is likely to be somewhere between these two values. Therefore, hot Auger-excited holes might have enough energy to escape into the cladding. However, it has been shown [67] that the escape probability for holes falls off quickly with distance from the cladding layers ($\sim 10x$ reduction within the first $\sim 75 \text{ nm}$) in similar 1.5 $\mu \text{m}$ structures due to the low hole mobility. The kinetic energy of the Auger-generated hot hole once it is in the SCH barrier material is $\sim 400 \text{ meV}$, and the ballistic transit time to reach the cladding interface which is 375 nm from where the hot hole is generated is therefore about 200-500 fs, depending on the effective mass. This is greater even than typical electron-phonon scattering times ($\sim 100 \text{ fs}$), hole-hole and hole-phonon scattering times are expected to be much shorter. We therefore conclude that it is unlikely that hot holes will be able to travel ballistically out into the cladding to recombine and constitute a leakage current.

2.10 Spontaneous emission analysis

The spontaneous emission analysis technique used here has been adapted for application to the MIR spectral range. Previously, investigations of the variation in spontaneous emission characteristics with temperature have successfully been used to examine and optimize the properties of near-infrared semiconductor lasers for optical fibre communications [74, 75]. It is hoped that the use of this technique in the MIR can help to broaden the understanding of the performance of these devices.

If the current flowing through a laser diode at threshold is described by EQN. (2.8), a few simple relationships can be used to analyse the change in the integrated spontaneous emission with current. It should be noted that for the approximations made in the following analysis using EQN. (2.8), it is important that the spontaneous emission measured has not experienced gain or absorption within the device and for this reason the spontaneous emission is collected through a window in the substrate metallisation as described in the next chapter, SECTION 3.2.1.
From Eqn. (2.8), over a limited current range, it may be written that $I \propto n^Z$ with $Z = 1, 2$ or 3, corresponding to dominant SRH, radiative or Auger recombination respectively. Since the spontaneous emission, $L_{spon}$, from the device is directly proportional to the radiative current at threshold ($I_{rad}$) and $I_{rad} \propto n^2$ (assuming $B$ is independent of $n$), we may write that $L_{spon} \propto n^2$ and hence $n \propto I_{spon}^{1/2}$. Consequently, $I \propto (I_{spon}^{1/2})^Z$ and thus, by plotting $\ln(I)$ versus $\ln(L_{spon}^{1/2})$ the gradient yields a value of $Z$, the power dependence of the current on carrier density. Therefore, the value of $Z$ close to threshold, $Z_{th}$, can indicate the dominant recombination mechanism at threshold. If carrier leakage becomes dominant at higher temperatures, $Z_{th}$ can take values higher than 3, as carrier leakage has an exponential dependency on carrier density.

2.11 The use of hydrostatic pressure to analyse III-V diode lasers

The application of hydrostatic pressure to a III-V semiconductor causes an increase in the direct band gap. Thus, we can use pressure as an externally variable parameter to investigate and quantify band gap dependent processes. The radiative current is expected to increase with increasing pressure (band gap). In a near-ideal QW laser with low loss the radiative current is expected to increase with the band gap as, $J_{rad} \propto E_g^2$ [76]. Experimental results show this relationship to be a reasonable approximation [77, 78]. However, the rate of change of $J_{rad}$ with pressure can vary as there is an increase in the optical confinement factor, $\Gamma$, with decreasing wavelength (increasing pressure). The decrease in $\Gamma$ leads to a decrease in loss and hence in $n_{th}$ which will cause $J_{rad}$ to have a weaker dependence than $E_g^2$.

The main non-radiative mechanisms will have different dependencies as summarised in Figure 2.12. Should a laser be dominated by SRH recombination, its threshold would be expected to be relatively independent of pressure. If Auger were the dominant current path, a decrease in threshold with pressure would be expected as Auger recombination becomes less significant with increasing band gap, as discussed in Section 2.8.3. Carrier leakage might be expected to affect the pressure dependence in one of two ways, depending on whether it is direct from the QW into the barrier material or indirect from the $\Gamma$-point in the QW to the L or X satellite valleys. Direct leakage is expected to be pressure independent, as the QW and barrier materials usually have very similar pressure coefficients. Also, the change in the valence band offset in III-V QW systems is measured [79] and calculated [80] to be...
negligibly small, i.e. there is no significant change in the band offset ratio. Figure 2.13 shows how the X and L valleys move relative to the $\Gamma$-point and how leakage to either of these valleys would increase as a function of pressure, but at different rates.

In summary, with some knowledge of the material band structure of a laser, pressure can prove a very useful tool to identify the dominant recombination path at threshold. Often, pressure can be used to distinguish between two loss mechanisms which are suspected to be important. Also, as the lasing wavelength is changing with pressure, information on how similar lasers of different wavelengths will behave can be collected.

2.12 Mid-infrared considerations

When applying analysis techniques used at visible and NIR wavelengths to the MIR spectral range, both experimental and theoretical differences associated with the MIR region need to be considered. The experimental challenges, considered in detail in the next chapter, have been a major focus of this work and addressing these challenges has allowed the application of spontaneous emission analysis and low temperature, high pressure techniques to a number of MIR devices. From a theoretical point of view, the analyses involve a number of approximations and simplifications which are mentioned throughout this chapter. Two of the most important assumptions made are to do with the parabolic-
Figure 2.13: The X and L satellite valleys have different pressure coefficients than the direct Γ-valley, hence the Γ-L and Γ-X energy splittings change with applied pressure. This can be used to identify when leakage to indirect satellite valleys is becoming important. The pressure coefficients shown for the X- and L-minima are approximate figures for GaSb [81] and the pressure coefficient of the direct band gap at the Γ-point is an approximate figure for the GaInAsSb material studied here.

ity and the symmetry of the bands. Non-parabolicity is known to be more significant in narrow band gap materials, as the conduction band and valence bands are close in energy and their influence on each other is more pronounced. The asymmetry of the effective masses \( m_e^* \ll m_h^* \) of the conduction band and heavy hole band is also more pronounced at longer wavelengths as shown previously in Figure 2.8. This effect causes the imbalance between the density of states of the bands to increase at longer wavelengths and can have a significant impact on the loss processes studied here [59].

Certainly, there is scope for future work to look at some of these approximations in more detail and make adjustments to the analysis and interpretation where appropriate. However, this was not possible within the scope of this project, so these approximations will be highlighted and taken into consideration in the interpretation of results.
Chapter 3

Experimental Development

3.1 Introduction

Working in the MIR spectral range presents a whole host of problems and difficulties which need to be addressed or sometimes just tolerated. Experiments in the NIR and visible regions tend to be more straight-forward as experimental equipment and instrumentation in these wavelength regimes is more highly developed and generally easier to work with. NIR silica fibres, detectors and spectrum analysers are not suitable for use at MIR wavelengths. Instead, specialist fibres, cryogenically-cooled detectors and Fourier Transform Infrared (FTIR) spectrometers have to be employed. The superior development of NIR/visible technologies is mainly due to the strong industry drivers which have existed at these wavelengths and the fact that some of the fundamental physical features make NIR and visible materials easier to engineer. In this chapter, two characterisation techniques, which are routinely used in the NIR and visible regions, will be described and the adaptation of these techniques to the MIR will be discussed. The motivation behind the development of these in-depth characterisation techniques for the MIR was to further the understanding of the physics of the particular devices studied and to develop investigative tools which will be beneficial to MIR research as a whole. Very little of this type of work at MIR wavelengths had been carried out previously, so a substantial amount of developmental work was necessary to make these experiments possible.
3.2 Spontaneous Emission Analysis

Analysis of the spontaneous emission characteristics of a semiconductor laser can be used to quantify the loss processes which affect its performance [74]. The technique involves collection of the spontaneous emission from an operating laser and the analysis of how the spontaneous emission characteristics vary with current and temperature. Spontaneous emission analysis on devices in the 2.3 - 2.6 μm range had been carried out previously, but the collection technique was from the side of the laser chip [34]. In the experiments presented here, it was chosen to collect the spontaneous emission from a window in the substrate contact of the laser chip, as spontaneous emission collected from the side can be susceptible to absorption or amplification within the laser cavity (particularly in devices with wide-stripe geometry). It is important for the analysis used that the collected light has not undergone any gain or absorption. Measurements of integrated spontaneous emission as a function of injected current are taken at each temperature and a profile of the radiative and non-radiative contributions to the threshold current can be built-up. An optical fibre, coupled to a window milled into the substrate contact of the device is used to collect the spontaneous emission as shown in Figure 3.1. Figure 3.2 shows a sample spontaneous emission $L_{se} - I$ curve and a facet (lasing) emission $L - I$ curve for a 2.37 μm laser at RT.

The spontaneous emission in an ideal QW laser is expected to pin above threshold, since the carrier

![Figure 3.1: Schematic diagram of the window in a laser, used to collect unamplified spontaneous emission.](image-url)
density is clamped when the lasing process begins and any additional injected carriers take part in stimulated emission. Complete pinning of the spontaneous emission above threshold is not observed in any of the devices analysed during this work. This raises two concerns. Firstly, is this non-pinning due to scattered lasing emission being collected through the window, and if so, is any amplified spontaneous emission (ASE) collected in the same way? Collection of ASE below threshold would compromise the determination of $Z_{th}$. Secondly, non-pinning can be an indicator of detrimental effects such as inhomogeneities in the QW material or lateral current spreading.

Spectral analysis was carried out on all the devices for which spontaneous emission data is presented, to ensure that ASE was not being collected and to investigate the origin of the non-pinning. Spectra of the spontaneous emission were measured for several drive current values, above and below threshold, using the FTIR setup described in Section 3.2.9. Sample spectra are shown in Figure 3.3 for a 2.37 μm laser at low temperature. A narrow lasing peak was observed in the above-threshold spectra, indicating that some scattered lasing light was being collected through the window. The fact that the lasing peak is more than half a mode-spacing ($\Delta \lambda / 2 \sim 0.38$ nm in these devices) from the spontaneous emission peak shows that the spectra measured below threshold are not affected by ASE. Integration of the spontaneous emission spectra with the contribution from lasing emission

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**Figure 3.2**: A sample $L_{se} - I$ curve measured with the fibre directly coupled to a InSb detector, where pinning of the spontaneous emission is not observed.
removed, showed that for this device the non-pinning was only as a result of the unintentional collection of scattered lasing emission. This was not the case for the 2.11 μm lasers, as will be discussed in Section 4.3.3.

### 3.2.1 Creating the window

The window through which the spontaneous emission is collected, is usually milled in the substrate contact of the laser, as the thick substrate ensures that the current spreading around the window does not affect the active region of the device. The objective is to form an area on the substrate contact of the device which has no metallisation and hence can transmit pure spontaneous emission. Two techniques were employed to form the windows in the devices studied here. The first was an argon-ion milling technique. Here, the device is mounted epi-side down on a glass slide using a small amount of photoresist. Next, a thin layer of photoresist is spun-on to cover the whole device. The desired window area is exposed to ultra violet (UV) light using a suitable mask and then the exposed
photoresist can be removed from the window area. The device is then loaded into an Argon ion-beam miller in order to remove the contact metallisation from the window area. Finally, the remaining photoresist can be removed using a suitable solvent and the window is ready.

The second technique is similar, but faster and more straight-forward. In this case, a focused ion beam (FIB) is used to form the window. The device is simply mounted on a stub inside the FIB, so there is no need for any photoresist or masking. Imaging can be done using an SEM which is part of the same instrument and the desired window can be easily selected and automatically milled using the FIB software. Control of the window diameter and depth is also much easier with this instrument. Figure 3.4 shows an SEM image of the window milled in a 2.11 μm laser using the FIB. Although a much more convenient and accurate technique, the FIB is a very expensive piece of instrumentation and it is not always a cost effective method of carrying out a simple process like this.

Of course, it is essential to make sure that the process which facilitates the analysis does not affect the device characteristics and for this reason the threshold current before and after window milling was always checked to be the same.
3.2.2 Device mounting

There were several important considerations to take into account when designing a suitable device mount for this project. As the devices were mounted substrate side down, it was necessary to be able to place the window of the laser over the top of an optic fibre to collect the spontaneous emission, while maintaining a good thermal and electrical contact for the device in general. The device must also be mounted in such a way that its position is adjustable, in order to allow adjustment of the window-fibre alignment. Choice of fibre was very important, since the loss in silica fibres greatly increases for wavelengths longer than 1.8 \( \mu \text{m} \). Therefore, it was necessary to identify a fibre that was suitable for use in this wavelength range. Chalcogenide fibre turned out to be the most suitable fibre for these measurements, although its characteristics are far from ideal.

3.2.3 Chalcogenide Fibre

The high speed internet connections we take for granted today, rely heavily on miles and miles of silica fibre which is flexible, cheap and relatively robust. Silica fibre has low loss and low dispersion at NIR wavelengths and hence light emitters and detectors were developed to take advantage of these properties. Optical fibres which are suitable for MIR applications tend to be brittle, expensive and lossy in comparison to silica fibres.

There are several materials which are used to manufacture MIR fibres including fluoride glass, silver halide and chalcogenide. Fluoride glass based fibres are currently very expensive and the silver halide based fibres are more suited to operation at \( \lambda > 4 \mu \text{m} \). Chalcogenide fibre, although not as flexible and easy to cleave as fluoride glass fibre, is not so expensive and can be obtained for about £90 per metre. Although not nearly as low as the loss in silica fibres at 1.5 \( \mu \text{m} \), the loss in chalcogenide fibre over the wavelength range of interest for this work is acceptable and relatively flat over this range, as shown in Figure 3.5. The particular chalcogenide used, which is \( \text{As}_2\text{S}_3 \), is a glassy material and has a number of characteristics which make it a difficult and tedious material to work with. Firstly, the fibre is relatively weak mechanically and can break easily if not properly protected. Another issue is the fact that the fibres are only available with diameters which are large in comparison with the substrate contact area of a typical laser chip. This means that the fibre can take up a significant fraction of the thermal and electrical contact area of the chip. The bend radius which is a function of
the core diameter, is also quite poor so for the 440 \( \mu \text{m} \)-diameter core used in this work the bend radius was 20 mm. This made installation in a cryostat mount very tricky and restrictive and required some modifications to be made to an existing cryostat arm. However, with these challenges overcome and the continual improvements to the overall design, the system using chalcogenide fibres worked quite well.

![Spectral response chart of chalcogenide optical fibre.](image)

**Figure 3.5:** Spectral response chart of chalcogenide optical fibre. The 2-4 \( \mu \text{m} \) wavelength range is the important spectral region for this particular project.

### 3.2.4 Preparation of cryostat mount

**Figure 3.6** shows the cryostat arm which came with the standard Oxford Instruments liquid-nitrogen, exchange-gas cryostat and was adapted for use in these measurements. The fibre and electrical connections are fed through the sealed top plate and down through the inner tube of the arm to the sample mount. The original sample mount required a 45° bend in the fibre, which was not possible due to the poor bend radius of the chalcogenide fibre. Therefore, it was necessary to re-design the sample mount to accommodate the chalcogenide fibre, as shown in **Figure 3.7**. The new design also including a removable bottom plate, which helped with the polishing process. Once the protective layers are removed from the fibre end, the bare fibre end (with only core and cladding) is glued tightly into a small hole in the removable bottom plate, ready for polishing. The exit end of the fibre is terminated with a bare fibre adapter. Its is very important to protect the fibre between
the exit end and the cryostat arm with some protective tubing. Since the fibre is so delicate, the tubing needs to be rigid enough to support the fibre and light enough that the fibre will not break under its own weight.

### 3.2.5 Fibre polishing

Chalcogenide optical fibre rarely cleaves well. So, to achieve a smooth, flat fibre end and optimise the light collection efficiency it is necessary to polish the fibre ends carefully. Several methods were tested for this particular application with varying degrees of success. The two most important points to bear in mind are to minimise the size and extent of surface scratches and to prevent pieces breaking off the sides during polishing.

To prevent breakage from the outer wall of the fibre, the fibre end must be well supported around its circumference. We began using a soft low-melting-point wax, which was recommended by the manufacturers, as it grinds away more quickly than the fibre material and can be removed by heating the fibre end slightly (inside tolerance for the fibre material). This wax proved very difficult to work with though, as it did not adhere to the fibre very well and tended to come away from the fibre end during polishing. For this reason, we opted to use epoxy resin instead, which adheres well to the fibre and supports the outer wall during polishing. Even though the epoxy resin is harder than the fibre material, this method still produced better results. Also, the fact that the epoxy resin is not easily removed from the fibre meant that the fibre needed to be polished in its final position. The sample mount illustrated in Figure 3.7, shows the removable bottom plate, which allowed polishing of the fibre in its final position. An advantage of in-situ polishing for this application is that it is easy to get the fibre end level with the bottom plate, allowing the laser chip (or copper slip, as discussed later) to sit level over the fibre, maintaining good electrical / thermal contact while maximising light collection efficiency.

A number of different polishing techniques were tried, until a successful method was developed for this application. Our original sample mount did not have a removable bottom plate so it was necessary to polish while the fibre was attached to the entire sample arm. At first, we used a rotating disc polisher with diamond polishing discs, starting with a 6 μm grade and working down to a 0.05 μm grade. This method proved too severe and often ended in breakages along the axis of the fibre. The
Figure 3.6: Cryostat arm with a re-designed mount which is fitted with a MIR chalcogenide optical fibre. The arm is loaded into the cryostat's sample chamber and sealed. The sample chamber is then evacuated and filled with the exchange gas (usually helium or nitrogen).
CHAPTER 3. EXPERIMENTAL DEVELOPMENT

Figure 3.7: Shown above are device mounts which can be attached to the end of the cryostat arm. On the left is the old design, where a 45° bend was necessary to successfully install a fibre. While this was fine for a silica fibre, it proved too stressful for the chalcogenide fibre and so the device mount was redesigned. The new device mount (right) does not require a bend in the fibre and incorporates a removable bottom plate which allows for easier polishing.

alternative was to use AlO$_2$ lapping film and de-ionised water as a lubricant, which also served to remove waste material. This proved awkward while the fibre was attached to the cryostat arm and it was necessary to cut sections of lapping film, attach them to a glass slide and polish with the lapping film on top of the fibre. Although, results using this technique were reasonable, a better sample mount design was clearly needed. The new sample mount design incorporated a removable bottom plate, making it possible to use a large sheet of lapping film on a glass plate and polish in a figure 8 pattern. This method was easier and demonstrated better results than with the previous device mount. Much patience is needed to avoid scratches caused by waste material and achieve a smooth finish. This method worked very well and was adopted as our standard procedure. Lapping films with a grade of 6 $\mu$m down to a grade of 0.5 $\mu$m were used. It was found that grades smaller than 0.5 $\mu$m tended to accumulate waste material and cause more surface scratches. The exit end of the fibre was mounted in a bare fibre adapter and polished in the same way.
3.2.6 Final adjustments

With the fibre polished and fixed in position, the actual device mount could be finished. As mentioned earlier, the milled window is approximately 100 $\mu$m in diameter, to minimise its effect on device performance while achieving sufficient light collection levels. Unfortunately, chalcogenide fibre is only available with large core diameters. The fibre used here had a total core/cladding diameter of about 450 $\mu$m (a core/cladding diameter of under 300 $\mu$m is available now), which would take up too much of the bottom contact of a typical 1 mm long, 100 $\mu$m-wide device. The solution was to use a 0.5 mm-thick copper slip with a hole slightly larger than 100 $\mu$m diameter in its centre. This slip could be fixed in position with the hole over the fibre end and the device could be placed on top. It was necessary to have a highly polished finish on the copper slip in order to dissipate as much heat as possible from the device, so the copper slip was polished in a similar fashion to the fibre ends. Although prone to oxidation, copper was the material of choice for the mounting components, as its thermal conductivity is over twice as good as alternative materials such as brass.

Finally, a spring clip as shown in Figure 3.8 was used to hold the device in place. The clip is easily lifted up and down by hand, making it possible to adjust the device position to optimise the window-fibre alignment.

![Figure 3.8](image)

*Figure 3.8: Lasers are mounted and held in position with a spring clip. This provides good electrical and thermal contact and allows the laser position to be adjusted in order to optimise the window-fibre alignment.*
3.2.7 Light detection

The choice of detectors in the MIR is limited and the performance characteristics of these detectors are a major weakness in MIR experiments. For laboratory experiments in the 2-5 μm wavelength range liquid-nitrogen-cooled InSb detectors are best suited. However, efficiency is relatively poor at shorter wavelengths, as shown in Figure 3.9, rise time is long and element sizes tend to be small. The liquid-nitrogen cooled InSb detector used in this project had a 1 mm² element and was approximately 40% efficient at 2.1 μm and 2.4 μm and 50% efficient at 3.25 μm, which were critical wavelengths for this work.

![Spectral response of the InSb detector used in these experiments.](image)

For example, the relatively weak spontaneous emission signal from a 2.11 μm laser will suffer losses on entry, transmission and exit from the fibre. More light will be lost at the window of the detector, which is essential as the detector is liquid nitrogen cooled and finally only about 40% of that signal will be detected. Therefore, it is very important to have good signal processing and a lock-in amplifier must be employed.

3.2.8 Temperature control

Once the cryostat arm was prepared, the device was mounted. Light-current characteristics were measured for both the facet (lasing) and window (spontaneous) emission and the laser position was adjusted to optimise the spontaneous emission signal, which is much weaker that the lasing emission.
The cryostat arm was then loaded into the Oxford Instruments cryostat. Temperature of the sample was controlled using liquid nitrogen, heater coils, a platinum resistance thermometer and an Oxford Instruments ITC502 temperature controller. In this particular cryostat, the thermal transfer takes place through a static exchange gas. The sample chamber was evacuated and flushed with nitrogen (the exchange gas used) several times before beginning each experiment. The range of the cryostat was 78 K to 350 K (close to the melting point of the fibre) and temperature stability was usually within a few tenths of a degree.

3.2.9 FTIR Spectroscopy

Often in spontaneous emission analysis experiments it is necessary to conduct spectral analysis of the spontaneous emission as a function of current. Since signal strengths are weak and signal to noise ratios for the spontaneous emission signal can be as low as 10, we opted to use a Fourier transform infrared (FTIR) interferometer opposed to a diffraction grating spectrometer. In general more light is lost in a grating spectrometer system due to the fact that the slits are tall and thin, whereas the beam is generally round, and using an FTIR for a small signal is more suitable as a full collimated beam can be coupled in and out easily. A schematic of an FTIR interferometer is shown in Figure 3.10. A fast-scanning Bomem MB-100 was used in these experiments. In brief, the FTIR operates by splitting the incoming beam into two separate beams and using the movable mirror, M1, to induce a phase difference between the two beams. An interference pattern is generated at the spectrometer output as a result of the interference between the two phase shifted beams.

During normal use, the detector output would simply be connected directly into the FTIR's built-in processing unit and measurements would be taken using its interfaced computer. In this particular application it was necessary to incorporate a lock-in amplifier into the experimental setup, to increase the signal to noise ratio and amplify the signal before it is processed by the FTIR. Careful consideration of the different frequencies and time constants involved is crucial. In order to achieve most effective operation of the FTIR, there are two important issues to consider; the external modulation frequency of the light source (the sample laser in this case) and the time constant (τ) selected for phase sensitive detection with the lock-in amplifier. The latter is only a factor as phase sensitive detection was used in conjunction with the FTIR.
The selection of the lock-in time constant $\tau$ requires that it is much smaller than the period of the interference fringes. The maximum modulation frequency, $f_{\text{max}}$, of the fringes produced by the FTIR is determined by the velocity of the moving mirror, $v$, and the shortest wavelength to be measured, $\lambda_{\text{min}}$. The value of $f_{\text{max}}$ is given by:

$$f_{\text{max}} = \frac{2v}{\lambda_{\text{min}}}$$  \hspace{1cm} (3.1)

It is recommended that the external modulation frequency, $f_{\text{mod}}$, which in this case is the repetition rate of the sample laser, be much greater than $f_{\text{max}}$. For instance, $f_{\text{max}}$ for the 2.11 $\mu$m laser experiment described in SECTION 4.3.2 is approximately 2.2 kHz, since the shortest wavelength to be measured throughout the experiment is $\sim 1.8$ $\mu$m. Consequently, the external modulation frequency of the sample laser should be many times greater than 2.2 kHz. These general requirements can be summarised as follows:

$$f_{\text{mod}} \gg \frac{1}{\tau_{\text{lock-in}}} \gg f_{\text{max}}$$  \hspace{1cm} (3.2)
Once the modulation frequency of the sample laser and the time constant of the lock-in amplifier have been selected, the light to be measured must be properly aligned through the interferometer.

When measuring the spontaneous emission exiting the chalcogenide fibre, the fibre was aligned with an adjustable parabolic mirror at the entrance window. The exit signal from is focused onto the InSb detector using a fixed parabolic mirror on top of the FTIR. Alignment of the signal through the spectrometer to the detector was a major problem with this experiment. As discussed in Section 4.3.2, signal strengths were rather weak even when the fibre was directly coupled to the detector. Therefore, inserting an FTIR in between the fibre and detector made it very difficult to obtain a meaningful spectrum.

A number of different alignment techniques were tested. The FTIR operates most effectively when a collimated beam is incident on mirror M1 in Figure 3.10. This requires the use of either a suitable MIR lens or a parabolic mirror. While a lens would have been easier to align, more light would be lost in the material (e.g. CaF, KrB, ZnSe) than would be lost upon reflection off the parabolic mirror. An approximate position for the focal point at the FTIR exit can be found by using the internal blackbody source and adjusting the position of the detector. When this is complete, the alignment at the entrance side can be carried out. Initially, alignment was attempted using a helium-neon (He-Ne) red laser but with no success. So, we decided to use a more divergent source, which would be more representative of light coming out of the fibre. At first, an InAs LED with a central wavelength of about 4.3 μm was employed with some degree of success. The LED was positioned at the approximate focal point (~50 mm from centre of mirror) of the parabolic mirror and the mirror height and angle of the mirror were carefully adjusted until a signal was found. The LED position was marked by an iris. Once the signal was optimised through adjustment of both the entrance and exit components, the LED could be replaced by the fibre and fine adjustment was carried out to optimise this signal. It was found that the signal from the fibre was very easily lost and slow careful adjustment of components was necessary to maximise the signal. In later experiments, it was found that using a broadband IR source made it easier to find the signal initially. The optimum position for the fibre could be determined by using an iris in front of the IR source and moving the position of both to optimise the signal. Then the hole of the iris could be closed down to further pinpoint the optimum fibre position.
Alignment procedures were carried out with the detector output connected to the lock-in amplifier and the amplitude of the signal on the lock-in could easily be monitored as adjustments were made. Once the signal was optimised, the lock-in amplifier output was fed-back into the processing unit of the FTIR and the spectrum was measured.

### 3.2.10 Overview of experimental arrangement

The overall experimental setup is shown in Figure 3.11. For the most part, instruments used were the same for all of the spontaneous emission experiments. The power supply used was an Avtec AV-1011-B pulse generator capable of applying voltages of up to 100 V, at an adequate range of pulse widths and repetition rates. Some of the "W" laser experiments required the use of a BNC 6040 pulse generator in order to apply voltages above 100 V, which were necessary for lasing. Measurement of the drive current was carried out using a Tektronix CT2 transformer probe connected to a Tektronix TDS 3012 oscilloscope. Processing of the optical output signal was carried out firstly by the InSb detector and pre-amplifier, then a pulsed electrical signal is then sent to an Stanford SR830 lock-in amplifier, where the signal is averaged and a DC output signal is sent to the computer. A laboratory computer equipped with a GPIB (IEEE 488) control card and Labview software was used to control the instrumentation for each experiment.
3.3 Hydrostatic pressure measurements

The hydrostatic pressure results described in this study were carried out using a helium gas compressor system. This system uses three piston-in-cylinder stages to compress helium gas into a small pressure cell, where the sample is mounted. This system is more complex and much more prone to failure than the liquid based piston-in-cylinder systems which are routinely used for NIR experiments. Still, the gas pressure system has two distinct advantages over the liquid system, which are particularly useful for MIR experiments. Firstly, the pressure medium (He) is transparent in the MIR, so absorption in the pressure medium is not a problem. Many of the liquid pressure media commonly used in NIR experiments have strong absorption features in the MIR. Secondly, the gas pressure system can be cooled to cryogenic temperatures, whereas this is not practical with the liquid systems, due to its bulk and the fact that the pressure media can freeze. High pressure experiments at low temperature are often desirable as not all MIR devices have reached a stage of development where easy RT operation is possible.

In the following sections, the basics of the gas pressure system will be explained, then details of the pressure cell, its preparation and the sample mount will be discussed. A description of the temperature control system which was developed will follow and finally the experimental setup and procedure will be outlined.

3.3.1 Helium gas pressure system

The helium gas pressure system consists of three gas compression stages. Each compression stage is a separate piston-in-cylinder arrangement, which is pressurised by using an oil compressor. A series of valves control the compression and pressurised gas is transferred to the pressure cell via a capillary tube. Stages 1 and 2 increase the pressure to 3.5 kbar and stage 3 is used to increase pressure to the maximum, which in the current arrangement is 10 kbar, limited by Cu:Be capillary and pressure cell. Stage 3 also houses the pressure gauge which consists of a manganine coil, whose resistance variation with pressure is well-known. The pressure gauge is checked and recalibrated before each experiment. As you can imagine, this system is far more complex than the single-cylinder liquid system and hence requires constant maintenance and repair. Also, helium is very fluid and leaks easily. In short, although ideally suited to MIR experiments, reliability of this system is rather poor and continually
hampered progress of this project, particularly during low temperature, high pressure measurements. Safety, is another major consideration for the gas pressure system, even more so than with liquid based systems as there is a great deal more energy stored in the pressurised gas (whereas liquids are much less compressible, so less work is done in the pressurisation). Approximately 90 litres of helium gas is compressed into a volume of 10 cm$^3$. For this reason, the entire experimental arrangement was surrounded by a polycarbonate enclosure. This presented more experimental challenges, which will be discussed in the following sections.

### 3.3.2 The pressure cell

The pressure cell used in this project is shown in Figure 3.12. A high pressure plug on each end allows exchange of samples and of the optical window. Helium gas enters the cell through a high pressure capillary, which is sealed in place.

As well as sealing one end of the pressure cell, the electrical plug has two electrical feed-throughs sealed by vespel seals and a custom-made laser mount which is attached to the high pressure side. The optical plug contains a sapphire window, which was chosen for this work as it is transparent.
from $\sim 150$ nm to $\sim 6 \mu m$. Both plugs are sealed using tin-coated brass seals rings. The seals rings, plugs and cell openings all need careful cleaning with solvent prior to the experiment to ensure a good seal can be obtained. The cell is then tightened at each end to a specified torque and ready for use.

### 3.3.3 Temperature control - pressure system

Temperature control was an important factor to make the high pressure, low temperature experiments described on 'W' lasers presented in Chapter 6 possible. MIR lasers, especially in the less developed 3 - 4 $\mu m$ range, do not operate easily at RT. The 'W' lasers described in Chapter 6 lie within this wavelength range and while pulsed operation at RT was possible with some of these devices, it was not easily accomplished and so it was impractical to attempt a pressure measurement at RT with these lasers. Instead, it was decided to develop a fully-controlled cryostat system to cool the entire pressure cell to a desired temperature and to maintain that temperature with minimal fluctuation.

A home-made cryostat already existed for the gas pressure system but lacked control of the temperature. The cryostat was comprised of a copper liquid nitrogen bath with fill and boil-off tubes, attached to the bath was a copper mount to which the pressure cell could be fixed. This was housed in a sealed aluminium outer chamber to allow evacuation of the system. In order to maintain a stable temperature throughout an experiment with this system it had been necessary to cool to the minimum temperature possible ($\sim 100$ K), which required constant filling with liquid nitrogen for about 7 hours, due to the large thermal mass of the pressure cell. Even at minimum temperature it was difficult to counter-act fluctuations in temperature as the pressure was changed. Also, from a physics point of view, many of the loss processes of interest are de-activated below 100 K and so an intermediate temperature between 100 K and RT is desirable.

A number of different modifications were needed to make the system more controlled and usable. Firstly, the source of the slow cooling problem was identified. The interface between the liquid nitrogen bath and the mounting rig was pinpointed as the thermal blockage. The copper surfaces of these two components had become oxidised, causing an increase in thermal resistance between them. Once these surfaces were polished, the thermal contact was much improved and cooling time was significantly reduced. In fact, the thermal contact was then too good and had to be regulated through
the insertion of insulating sheets. Testing was then conducted to ascertain the optimum balance between cooling power and temperature stability. Secondly, a platinum resistance thermometer was installed in such a way that it could be connected to the bottom of the pressure cell. The cell temperature could already be monitored by two thermocouples but these were not compatible with the temperature controller to be used.

Lastly, some form of heater was required. Two 25 W heater pads were employed and were fixed to the sides of the mounting rig. The heaters and thermometer are both wired back to the Oxford Instruments ITC504 temperature controller. Although maybe not as efficient as a commercial system, this system performed reasonably well. Temperature stability within 2 K over a full pressure experiment was possible but cooling was still quite time-consuming due to the bulk of the pressure cell and mounting rig.

3.3.4 Overview of experimental arrangement

Pressure experiments throughout this project ranged in complexity from a basic measurement of the light-current \((L - I)\) curve of a laser as a function of pressure to measurement of its \(L - I\) curve and wavelength as a function of pressure, at low temperature. In a simple measurement of \(I_{th}\) with pressure, the liquid nitrogen cooled InSb detector was simply positioned in front of the optical window of the pressure cell. The L-I is first measured at atmospheric pressure and the position of the detector is adjusted and fixed, prior to the application of pressure. The signal strength must be sufficiently strong but there should be no risk of detector overload when the detector is fixed in its position, since the enclosure cannot be accessed while the system is pressurised. All other control equipment was positioned outside the polycarbonate enclosure.

When spectral measurements were required, the optical output beam had to be directed out of the main enclosure to allow for adjustments to optical components when the system was pressurised. The arrangement for this type of measurement is illustrated in FIGURE 3.13. A CaF\(_{2}\) lens of suitable focal length was used to collimate the output laser beam as it emerged from the cryostat window. A periscope arrangement then directed the output beam through an opening in the enclosure, which must be well away from the axis of the pressure cell for safety purposes (in case of pressure cell window failure). Once on the safe-side of the enclosure, a flip-mounted mirror was used to either
allow the beam to pass to another lens where it was focused onto a detector, or to direct the beam into the FTIR for wavelength measurement. As a strong laser signal was to be measured, the tedious alignment procedures described in SECTION 3.2.9 were not necessary and initial alignment could be carried out with a red He-Ne laser.

High pressure measurements at low temperature presented additional complications to an already challenging experiment. Experiments were performed in the same manner as described above but with the pressure cell mounted inside the cryostat. As some of the devices studied here could not be operated at RT, it was necessary to cool the pressure cell to low temperature and set the final alignment. When alignment was complete, the system was warmed back to RT, since it was necessary to bring the system to high pressure at RT first, in order to achieve an adequate seal. When the system was successfully sealed at high pressure, it could then be cooled again and experiments could begin. Once pressurised, only the optics on the safe-side of the enclosure could be adjusted. All pressure measurements were taken while decreasing pressure and then repeated while increasing pressure (or vice versa for RT experiments) in increments of 0.5 or 1 kbar, in order to identify any hysteresis. Temperature control was carried out as detailed in SECTION 3.3.3.
3.4 Summary

In essence, the experimental setup used for the spontaneous emission analysis is very similar to that used in NIR spontaneous emission analysis experiments, except that some key elements have to be replaced by elements suitable for MIR wavelengths. It is these key elements which are weaker and more technologically immature in comparison to their NIR equivalents. The use of these weaker elements to achieve reasonable, quantitative results required much development work. A new MIR spontaneous emission analysis setup was developed during this project, through development of techniques to cope with the less advanced MIR components. Knowledge and experience was called upon as much as possible but often learning by trial and error was the only way forward.

Hydrostatic pressure experiments for the MIR devices were more challenging for a number of reasons including; using the less reliable gas pressure system, using MIR optical components and the need to cool the system to low temperature in some cases. For example, a complex high pressure, low temperature experiment to measure the change in $I_{th}$ and wavelength with pressure has many crucial elements, each of which is susceptible to failure. In spite of these difficulties, the high pressure experiments yielded some very interesting results.

In summary, the MIR experiments performed in this project were inherently more complicated and less well-established than their NIR counterparts but through innovation and perseverance, successful results were achieved.
Chapter 4

Spontaneous emission analysis of type-I GaInAsSb lasers

4.1 Introduction

The analysis of spontaneous emission characteristics as a function of current and temperature has been successfully used to quantify the loss processes in near-infrared semiconductor lasers for telecommunications applications [74]. Here, this technique has been applied to mid-infrared (MIR) lasers with GaInAsSb QWs in their active region and a type-I band alignment between the QW and the AlGaAsSb barrier layers. The experimental technique was adapted for use at MIR wavelengths as described in SECTION 3.2. Integrated spontaneous emission was measured as a function of current at a range of temperatures between 80 K and RT. Results are used to examine the relative importance of different loss mechanisms in these devices and comparison to similarly structured near-infrared (NIR) devices is made. Further analysis of the spontaneous emission characteristics can yield quantitative information on the relative contributions from different loss mechanisms and such information can be used to implement changes which minimise the contribution from these loss mechanisms and enhance device performance. This data can help device growers to make more informed engineering decisions and avoid many 'trial and error' steps, which themselves are subject to variations in growth quality and other repeatability issues.

The increased threshold current and temperature sensitivity of NIR QW lasers with increasing wave-
length has been shown to be as a result of the increased contribution from Auger recombination with decreasing band gap. FIGURE 4.1 (from data published by Sweeney et al [82,83]), generated using the application of hydrostatic pressure to several NIR devices, shows the trend of increasing threshold current towards longer wavelength, which is attributed to the increased influence of Auger recombination [82]. It is interesting to consider how this trend may continue into the narrower band gap MIR region and how the threshold current densities of MIR devices will compare to that of the wider band gap NIR lasers. Looking at FIGURE 4.1, it can be seen that at wavelengths longer than 2 \( \mu \text{m} \) (\( \sim 620 \text{ meV} \)), the threshold current density would be expected to be many times greater than that of a 1.5 \( \mu \text{m} \) device.

Figure 4.1: Variation of the normalised threshold current density with lasing energy, \( E_{\text{lase}} \), using high pressure techniques to vary the band gap energy of several near-infrared lasers, as previously published by Sweeney et al [82,83].
CHAPTER 4. SPONTANEOUS EMISSION ANALYSIS OF TYPE-I GaInAsSb LASERS

In this chapter, the results for GaInAsSb devices emitting at 2.37 µm will be shown and compared to the results for similarly structured NIR InP-based devices emitting at 1.5 µm. Then, analysis of GaInAsSb devices with an emission wavelength of 2.11 µm and similar structure to the 2.37 µm lasers will be presented and discussed in relation to both the 2.37 µm and 1.5 µm lasers. Experiments on the 2.11 µm devices were motivated partly through interest in how these devices operate at wavelengths closer to 2 µm and partly by the interesting experimental results of the 2.37 µm devices.

Both the 2.37 µm and the 2.11 µm lasers studied in this chapter were grown by solid-source molecular beam epitaxy (SS-MBE) on n-type (100) GaSb substrates (for the reasons discussed in SECTION 1.3) by researchers at the University of Montpellier, France. SS-MBE is the growth technique of choice for these type of lasers, as very high quality material can be grown and the high throughput of metal organic chemical vapour deposition (MOCVD) is not necessary at this stage of development. Both devices contain compressively strained GaInAsSb QWs separated by AlGaAsSb barrier layers. The 2.37 µm devices have three QWs and 1.42 % strain, while the 2.11 µm devices have different composition, only two QWs and 1.3 % strain. The main differences in the two devices are highlighted in Table 4.1. Full details of the device structure for both lasers can be found in APPENDIX A.

Standard photolithography techniques were used to fabricate lasers with a 100 µm-wide metal contact stripe for the 2.37 µm lasers. The metal contacts on the top and bottom of the devices consisted of Pt/Au and a thick gold layer deposited respectively. The 2.11 µm lasers were fabricated with a ridge-waveguide geometry with a ridge width of 6 µm, which was fabricated using chemical etching and SiO₂ for electrical isolation.

4.2 Spontaneous emission analysis of λ=2.37µm lasers

Investigations of the temperature dependence of the spontaneous emission characteristics of the 2.37 µm lasers described above were conducted with the aim of exploring the important recombination
processes which influence their operation.

The devices were received in wafer form. At Surrey, the wafer was cleaved into bars and then into individual Fabry-Perot lasers with cavity lengths of 0.5 mm and 1 mm. Although an increase in output power could have been achieved through the application of highly reflective and anti-reflection coatings, the facets were left uncoated for these experiments for simplicity purposes [31].

The lasers were measured in pulsed mode at a duty cycle of 2% with a 1 μs long pulse, to minimise Joule heating effects. Devices were initially tested at lower duty cycles but no heating effects were observed by increasing the duty cycle to 2% (which helped to increase the signal to noise ratio of the spontaneous emission signal). The experimental setup used in these measurements is described in SECTION 3.2. The threshold current density of the devices was measured to be approximately

Figure 4.2: Temperature dependence of the threshold current density per QW for 1.5 μm lasers (data taken from Sweeney et al [74]) and for the 2.37 μm devices. The 2.37 μm devices clearly have a lower threshold density, contrary to expectations from FIGURE 4.1.
126 A cm\(^{-2}\) (42 A cm\(^{-2}\)/QW) at RT, which is considerably lower than that of a typical near-infrared (NIR) InGaAs(P) device emitting at 1.5 \(\mu m\) [74], as plotted in Figure 4.2. This is rather surprising given the suggested trend of Figure 4.1, which indicates that the threshold current density of the MIR device should be expected to be several times larger than that of the NIR device. Identification of the primary reason for this low threshold value prompted further investigation and became an important objective of this part of the project. Reduction of internal losses [3, 31, 84], reduction of defects in the material [31] and the use of strain engineering to reduce the \(m^\ast_m/m^\ast_c\) ratio [3], and hence the transparency current, have been cited as reasons for the low thresholds observed at these wavelengths. However, it is unclear why the threshold current densities of these lasers were so low in comparison to NIR devices. Although lower than that of the 1.5 \(\mu m\) InP-based NIR devices [74], the threshold current density of the 2.37 \(\mu m\) lasers is still temperature sensitive (Figure 4.2) and the origin of this temperature sensitivity will also be explored.

The low threshold current density measured for the 2.37 \(\mu m\) devices can be investigated by considering how the different recombination processes depend on the band gap, \(E_g\). Firstly, consider how radiative recombination depends on \(E_g\). The radiative current density at threshold, \(J_{rad}\), of the 2.37 \(\mu m\) device would be expected to be smaller than that of the 1.5 \(\mu m\) device, since \(E_g\) of the 2.37 \(\mu m\) device is smaller, but could this difference account for the difference in \(J_{th}/QW\) of the two devices? As discussed with regard to the change in \(E_g\) with increasing pressure in Section 2.11, the \(J_{rad} \propto E_g^2\) relationship for a near-ideal QW laser is a reasonable approximation. Therefore \(J_{rad}\) for the 2.37 \(\mu m\) device should be 40\% of \(J_{rad}\) for a 1.5 \(\mu m\) device. \(J_{rad}\) is known to account for 20\% of \(J_{th}\) (200 Acm\(^{-2}\)) in the 1.5 \(\mu m\) device [74]. Therefore, if \(J_{rad}\) for the 1.5 \(\mu m\) device is 40 Acm\(^{-2}\), \(J_{rad}\) of the 2.37 \(\mu m\) device would be expected to be \(\sim 16\) Acm\(^{-2}\) (through the \(J_{rad} \propto E_g^2\) relationship). Since \(J_{th} > 16\) Acm\(^{-2}\) for the 2.37 \(\mu m\) device, the effect of the reduction in \(J_{rad}\) alone, cannot explain the difference in \(J_{th}\) of the two devices. The difference in the non-radiative processes which influence the threshold current of the devices must therefore be considered. An analysis of the spontaneous emission characteristics, as described in Section 3.2 was carried out, in order to examine these recombination processes, experimentally.

Figure 4.3 shows a typical light-current \((L - I)\) characteristic for the facet emission and a typical spontaneous emission light-current \((L_{se} - I)\) curve at RT. The fact that the \(L_{se} - I\) curve does
Figure 4.3: (a) Room temperature facet emission $L - I$ curve, (b) spontaneous emission $L_{se} - I$ curve and (c) a In-In plot where the gradient close to threshold, $Z_{th}$, indicates the dominant recombination path.
not pin above threshold was investigated as described in Section 3.2. There is no evidence of the collection of ASE in the spectra and the non-pinning of the $L_{sc} - I$ curve is proven to be simply as a result of the scattered lasing light collected above threshold. As shown in Section 2.10, the gradient of a plot of $\ln(L_{sc}^{1/2})$ versus $\ln(I)$ at threshold gives us the value $Z_{th}$, which is the power dependence of the current on carrier density at threshold. A plot of $Z_{th}$ as a function of temperature in Figure 4.4 shows that $Z_{th} \sim 3$ at room temperature, indicating that Auger recombination ($\propto n^3$) is the primary current path, while at low temperature $Z_{th}$ drops to approximately 2, indicating that radiative recombination ($\propto n^2$) is dominant.

$Z_{th} \sim 2$ at low temperature indicates that there is no significant defect/impurity current, since this would be evident at these temperatures when other thermally activated non-radiative recombination processes are frozen-out. This evidence indicates that the material quality is high.

![Figure 4.4](image-url)

**Figure 4.4:** The power dependence of the current on carrier density at threshold ($Z_{th}$) as a function of temperature. At RT, $Z_{th}$ is approximately 3, which is characteristic of Auger recombination dominance.
It is possible to estimate the proportional contributions of different recombination processes by looking at the change in $L_{th}$ in Figure 4.3(b) with temperature. The value of $L_{th}$ is proportional to the radiative current density at threshold, $J_{rad}$, so if $J_{rad}$ is known at one temperature, it can be found at all temperatures from the measured $L_{th}(T)$. If the assumption that all of the threshold current density at 80 K is radiative is made (i.e. $J_{rad}(80 \text{ K}) = J_{th}(80 \text{ K})$) and the proportional change in $L_{th}$ with temperature is measured, then the temperature dependence of $J_{rad}$ and hence $J_{non-rad}$, the non-radiative current density at threshold, can be determined.

Radiative and non-radiative contributions to the threshold current density have been estimated over a wide temperature range as displayed in Figure 4.5. The results suggest that at RT the threshold current consists of at most 20% radiative recombination and at least 80% non-radiative recombination. The $Z_{th}$-value of $\sim 3$ at RT implies that the 80% non-radiative component at RT is mainly Auger recombination. Interestingly, whilst the relative fraction of Auger recombination is high, it is no greater than is observed in the much larger band gap GaInAsP/InP lasers operating at 1.5 $\mu$m [8]. This may be explained by the fact that the spin-orbit splitting energy, $\Delta_{so}$, is greater than the band gap of the 2.37 $\mu$m material. Hence, the hot-hole generating CHSH Auger process, is suppressed. However, the remaining Auger recombination paths such as the hot-electron generating CHCC and the hot-hole generating CHLH processes persist and are enhanced by the small band gap and small electron effective mass of these MIR devices. The CHCC and CHLH Auger processes appear to dominate the temperature sensitivity of these devices and their RT threshold current. In the 1.5 $\mu$m lasers, it has been shown that CHSH Auger recombination is in fact the main Auger process in these devices [67] because $E_g > \Delta_{so}$ in these structures and the CHSH process is allowed. Further evidence for the importance of Auger processes in the 2.37 $\mu$m devices can be obtained from high pressure measurements, which will be presented in the next chapter.

Of course, the possibility of carrier leakage must also be addressed as this cannot be ruled out with the above argument. However, direct leakage is not expected to be a problem as it would appear that the heterobarsriers between the QW and barrier layers are sufficiently high to prevent carrier leakage. It is estimated that in this structure, the conduction band offset, $\Delta E_c \sim 370$ meV and the valence band offset, $\Delta E_v \sim 160$ meV [34,68] which are both large compared with $kT$ at room temperature. Also, experimental results on lasers emitting at 2.3 $\mu$m where the hole leakage current was measured.
directly using a test device with a hole collection layer, suggest that hole leakage is not a significant
current path in these structures [85]. Indirect leakage into satellite minima is not expected to play
a major role either. Using the L and X indirect energy gap values calculated by Adachi [69] and
the measured lasing energy, the Γ-L and Γ-X energy splittings in the QW have been estimated at ~
380 meV and ~700 meV respectively, for the 2.37 μm structure. The energy splitting between the
Γ-point in the QW and the L-point in the barrier layers is estimated to be smaller, at ~360 meV, but
all of these energy separations are much greater than $kT$ at room temperature. It should be noted
that while using the measured value of lasing energy accounts for strain and quantum confinement,
the values for the L- and X-points are calculated for bulk, unstrained material and therefore carry a
large uncertainty.
4.3 Spontaneous emission analysis of $\lambda=2.11\mu m$ lasers

4.3.1 Temperature dependence of $J_{th}$

Spontaneous emission analysis was also carried out on 2.11 $\mu m$ devices. As these devices have a larger band gap than the 2.37 $\mu m$ devices ($\sim 60$ meV larger), they are interesting from a comparative point of view as well as being representative of the shorter wavelength end of the range achievable in this material system. The energy difference between the band gap and the spin-orbit splitting energy ($\Delta_{so} - E_g$) is expected to be less than in the 2.37 $\mu m$ devices and hence the CHSH Auger processes may be allowed and may have significant impact on the threshold current density and temperature sensitivity of these devices. Also, CHCC and CHLH Auger processes are expected to have reduced significance, as a consequence of the larger band gap. As detailed in the introductory section of this chapter, the 2.11 $\mu m$ devices have lower compressive strain in the QWs and different composition than the 2.37 $\mu m$ devices. The 2.11 $\mu m$ lasers are narrow ridge-waveguide structures with a 6 $\mu m$-wide ridge. These devices were also grown at the University of Montpellier, France and were received in bar form. Devices of several cavity lengths were cleaved from 0.5 to 1.9 mm and measured as-cleaved. Measurements were carried out in pulsed mode using the experimental apparatus described in Section 3.2. A duty cycle of 2% was chosen to avoid adverse heating effects.

The threshold current density of these devices was measured to be 309 $A cm^{-2}$ at RT for the 1.32 mm long devices used in this experiment. This corresponds to 154 $A cm^{-2}$ per QW in comparison to the 2.37 $\mu m$ devices which have a $J_{th}$ per QW of 42 $A cm^{-2}$ and the 1.5 $\mu m$ devices which have $J_{th}/QW \sim 200$ $A cm^{-2}$ at RT [74]. Although significantly higher than that of the 2.37 $\mu m$ devices, $J_{th}/QW$ at RT is lower than that of the 1.5 $\mu m$ devices, which is still in contrast with the predicted trend of Figure 4.1. This is an initial indication that the 2.11 $\mu m$ devices also benefit from the suppression of the CHSH process. The fact that $J_{th}/QW$ for the 2.11 $\mu m$ devices is so much greater than $J_{th}/QW$ of the 2.37 $\mu m$ could be related to several factors. Indeed, an increase in the radiative current and a decrease in the contribution from CHCC and CHLH Auger recombination would be expected and the possible introduction of the CHSH process will cause a rise in $J_{th}/QW$. However, these effects would not be expected to account for the increased $J_{th}/QW$ observed at 2.11 $\mu m$, which is more than a factor of 3 larger. One likely effect is lateral current spreading, which is highly probable in these
lasers as the ridge width is only 6 \( \mu \text{m} \). This could cause an under-estimation of the device area and hence an over-estimation in \( J_{th} \). Unfortunately, it was not possible to quantify the current spreading during this work, as devices of different ridge widths were not available. However, an awareness of the possible influence of current spreading will be maintained throughout the analysis. Another factor which appears to be important is the presence of a large non-radiative current through defects and impurities (SRH recombination).

The temperature dependence of \( J_{th} \) per QW for the two MIR devices and the 1.5 \( \mu \text{m} \) devices [74] is shown in Figure 4.6. The flat region in the temperature dependence between 125 K and 215 K indicates the presence of a non-radiative process which is not very temperature dependent. This is consistent with SRH recombination having a considerable influence on the threshold current and becoming dominant at lower temperature. The origin of the decrease in \( J_{th} \) at the lowest two
temperature data points is less clear but could be attributed to the de-activation of defects and hence a reduction of SRH recombination at these temperatures.

4.3.2 Temperature dependence of \( Z_{th} \)

\( Z_{th} \) is determined for these devices in the same fashion as for the 2.37 \( \mu m \) devices, where the slope of a \( \ln(I) \) versus \( \ln(L_{se}^{1/2}) \) plot near threshold gives a value for \( Z_{th} \). As non-pinning of the \( L_{se} - I \) curve was also observed in these devices, spectral analysis was carried out as described in Section 3.2. There was no evidence of unintentional collection of ASE below threshold. The non-pinning did not appear to be entirely due to scattered lasing emission and will be discussed in the next sub-section. Figure 4.7 shows the temperature dependence of \( Z_{th} \), where \( Z_{th} \sim 1 \) at 80 K, rising to about 2.6 at RT. This indicates that at low temperature the threshold current is dominated by SRH recombination (through defects and impurities) and at RT it is dominated by Auger recombination. In fact, if a \( Z = 1 \) line is fitted to the \( \ln I \) vs \( \ln L^{1/2} \) plot at 80 K as shown in Figure 4.8(a), the contribution from SRH current can be estimated at \( \sim 90\% \). This corresponds to a minimum SRH contribution to the threshold current at RT of \( \sim 40\% \).

\( Z_{th} \sim 2.6 \) at RT (Figure 4.8(b)) suggests that the threshold current at RT is dominated by Auger recombination. The substantial contribution from SRH current will cause a decrease in the value of \( Z_{th} \) that is measured. The influence of the high SRH current on the measured \( Z_{th} \)-value at RT can be estimated if we make the approximation that 40\% of the threshold current at RT is due to SRH recombination and that the remaining 60\% is due to a combination of radiative and Auger recombination. The maximum value of \( Z_{th} \) at RT when 40\% of the threshold current is attributed to SRH recombination occurs when the remaining 60\% is assumed to be all as due to Auger recombination and can be determined by an expression for \( Z \) [86]:

\[
Z = 1 + \frac{I_{rad}}{I_{th}} + 2\frac{I_{Aug}}{I_{th}} \quad (4.1)
\]

This gives a maximum value for \( Z_{th} \) of 2.2. This value will decrease when the contribution from radiative recombination is included. Clearly, the measured value of \( Z_{th} \sim 2.6 \) is larger than the calculated maximum. This inconsistency is a possible indicator of carrier leakage, which will be
explored further with regard to the pressure measurements, presented in the next chapter.

Also, lateral current spreading could be expected to influence the measured $Z_{th}$-values if there is significant variation in the carrier density across the width of the device. However, it is difficult to estimate the magnitude of this effect without measuring devices of different ridge widths.

### 4.3.3 Pinning of the $L_{sc} - I$ curve

As mentioned in SECTION 1.3, non-pinning of the spontaneous emission $L_{sc} - I$ curves above threshold can be an indication of effects which have a negative influence on laser performance. It can be seen from Figure 4.9 (black line) that the $L_{sc} - I$ curve does not pin above threshold as expected when the carrier density clamps at threshold. Spectral measurements were taken at several drive current values above and below threshold and evidence of the collection of scattered lasing emission was
observed. The measured lasing peak did not occur with half a mode spacing of the spontaneous emission peak, confirming that ASE is not collected and does not affect the measured $Z_{th}$-values.

If the spectra are integrated with the contribution from lasing emission subtracted it can be seen from Figure 4.9, where the red circles represent the spectral data points and the black line represents the data taken with just the detector (where all light within the detector’s spectral range will be integrated), that pinning is still not observed, which indicates that some other effect is also contributing to non-pinning. It is possible that the increasing spontaneous emission above threshold is as a result of the contribution from current spreading regions (regions not lying directly under the ridge). These regions may be pumped with a lower carrier density than the region directly beneath the ridge and hence may not have enough gain to reach threshold. Therefore, spontaneous emission from these sections could continue to increase above the threshold current of the laser. Other possibilities include, inhomogeneities in the material and internal heating.
4.4 Summary

In conclusion, the 2.37 μm devices are dominated by radiative recombination at low temperature, while their RT operation is dominated by Auger recombination. It is estimated that up to 80% of the threshold current of these devices at RT is due to Auger recombination, which is no more than in 1.5 μm InGaAs(P) devices [74] which have a much larger band gap. It is suggested that the suppression of the CHSH Auger process, which is dominant in the 1.5 μm lasers [67] is primarily responsible for the low threshold current densities measured. Carrier leakage is considered unlikely to be of significance in these lasers, since estimates of band offsets are many times $kT$.

$Z_{th}$-values for the 2.11 μm vary from $Z_{th} \sim 1$ at 80 K, indicating that most of the threshold current at this temperature is due to SRH recombination, to about $Z_{th} \sim 2.6$ at RT, suggesting that Auger
recombination is the dominant current path at RT. However, these results need to be considered with caution, as there is the possibility that current spreading could have an impact on the measured $Z_{th}$-values and that carrier leakage could also play a role in the operation of these lasers. Overall, these results suggest that different processes dominate the low-temperature threshold current of the two devices but that the RT threshold current of both devices is dominated by Auger recombination. Further exploration of these issues will be carried out with reference to the pressure dependence data for these devices, presented in the next chapter.
Chapter 5

Hydrostatic pressure dependence of GaInAsSb type-I lasers

5.1 Introduction

The use of hydrostatic pressure as an investigative tool in the study of III-V semiconductors is discussed in Section 2.11. Indeed, this technique has been used extensively in the study of band gap dependent processes in NIR and visible laser devices [87-89]. In this chapter, the results of high pressure measurements on GaInAsSb type-I lasers emitting in the MIR spectral range are discussed. These results will be analysed in conjunction with the spontaneous emission results presented in the previous chapter, to fully assess the loss processes affecting the performance of these devices. While high pressure measurements are often a very good method of identifying the dominant recombination mechanism in a semiconductor laser quickly, if several different loss processes are possible, it is sometimes difficult to distinguish between them. It is then, that the use of high pressure measurements in tandem with spontaneous emission analysis can help bring clarity to the assessment of the important loss processes in a device. Section 3.3 describes the experimental equipment and techniques used in these measurements.

The spontaneous emission analysis presented in the previous chapter was carried out on two devices emitting at 2.37 µm and 2.11 µm. The same devices are studied here, except the shorter cavity lengths (~0.5 mm), which are more suited to mounting in the pressure apparatus, are measured.
The objective is to help build an overall picture of the important non-radiative processes in the GaInAsSb material system. In particular, hydrostatic pressure results will be used to identify the type of Auger process which is most important in each device. As discussed in Section 2.8.3, there are three main types of Auger recombination processes which are usually considered important in III-V materials, and it is often helpful to know which of these processes is most important. Additionally, the pressure dependence of a third device grown by researchers at Arizona State University, USA, emitting at 2.18 \( \mu m \) will be presented. These lasers arrived at Surrey in individual chip form without any facet coatings. The stripe width was 60 \( \mu m \), while the cavity lengths were approximately 1.6 mm. Details of the structure of all three devices are described in Appendix A and key differences are summarised in Table 5.1, for clarity.

### 5.2 How the threshold current density varies with pressure

**Figure 5.1** shows the variation of \( J_{th} \) with pressure for the 2.37 \( \mu m \), the 2.18 \( \mu m \) and the 2.11 \( \mu m \) devices. For the 2.11\( \mu m \) data, the estimated minimum SRH contribution to the threshold current density of 40\% at RT (as determined from the spontaneous emission analysis in the previous chapter) has been removed from the \( J_{th} \)-value at ambient pressure to allow better comparison with the 2.37 \( \mu m \) lasers. The same value of \( J_{SRH} \) has been subtracted from the \( J_{th} \)-value at each pressure, as \( J_{SRH} \) is assumed to be independent of pressure. The general approach to the interpretation of the pressure dependence of \( I_{th}/J_{th} \) of QW lasers is considered in Section 2.11.

Clear differences can be seen in the pressure dependence of \( J_{th} \) for the three devices measured which indicates that different processes dominate their threshold currents. \( J_{th} \) for the 2.37 \( \mu m \) lasers decreases with pressure while in the two shorter wavelength devices \( J_{th} \) increases with applied pressure. The fact that \( J_{th} \) of the 2.11 \( \mu m \) device is not comparable to that of the 2.37 \( \mu m \) devices can be partly attributed to the fact that current spreading (which is likely to be significant in these 6
$\mu m$-ridge structures) will cause an over-estimation of $J_{th}$ in the $2.11 \mu m$ lasers. Also, while the $2.37 \mu m$ devices have 3 QWs and very low internal losses of $4 \text{ cm}^{-1}$ [31], the $2.11 \mu m$ structures only have 2 QWs and may have significantly higher losses. This would increase the threshold carrier concentration $n_{th}$ and hence increase $J_{th}$ (Auger recombination ($\propto n^3$) would also become more dominant at higher $n_{th}$). The differences in the general trend of each device can be more easily appreciated in the plot of Figure 5.2 where $J_{th}$ for each device is normalised to 1 at atmospheric pressure. The distinct difference in the pressure dependence of the $2.37 \mu m$ and the $2.11 \mu m$ devices must be considered in light of the fact that the spontaneous emission analysis presented in the previous chapter, indicates that both devices are dominated by Auger recombination at RT.

The threshold current of the $2.37 \mu m$ lasers initially decreases with pressure, which is consistent with the band gap induced decrease in the Auger recombination processes. This is consistent with

![Figure 5.1: Pressure dependence of the threshold current density of all three GainAsSb lasers at RT. (The $J_{SRH}$ contribution to $J_{th}$ in the $2.11 \mu m$ lasers has been removed)](image-url)
our temperature dependence measurements. At about 7 kbar, the threshold current appears to go through a minimum and then begins to increase, indicating the introduction of another important recombination process. While this is not a problem for normal operation of the 2.37 µm devices, it is of interest for devices emitting closer to 2 µm, since at 7 kbar, \( E_{\text{lase}} \sim 605 \text{ meV} \) and \( \lambda \sim 2.05 \) µm. The process most likely to be responsible for the above-7 kbar increase, is CHSH Auger recombination. At atmospheric pressure the CHSH Auger process is suppressed in this device, since the spin-orbit splitting energy, \( \Delta_{\text{so}} \), is greater than the band gap, \( E_g \), but at high pressures \( E_g \) approaches \( \Delta_{\text{so}} \) and the CHSH process can become significant [68,90] as shown in FIGURE 5.3. This may also be accompanied by inter-valence-band absorption (IVBA) between the spin-split-off band and the heavy hole band, which will further increase the threshold current and reduce the slope efficiency above threshold [70]. Unfortunately, it was not possible to collect reliable slope efficiency.

![Figure 5.2: Pressure dependence of the normalised threshold current density of all three GainAsSb lasers at RT. (The J_{SRH} contribution to J_{th} in the 2.11 µm lasers has been removed)](image-url)
data in this experiment which would have been useful to help identify IVBA. Another significant outcome of this measurement is that the potential role of carrier leakage, which could not be ruled out through the spontaneous emission analysis, can be better assessed with respect to the measured pressure dependence. The possibility of carrier leakage is discussed separately in detail in Section 5.3.1.

Figure 5.3: (a) Suppression of the CHSH Auger process when $\Delta_{so} > E_g$ and (b) the activation of the CHSH process with applied pressure, as $E_g$ is increased and becomes comparable to $\Delta_{so}$.

Turning to the pressure dependence of the larger band gap 2.18 $\mu$m devices, we see that it shows an increase in threshold current from atmospheric pressure, suggesting that the CHSH process may already be occurring at ambient pressure. As pressure is increased and $E_g$ approaches $\Delta_{so}$ there is an increase in CHSH Auger recombination which causes an increase in $J_{th}$. The rise in threshold of the 2.11 $\mu$m devices is even more pronounced, as its band gap is larger than that of the 2.18 $\mu$m devices. Additionally the higher compressive strain in the 2.18 $\mu$m lasers mean that they have a significantly reduced contribution from Auger recombination, due to the reduction in the effective mass for holes in the valence band. As mentioned for the above-7 kbar 2.37 $\mu$m results, it is very possible that IVBA also occurs and couples to the CHSH process, as the resonance between the $E_g$ and $\Delta_{so}$ is approached. These results show that although both the 2.37 $\mu$m lasers and the shorter wavelength
2.11 μm devices are dominated by Auger recombination, they are dominated by different types of Auger process. The introduction of CHSH Auger, which will increase as $E_g$ approaches $\Delta_{so}$, is most likely to be responsible for the rise in threshold current with pressure in the 2.11 μm devices. The increase in the radiative component of the threshold current will also contribute to the rise in $J_{th}$ with pressure, although radiative recombination does not appear to be the dominant current path. The increase in $J_{rad}$ is expected to be approximately proportional to $E_g^2$, but the change in optical confinement factor may reduce this rate of increase as discussed in Section 2.11.
5.3 How the threshold current density varies with lasing energy

In order to take into account the difference in band gap of the three devices, the threshold current is plotted versus the lasing energy, $E_{lase}$, in Figure 5.4. The pressure dependence of $E_{lase}$ for the 2.37 $\mu$m and 2.18 $\mu$m devices is taken from ref. [91] and for the 2.11 $\mu$m device (Figure 5.6) it was measured using the setup described in Section 3.3. Figure 5.5 shows the same results on a plot where the 2.37 $\mu$m data is normalised to atmospheric pressure and the data for the two shorter wavelength devices is normalised to the 2.37 $\mu$m data at their ambient $E_{lase}$-values.

These results clearly indicate the energy regimes in which the different Auger processes dominate. For the 2.37 $\mu$m lasers, the optimum lasing energy is $\sim$600 meV (2.1 $\mu$m) for which the CHCC or CHLH processes have been minimised and before the CHSH process has switched-on. The 2.18 $\mu$m and

![Figure 5.4: Threshold current density as a function of lasing energy, $E_{lase}$, for type-I GainAsSb lasers emitting at 2.37 $\mu$m, 2.11 $\mu$m (with SRH component removed) and 2.18 $\mu$m.](image-url)
2.11 μm devices have their minimum threshold current at atmospheric pressure which corresponds to lasing energies of approximately 570 meV and 590 meV respectively. The immediate increase in threshold current with lasing energy in these devices suggests that the CHSH Auger process is allowed to occur in these devices at ambient pressure. The fact that the minimum for all three devices does not occur at the same lasing energy is most probably related to several aspects of the band structure and to possible differences in $n_{th}$. The difference in $\Delta_{so}$ and in the effective masses of the bands with different composition and strain are not very well known for quaternary alloys and will have an impact on the contributions from different recombination processes.

Figure 5.5: Normalised threshold current as a function of lasing energy, $E_{lase}$, for type-I GaInAsSb lasers emitting at 2.37 μm, 2.11 μm (with SRH component removed) and 2.18 μm.
5.3.1 Is it possible that carrier leakage could play a major role?

Another possible loss process which must be taken into consideration is carrier leakage, whether directly from the QW into the barrier layers or indirectly from the Γ-valley in the QW to the L or X-valleys of the QWs and/or other layers. At this point it is easier to fully assess the probability of carrier leakage, in light of experimental spontaneous emission and high pressure results and theoretical estimates of band offsets.

If direct leakage from the QW into the barrier layers were the dominant loss process, a pressure independent threshold current would be expected. This is related to the fact that the band gap pressure coefficients of the QW and barrier layers are similar and that the change in the valence band offset in III-V QW systems is measured [79] and calculated [80] to be negligibly small i.e. there is no significant change in the band offset ratio. Also, the direct band offsets between the QW and barrier materials in this device are estimated to be over 325 meV in the conduction band and over 140 meV in the valence band [34,68]. These values are many times $kT$ at RT and hence are not
expected to give rise to a significant carrier leakage path.

Leakage to indirect satellite valleys must also be considered as a possible loss mechanism. An alternative explanation for the rise in \( J_{th} \) observed in the 2.11 \( \mu m \) and 2.18 \( \mu m \) devices and also in the 2.37 \( \mu m \) devices above 7 kbar could involve indirect leakage into the L-minima. The L-minima in the barrier and QW layers are closest in energy to the \( \Gamma \)-point in the QW and the \( \Gamma \)-L splitting energy is known to decrease with increasing pressure [81]. Indeed, a continued increase in \( J_{th} \) for the same 2.37 \( \mu m \) devices up to 19 kbar has been measured by Adamiec et al [91]. Figure 5.7 shows a fit to the data measured by Adamiec et al, where the black circles represent the non-radiative component of the threshold current and the red line represents a line of best fit to this data assuming that CHSH Auger recombination plays no role and that the threshold current is made up of contributions from the remaining Auger processes and indirect carrier leakage to the L-minima.

Firstly, the radiative component of the threshold current, which is known from the spontaneous emission analysis presented in the previous chapter to be (~20%) is scaled as a function of pressure using the \( I_{rad} \propto E_g^2 \) approximation. This component is then removed to leave only the pressure dependence of the non-radiative threshold current, \( I_{non-rad} \). The exponential decay of Auger recombination in these devices with pressure (where CHSH Auger is suppressed) is estimated from the decrease in \( I_{non-rad} \) from ambient pressure to about 6 kbar. This was actually calculated from a ln-plot of the 2.37 \( \mu m \) data shown in Figure 5.2, as a good fit to a reasonable number of data points was possible. The rate of decrease of Auger recombination with pressure is then calculated across the entire pressure range using Eqn.(5.1)

\[
I_{Aug} = I_0 e^{\alpha P}
\]

where \( I_0 \) is the current due to Auger at ambient pressure, \(-\alpha \) is determined from the measured decrease in \( I_{non-rad} \) as described above and \( P \) is the applied pressure.

The increase in indirect leakage with pressure is calculated from Eqn.(5.2) below:

\[
I_{leak} = I_0 e^{\frac{dE_a}{dP} P} \frac{P}{kT}
\]

where \( dE_a/dP \) is the change in the \( \Gamma \)-L splitting energy with pressure. Here, the value for \( dE_a/dP \)
is taken to be -5 meV/kbar, which is taken from the measured shift in lasing energy with pressure of about 10.5 meV/kbar [91], and an experimental value for the pressure dependence of the band gap at the L-point for GaSb of 5.5 meV/kbar, measured by Noack et al [81]. The relative contributions from Auger and leakage current were varied to get the optimum fit to the experimental data.

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**Figure 5.7:** Fit to experimental data of Adamiec et al [91]. The fit assumes 3.3% of the threshold current at ambient pressure is due to indirect carrier leakage and 96.7% is due to Auger recombination. The CHSH Auger process is assumed to be suppressed throughout the range.

**Figure 5.7,** shows that for a small contribution of 3.3 % leakage at atmospheric pressure, a good fit to the experimental data can be achieved. This result suggests that the alternative explanation, which does not involve any introduction of CHSH Auger recombination, is certainly possible if such a leakage path exists. As outlined in Section 4.2, approximations of the lowest \( \Gamma_{QW} - L \) splitting energy show that the splitting between the \( \Gamma_{QW} \)-point of the QW and the L-point of the barrier
layers is in the region of 360 meV. While there is uncertainty in this value, since the L-point energy is determined for bulk, unstrained material, and bearing in mind that the L-minima have a high density of states, it would seem that the uncertainty in this value would need to be very large indeed to make this explanation plausible.

The smallest indirect energy separations in the 2.11 μm devices, occur between the \( \Gamma_{QW} \)-point in the QW and the L-points in the QW and barrier layers. We estimate the \( \Gamma_{QW} \)-\( L_{QW} \) splitting to be \( \sim 260 \) meV and the \( \Gamma_{QW} \)-\( L_{\text{barrier}} \) splitting to be approximately 320 meV in the 2.11 μm devices \([69]\). 2.11 μm corresponds to about 6 kbar on the plot of Figure 5.7, where the proportion of leakage current is estimated to be about 16%. Again, there would need to be a substantial uncertainty in this 260 meV approximation for the \( \Gamma_{QW} \)-\( L_{QW} \) splitting to suggest that 16% of the threshold current is lost through leakage.

### 5.4 Conclusions

In summary, it was found, through the use of spontaneous emission analysis, that the threshold current of both the 2.11 μm and 2.37 μm lasers is dominated by Auger recombination. The high pressure results show that different types of Auger processes dominate the threshold current of the two devices. In the 2.37 μm device the threshold current decreases with pressure, which is consistent with Auger recombination being the primary current path at threshold. However, at higher pressures, the CHSH Auger recombination process (which is suppressed at ambient pressure as \( \Delta_{so} > E_g \)) is allowed and causes an increase in the threshold current. In the 2.18 μm and 2.11 μm devices, where \( E_g \) is larger, it seems that the CHSH Auger process is allowed at atmospheric pressure and increases in significance as pressure is applied and \( E_g \Rightarrow \Delta_{so} \). It is evident from Figure 5.5 that there is an energy regime for which the CHCC or CHLH processes have been minimised and the CHSH process is suppressed. The energy at which this occurs will depend on the value of \( \Delta_{so} - E_g \). For these devices the minimum occurs in the \( E_{\text{linear}} \)-band of 570-610 meV. It would appear that precise engineering of the strain and composition of lasers at these wavelengths, could keep them in this ‘minimal-Auger region’ and help maximise device performance. The effect of strain on the Auger mechanism in the different devices will also be important. The higher strain in the 2.18 μm lasers may help to reduce Auger recombination in this device, making it less sensitive to pressure than the 2.11 μm laser.
Chapter 6

Origins of temperature sensitivity in "W" diode lasers

6.1 Introduction

In the 3.2 - 3.8 $\mu$m spectral range, type-II "W" structure lasers display very good performance in comparison to competing technologies. However, the realisation of electrically-pumped lasers operating in CW mode at RT in this spectral region has proven challenging. As discussed in Section 1.4, CW lasing has only been achieved up to a temperature of 257 K within this material system. The objective of the work presented in this chapter is to identify the primary mechanism responsible for inhibiting CW operation at RT. It has previously been speculated that defect-related (SRH) recombination was the dominant recombination mechanism at 78 K in similar optically pumped devices [55]. However, it is unclear from the available literature what the primary cause of performance degradation at higher temperature is and the aim of this study is to investigate this. It is also suggested that suppression of Auger recombination has been achieved through the use of this structure. However, the extent of this suppression needs to be assessed and considered in relation to the inherent reduction in the radiative recombination rate which is unavoidable in a type-II structure. Most MIR-systems need some form of Auger suppression due to their narrow band gaps but this may only be a start-point, reducing Auger recombination to a point where low temperature lasing is possible. Spontaneous emission analysis and hydrostatic pressure techniques have been used here to identify and examine
the important loss mechanisms involved in the operation of these lasers.

Spontaneous emission experiments were carried out between 80 K and 200 K, using the technique outlined in Section 3.2. The spontaneous emission light-current (L-I) characteristic curves will be presented and analysed in order to determine the significance of the radiative and non-radiative processes over the temperature range. Results from hydrostatic pressure measurements, where pressure was used to examine the band gap dependent processes, will be shown and used in conjunction with the spontaneous emission analysis to build a clearer picture of the radiative and non-radiative processes involved in device operation. The helium gas pressure system described in Section 3.3 was used to perform these measurements.

6.2 Device Structure

The lasers were grown by molecular beam epitaxy on GaSb substrates by our collaborators at the Naval Research Laboratory, Washington D.C., U.S.A. They contain 5 “W” periods, each comprising a Ga(In)Sb (30 Å) hole QW surrounded by two InAs (21.2 Å) electron QWs, all enclosed between AlGaSb (40 Å) barrier layers. A schematic of the active region is shown in Figure 6.1. The emission wavelength of these devices is 3.24 μm at 78 K. Lasers with a 100 μm-wide contact stripe, uncoated facets and a cavity length of 1.23 mm were measured.

As detailed in Section 1.3, growing type-I antimonide-based lasers for emission at $\lambda > 3 \, \mu m$ is not easy, as it is difficult to achieve sufficient carrier confinement while maintaining a reasonable level of strain. Moving to a type-II structure can offer benefits such as good carrier confinement and the opportunity to reduce the significance of the non-radiative Auger process, as described in Section 1.4. The structure in Figure 6.1 offers several distinct advantages over more conventional type-II designs but the important issue is whether these advantages are sufficient in comparison to the reduction in the radiative recombination coefficient, $B$, which is associated with using a type-II design. Here, we hope to assess the effectiveness of these advantages through use of high pressure and spontaneous emission analysis.
6.3 Spontaneous Emission Analysis

Although the experimental technique is similar to that used for the results described in Section 4.2, the approach to the analysis of results here will be slightly different. In these lasers, the device design means that the band structure is more complicated than a simple type-I structure and hence a more cautious approach to the interpretation of experimental results is needed. As the band alignment of these devices is type-II, the assumption made in EQN.(2.8) that the three main non-radiative recombination paths of SRH, radiative and Auger recombination are \( n \), \( n^2 \), and \( n^3 \)-dependent respectively, is not as safe as for type-I structures. Therefore, a more simple approach will be taken, relating to the shape of the measured \( L_{se} - I \) curve. For the case of radiative dominance \( L_{se} \propto I \), even if \( I \propto n^2 \) is not a safe assumption. If SRH recombination is present, it will be observed as a super-linearity in the \( L_{se} - I \) curve at low current, since SRH recombination will always have a lower \( n \)-dependence than the radiative current and as \( n \) is increased the ratio of radiative to SRH current will increase. Conversely, if a process with a higher \( n \)-dependence than radiative recombination comes into play, a sub-linearity in the \( L_{se} - I \) curve will be observed. For Auger recombination, which can be assumed to have a higher \( n \)-dependence than the radiative current, the ratio \( I_{rad}/I_{Aug} \) will decrease as the current (and hence \( n \)) is increased. Addressing the interpretation in this way, assumes that some
recombination process have a weaker dependence on \( n \) than radiative recombination and others have a stronger \( n \)-dependence but does not assume any exact \( n \)-dependence.

An example of a spontaneous emission versus current curve at 80 K is shown in Figure 6.2(a). The linear section of the \( L_{se} - I \) curve indicates that over this range, the injected current is dominated by radiative recombination. Above 50 mA, a strongly sub-linear variation is observed, indicating the presence of a non-radiative current path with a stronger carrier density dependence than the radiative current. This is attributable to Auger recombination, which is known to be the primary cause of performance degradation in mid-infrared lasers at higher temperatures [8]. That this sub-linearity of the L-I curve becomes more severe with increasing temperature, as shown in Figure 6.2(b), is also consistent with Auger recombination. Once again, pinning of the \( L_{se} - I \) curve is not observed in these lasers. Spectral analysis showed that there was no collection of ASE, which supports the validity of these results.

From Figure 6.2(a), by extrapolating the linear region of the \( L_{se} - I \) characteristic to the threshold current (\( I_{th} \)) and knowing that when radiative recombination dominates \( L_{se} \propto I \) always, we can estimate the relative contributions of the radiative and non-radiative current paths at low temperature. Then, since the integrated spontaneous emission at threshold, \( L_{th} \), is proportional to the radiative current at threshold, \( I_{rad} \), by measuring the variation of \( L_{th} \) with temperature, the temperature dependence of \( I_{rad} \) and hence the non-radiative current, \( I_{non-rad} \), can be determined as shown in Figure 6.3. So, in short Figure 6.3 is generated by determining \( I_{rad} \) at 80 K using the graphical method in Figure 6.2(a) and then the proportional change in \( L_{th} \) (\( \propto I_{rad} \)) over the measured temperature range is used to determine the temperature dependence of \( I_{rad} \). The graphical method shown in Figure 6.2(a) was only used quantitatively at 80 K, as there is a reasonable linear section to which a straight line could be fitted. The \( I_{rad} / I_{non-rad} \) proportions shown graphically in Figure 6.2(b) at 140 K are only to aid visual comparison with the 80 K \( L_{se} - I \) curve.

In Figure 6.3, we see that the non-radiative component of the threshold current increases from approximately 32% at 80 K, where \( I_{th} \) is 78 mA, to 87% at 200 K, where \( I_{th} \) is 1185 mA. So, initial examination of the shape of the \( L_{se} - I \) curves shows a sub-linear dependence of light on current at high current which is suggestive of an important contribution from Auger recombination. The contribution from Auger recombination is estimated to be as much as 32% at a low temperature of
Figure 6.2: Integrated spontaneous emission light (measured through a window in the substrate contact of the laser) versus current curves. The red line indicates the threshold current of the device, measured from the facet emission at the same time. (a) The $L_{ae-1}$ curve at 80 K where we estimate the radiative and non-radiative contributions to the threshold current by the graphical method described in the main text and (b) at 140 K where the sub-linear section has clearly increased in significance, indicating that a strongly temperature dependent non-radiative recombination process is becoming important.
80 K and up to 87% at 200 K. These results are an initial indication that, although some Auger suppression is achieved through the use of a type-II band alignment, Auger recombination is still very significant in these devices and may be the primary reason for the high temperature sensitivity and low maximum operating temperature.

Another notable point regarding these results is that there is no evidence of significant SRH current. SRH recombination had been suspected to govern the lasing threshold in similarly structured optically pumped W-lasers [55] and the photoluminescence (PL) results of ref. [45] show that it could be important in these electrically pumped devices. The fact that there is no evidence of SRH recombination in the $L_{se} - I$ curves, suggests that the material and layer interface quality is good which is encouraging for this growth technology.
6.3.1 Pinning of the spontaneous emission above threshold

As mentioned in the previous section, complete pinning of the spontaneous emission $L_{se} - I$ curve above threshold was not observed in these devices Figure 6.2. As explained in SECTION 3.2, non-pinning can be due to a number of factors such as inhomogeneities in the material, current spreading or the unintentional collection of scattered lasing light. Spectral analysis was carried out in order to check for evidence of ASE collected below threshold and examine the origin of the non-pinning. Figure 6.4 shows two spectra, one below threshold and one above threshold. The above threshold spectrum shows a narrow lasing peak within the spontaneous emission spectrum which indicates that some scattered lasing light is collected above threshold. The fact that the lasing peak appears ~30 nm from the spontaneous emission peak and that there is no observable narrowing of the spontaneous emission spectrum above threshold, suggests that there is no ASE collected below threshold.

Ideally to investigate the origin of the non-pinning of the $L_{se} - I$ curve, one would carry out spectral analysis at several different drive currents and integrate the spectra to compare with the detector-only $L_{se} - I$ curve. Unfortunately, this was not possible as signal strengths were very weak and each spectrum took many hours to measure but it is still worthwhile to discuss this in relation to the $L_{se} - I$ curves in Figure 6.2. Although a lasing peak is observed in the above threshold spontaneous emission spectrum, the observed non-pinning of the spontaneous emission above threshold cannot be entirely attributed to scattered lasing emission by this analysis. In fact, the lack of a significant change of slope in the $L_{se} - I$ curves at threshold in Figure 6.2 is evidence that non-pinning may not be solely as a result of scattered lasing emission. The apparent continuation of the measured light output above threshold with the same curvature is more consistent with inhomogeneities in the QWs or uneven pumping of all five "W" periods. Uneven pumping of holes across all "W" periods has been investigated and it was concluded that this is no longer a problem with the current structure, where the confinement energies of valence subbands are engineered to provide efficient inter-well transport via light hole states [48]. However, growth of the Sb-based materials is not as advanced as other more commercially driven systems and the "W" lasers have quite a complex structure with very thin QW layers. This would suggest that inhomogeneous material growth or layer thickness could be an issue in these devices. The relatively broad linewidths measured from "W" lasers would support this suggestion [45, 54].
Figure 6.4: (a) Spectrum of the spontaneous emission collected from a W-laser below threshold and (b) the spectrum above threshold showing a narrow lasing peak indicating that scattered lasing light is being collected above threshold. Spectra were measured at 160 K.
6.4 Hydrostatic Pressure Dependence

In Chapter 5, the application of high pressure to type-I III-V MIR lasers was presented where pressure causes an increase in the fundamental band gap, $E_g$. In these type-II structures, an increase in $E_g$ of both the InAs electron confining layer and the Ga(In)Sb hole confining layer will result in an overall increase in the effective type-II band gap and the laser emission energy, $E_{lase}$. Therefore, high pressure can be used in a similar way to examine band gap dependent processes, although there may be some additional considerations to take into account. The pressure dependence of threshold current and the lasing wavelength were measured at low temperature using the helium high pressure system discussed in Section 3.3. The measured wavelength shift with pressure of these devices, as shown in Figure 6.5, yielded a pressure coefficient of $E_{lase}$ of 8.7 meV/kbar, which is in excellent agreement with the results of an 8-band k-p calculation carried out by our collaborators at the Naval Research Laboratory in the US.

![Figure 6.5: Pressure dependence of the wavelength of the devices measured experimentally (circles) and calculated theoretically (line).](image)
Figure 6.6 shows the pressure dependence of the threshold current, $I_{th}$, at a temperature of 138 K. Initially a decrease in threshold current with pressure is observed. In general, an increase in band gap (pressure) will cause a decrease of the Auger coefficient $C$ and hence in a device dominated by Auger recombination, a reduction in the threshold current will usually be observed as pressure is increased. Devices dominated by radiative recombination would be expected to show an increase in $I_{th}$ with pressure (band gap), which is shown experimentally for III-V lasers in ref. [92]. However, the change in optical confinement factor, $\Gamma$, with pressure will cause the rate of increase of $I_{rad}$ to be reduced, due to the 400 nm change in $\lambda$ over the pressure range. On the other hand, the radiative current will also be influenced by a decrease in the overlap of the electron and hole wavefunctions, since the Ga(In)Sb hole well has a larger pressure coefficient ($\sim 14.5$ meV/kbar [81]) than the InAs ($\sim 10$ meV/kbar [93]) electron wells. This will cause an increase in the barrier height for electrons in the InAs QWs with pressure. In any case, it is difficult to predict the pressure dependence of the radiative current without detailed calculations but it is unlikely to be the source of the observed decrease in $I_{th}$ with pressure.

The decrease in $I_{th}$ with pressure and the sublinearity in the $L_{se} - I$ curves appear to correlate and indicate that Auger recombination is the important non-radiative process at threshold. However, the different type of Auger processes possible in the "W" structures need to be considered. An Auger process involving recombination of a conduction band electron and a valence band hole, followed by excitation of another conduction band electron higher into the conduction band would be reduced with increasing band gap (pressure) but hole-exciting Auger processes in the "W" structure are a little more complicated. Hole-exciting Auger processes in this structure, involve the energy from the recombination of a conduction band electron and a valence band hole being used to excite another valence band hole deeper into the valence band. From Figure 6.1 it can be seen that there are many valence band sub-levels close together. Energy separations between these subbands could easily become resonant with the band gap, promoting a hole-exciting Auger process. The pressure dependence of these hole-exciting Auger processes will depend on whether the process is approaching or move away from resonance. Additionally, this complex valence sub-band structure could cause IVBA [70] processes to move in and out of resonance with pressure. Any increase in loss increases the threshold carrier concentration and hence can increase $I_{th}$. This increase in threshold carrier concentration will also couple strongly to Auger recombination ($\propto n_{th}^3$) leading to a further increase
in $I_{th}$ [72].

The increase in $I_{th}$ at pressures above 4 kbar could be related to IVBA and/or hole-exciting Auger processes, as a result of the complex nature of the valence subbands. However, it is difficult to draw firm conclusions about the observed increase at higher pressures.

---

**Figure 6.6:** Pressure dependence of the threshold current, which indicates the dominant loss mechanism in these lasers. The average error, estimated from the repeated measurements (increasing and decreasing pressure), is about 1.1 mA and the maximum error is 4.2 mA.

---

### 6.5 Conclusions

In summary, a strong loss process which increases with increasing temperature has been observed and appears to be the main source of temperature sensitivity in these devices. The sub-linear nature of the spontaneous emission $L_{se} - I$ curves is characteristic of Auger recombination. Further evidence for the importance of Auger recombination can be seen in the pressure dependence of the threshold current, which decreases from atmospheric pressure. It is estimated that as much as 87% of the
threshold current at 200 K is due to Auger recombination. Also, IVBA may contribute to the temperature dependence by raising the threshold carrier density $n_{th}$, hence raising the threshold current and the significance of Auger recombination (∝ $n^3$). Understanding of the complex valence sub-band structure and controlling of the hole concentration are key issues to be addressed in these devices.

The observed non-pinning of the $L_{se} - I$ curves could be a sign of inhomogeneous growth of material/layer thickness or a non-uniform injection issue. In any case, it indicates that these lasers are not yet fully optimised.
Chapter 7

Thesis review and further work

7.1 Introduction

In this chapter, the material presented throughout this thesis will be reviewed and the main conclusions reached will be discussed. As well as producing useful scientific results, the work carried out during the course of this project had a strong experimental development aspect. The tools and techniques developed will prove useful to future researchers working on MIR semiconductor devices and will be outlined briefly here. Finally, the author's views on possible future work to complement the work presented here and advance the development of MIR semiconductor lasers will be discussed.

7.2 Conclusions

Presented in Chapter 3 are details of the development of experimental techniques and equipment during this project. To facilitate the analysis of the spontaneous emission characteristics of MIR diode lasers, it was necessary to make certain modifications to the existing technique described in [74]. To the author's knowledge this technique, where spontaneous emission is collected from a window in the substrate contact of the laser (to avoid collection of amplified spontaneous emission), had not been applied to MIR lasers before this work. Much development was required to incorporate MIR components and many experimental challenges were overcome.

The main adaptations that were made to the available experimental equipment, for use at MIR
wavelengths, centred around the guiding of spontaneous emission from the window in the laser, out of the cryostat and to a detector. The high attenuation of silica fibres above 1.8 µm, meant that these fibres were not suitable and chalcogenide optical fibre (which has low loss from 2-4 µm had to be employed. Many different adjustments were necessary to accommodate the chalcogenide fibre. Since signal strengths were low, partly due to loss in the fibre and poor detector sensitivity (~40%) at these wavelengths, refinement of the polishing and installation techniques was required, in order to maximise the collection efficiency of the system. The brittle nature of the chalcogenide fibre and the lack of a suitably small fibre diameter meant that the cryostat mount needed to be re-designed and protective measures were also required to prevent breakage.

As a result of this work, experimental apparatus has been developed which can be used to assess the recombination mechanisms of MIR semiconductor lasers through measurement of their spontaneous emission characteristics as a function of current and temperature. This apparatus is now available for regular use at Surrey and can be re-constructed more easily, owing to the lessons learned here. Developmental work on the gas high pressure system at Surrey enabled measurement of devices at low temperature and high pressure. As part of this project, temperature control was introduced to the high pressure apparatus, whereas previously it was necessary to spend many hours cooling to the minimum temperature before beginning a pressure experiment. This is particularly useful for MIR measurements, as many MIR lasers are at an early stage of development and do not operate at RT. MIR measurements at high pressure and low temperature are now readily achievable at Surrey and the ability to carry out stable measurements at intermediate temperatures between 100 K and RT is possible.

Equipped with these experimental techniques, it has been possible to collect some very interesting and helpful results on semiconductor lasers emitting in the 2-4 µm wavelength region. In the 2-3 µm range type-I Sb-based lasers were examined. Around the mid-point of this range, 2.37 µm lasers were studied. These devices have particularly low threshold current densities of ~ 42 Acm⁻² but the primary reason for this was unclear. Measurements presented here, showed that the about 80% of the threshold current of the 2.37 µm lasers at RT could be attributed to Auger recombination. Although an interesting result in itself, this is even more significant in comparison to the measured Auger proportion in 1.5 µm InGaAs(P) devices [74], where it is also approximately 80%. The 2.37
μm device would be expected to have a much higher contribution from Auger recombination, since its band gap is ~300 meV narrower than the 1.5 μm device and hence the MIR device must have significant suppression of the Auger recombination mechanism. In fact, suppression of the CHSH Auger process (shown to be most significant in the 1.5 μm devices [67]) can be pin-pointed as the primary reason for the high performance of these devices, since the spin-orbit splitting energy is greater than the band gap in this material. It would seem that the remaining Auger processes, of CHLIH and CHCC are responsible for the temperature sensitivity in these lasers.

The results for shorter wavelength devices emitting at λ ~ 2.1 μm are not as straightforward. The $Z_{th}$ value at 80 K indicates that SRH recombination (through defects and impurities) is the dominant current path. Further analysis reveals that over 90% of its threshold current at this temperature is related to recombination through defects and impurities. This large SRH contribution to the threshold current is likely to be responsible for the low-temperature flat region observed in the temperature dependence of the threshold current density of these devices. As it was not possible to determine the change in SRH current with temperature from the measured data, we can only estimate a lower bound for the SRH current at RT of ~40% (assuming a constant SRH current with temperature). $Z_{th} = 2.6$ at RT suggests that Auger recombination is also the dominant current path in these lasers at RT, although this figure is higher than is expected theoretically for a device with 40% SRH current at RT. Current spreading effects may contribute to this inconsistency.

The pressure dependence of the threshold current of 2.11 μm and 2.37 μm devices was used to further investigate the findings of the spontaneous emission analysis. For the 2.37 μm laser the threshold current decreases from ambient pressure which is consistent with Auger recombination being the dominant current path. At pressures above 6 kbar the threshold current goes through a minimum and then begins to increase. This is particularly interesting as the lasing wavelength at 6 kbar is close to 2.1 μm and hence the behaviour at pressures above 6 kbar is representative of what might be expected for lasers at the shorter wavelength end of this material system’s range. The increase in threshold above 6 kbar suggests that as the band gap increases with applied pressure, it becomes comparable to the spin-orbit splitting energy and the CHSH Auger process is activated. This is also evident in the 2.11 μm and 2.18 μm lasers where the threshold current increases from atmospheric pressure up to 8 kbar. It would appear that in the shorter wavelength devices (larger band gap) the
CHSH Auger process is already allowed at atmospheric pressure and that it increases in significance as pressure is applied and \( E_g \) continues to approach \( \Delta_{so} \). Clearly, high pressure studies were an important tool here, as although both the 2.11 \( \mu m \) and 2.37 \( \mu m \) lasers appear to be dominated by Auger recombination (from spontaneous emission results), it is clear that they are dominated by different types of Auger processes. The alternative interpretation, that indirect carrier leakage could be responsible for the increase in threshold current with pressure in the shorter wavelength devices and the 2.37 \( \mu m \) above 6 kbar was explored. Fitting to the experimental data showed that this explanation could conceivably explain the observed pressure dependencies. However, estimates of \( \Gamma-L \) splitting energies (although subject to uncertainty) seem far larger than the energies where carrier leakage would be of concern.

It can be seen from Figure 5.5 that for particular lasing energies between 570 meV and 610 meV there exists a situation where CHSH Auger is suppressed and the remaining important Auger processes have been minimised. One might expect the 2.11 \( \mu m \) and 2.18 \( \mu m \) lasers to follow the pressure dependence of the 2.37 \( \mu m \) lasers more closely, having a minimum which occurs closer to the minimum in the threshold current for the 2.37 \( \mu m \) lasers. Variation in \( \Delta_{so} \), which is expected to change with composition and strain but is not expected to change significantly with pressure [94] may partly explain the difference in the minimum energy positions for different devices. These results demonstrate the importance of calculating the \( \Delta_{so} \)-value for a particular combination of strain and material composition. Accurate determination of \( \Delta_{so} \) could allow one to minimise Auger recombination but adjusting the strain, composition and QW thickness, while still achieving the target wavelength.

High pressure results can help to show the general trends of a particular material system. Figure 7.1 shows a schematic of the expected trends of Auger recombination from 1-4 \( \mu m \), where the trend implied by the pressure dependencies measured here are indicated. Also shown, are the 1.5 \( \mu m \) devices [74] and the expected trend of devices emitting close to 3 \( \mu m \). Unfortunately it was not possible to measure devices close to 3 \( \mu m \), as the devices we acquired were unsuitable for pressure experiments. It is easy to see the advantage gained by moving to an Sb-based system in Figure 7.1, where CHSH can be suppressed completely at longer wavelengths and it is helpful to visualise how Auger recombination might be expected to vary across the range of this material system.

The objective of experiments on the "W" structure lasers was to try to identify the primary loss
mechanism responsible for performance degradation at high temperatures. Analysis of the shape of the $L_{se} - I$ curve revealed a sub-linear section close to threshold which increases substantially with increasing temperature. This sub-linearity is characteristic of a process with a higher $n$-dependence than the radiative current and is most likely due to Auger recombination. The decrease in threshold current with applied pressure is consistent with Auger recombination being the primary current path. The Auger contribution to the threshold current at 80 K is estimated at 32%, rising to 87% at 200 K. It is suggested that the high contribution from Auger recombination at cryogenic temperatures may be due to a resonance between the effective type-II band gap and an energy separation in the valance band. The thin QW layers in these structures means that confinement energies are high and there is a significant splitting of the heavy and light hole sub-bands in the Ga(In)Sb QW. In general, it
would appear that the suppression of the Auger process in these devices is not as effective as had been hoped. A reduction in the Auger coefficient, \( C \), may have been achieved but could be outweighed by the increase in \( n_{th} \) required as a result of the reduction in the radiative coefficient, \( B \). We must remember that these devices are some of the longest wavelength interband III-V lasers and hence efforts to reduce Auger recombination even further are needed. Efforts to reduce the population of holes in the valence band may prove successful in reducing hot-hole generating Auger processes. In summary, the expected suppression of CHSH Auger in type-I GaInAsSb lasers emitting at \( \sim 2.4 \) \( \mu m \) seems to have been achieved and allows lasers with very low threshold current to be grown in this wavelength region. In devices closer to \( \sim 2 \) \( \mu m \), the CHSH process begins to become important. Careful design of composition and strain for the desired wavelength should help to minimise the effect the Auger process in these devices. The suggested suppression of Auger recombination with the use of the "W" structure is not as great as had been expected, as there is evidence of a significant current path due to Auger recombination, even at 80 K. Spontaneous emission measurements suggest that Auger recombination is responsible for the high temperature sensitivity in these devices. It is possible that hole-exciting Auger processes play an important role in these devices and their impact could be reduced by controlling the hole population and attempting to remove resonances between the band gap and energy separations in the valence band.

### 7.3 Further work

As a continuation of this work, it would be very interesting to apply high pressure and spontaneous emission techniques to type-I Sb-lasers emitting close to 3 \( \mu m \). This type of analysis could be very useful to assess the balance between carrier leakage and SRH recombination in these lasers. Investigation of modified Sb-based systems using quaternary barrier materials and dilute nitrides would also be of interest, as these systems could offer significant extension of the longest operation wavelength of the type-I Sb-system. Also, spontaneous emission experiments on broad-stripe lasers in the 2.1 \( \mu m \) range would be useful to clarify some of the conclusions reached in the 2.11 \( \mu m \) spontaneous emission work presented here, in the absence of significant current spreading issues.

As regards, "W" lasers the study of devices at longer wavelengths would be worthwhile, since, if resonances with valence subbands are important, increasing pressure would help to identify the
wavelengths for which they are minimised. These results may indicate steps which need to be taken to
minimise the IVBA/Auger resonances across the full wavelength range. High pressure measurements
on ICLs using the “W” structure would also be interesting, although interpretation of the results of
such experiments could be complicated.

Finally, this type of work could be aided by a theoretical assessment of effects which are more
significant at MIR wavelengths, such as the imbalance of the density of states between the conduction
band and valence band and the effect of non-parabolicity. More accurate estimations of the band
structure parameters of the quaternary alloys used in type-I Sb-based lasers would also be useful to
aid the interpretation of results.
Appendices
# Appendix A

## Growth details of type-I structures

### Table A.1: Growth details of 2.37 μm devices.

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109
### Table A.2: Growth details of 2.11 μm devices.

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Table A.3: Growth details of 2.18 μm devices.

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<td>p</td>
<td></td>
</tr>
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</table>
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