Recombination processes in quantum dot lasers

by

Nicolas Massé

Submitted for the degree of Doctor of Philosophy

Advanced Technology Institute
Faculty of Engineering and Physical Sciences
University of Surrey

December 2007
Abstract

The drive for low threshold and temperature-stable semiconductor lasers for telecommunication applications has led to a significant interest in quantum dot (QD) lasers emitting in the 1.3 μm and 1.5 μm wavelength range. The literature shows that although low threshold current densities can be achieved, this is usually at the expense of a poor temperature stability.

Low-temperature and high-pressure measurements of the threshold current and its radiative component are performed on undoped and p-doped 1.3 μm InAs/GaAs and 1.5 μm InAs/InP (311)B QD lasers. The results show that despite a fairly temperature-stable radiative current around room temperature, undoped QD lasers suffer from a poor temperature stability of their threshold current. This is because there is a large contribution (70% and 90% of the threshold current at room temperature in 1.3 and 1.5 μm lasers, respectively) from a strongly temperature sensitive non-radiative Auger recombination process. Several pieces of evidence are found to explain the observed decrease of the radiative current, explained by an improvement of the carrier distribution with increasing temperature.

We find that in p-doped devices the temperature dependence of the radiative component of the threshold current can be modified by the doping. In these devices the radiative current can decrease with increasing temperature around room temperature while the non-radiative current increases. This results in a small range of temperatures over which the threshold current is constant (from ~ 270 to 300 K). This effect is very sensitive to the doping concentration. If the doping concentration is carefully chosen, this can result in high T0 devices but with larger threshold currents than in comparable undoped lasers.

Gain measurements reveal that the differential gain of p-doped lasers is less than that of the undoped devices because of the increased non-radiative current and the non-thermal distribution of the carriers induced by the doping.

Finally, a new method is demonstrated to measure the band gap dependence of the Auger coefficient, C, using a combination of high hydrostatic pressure measurements coupled with gain calculations.
Acknowledgements

I could not start this thesis without saying a big thank you to my supervisors Stephen Sweeney and Alf Adams. Not only without them I would not have done a PhD, but also, thanks to them, it has been a fantastic experience. Obviously there has been some ups and downs, Stephen would remember these occasions when I came into his office saying "Now I'm confused...", but looking back at it it's been a great time. Their knowledge, experience and commitment are inspirational. I was also lucky to have a third unofficial supervisor, Igor Marko, who introduced me to QD lasers and helped me a lot, especially in the labs. Aleksey Andreev was also here to help with the theory. Thank you!

Although a lot of time was spent in underground labs demonstrating the importance of blue-tack in science, a reasonable amount of time was spent in Wates too, studying the chemistry of ethanol. And for both labs and Wates, there was a bunch of people on which I could rely for help and company: Daniel McConville, Kevin O'Brien, James Chamings, Richard Sutton, Carl O'Rourke, Stuart Cripps, Jamie Parkin, Gunnar Blume, Lisa Ahmed, Jo Coote, Andy Prins and the irreplaceable Garry Strudwick, the curator of the ATI. All these people are now my friends and, thanks to them I feel like at home here in England. I would like to say thanks for all the great times we have had together.

There are also people who were not in the ATI but nonetheless played a crucial role in this PhD. My parents, brothers and grand-parents have always been there behind me, helping me, supporting me. Without them I would not have become Dr Nico. So... merci beaucoup! There is also Mr René Cloup, the best teacher I have ever had, who gave me a taste for physics, and Prof. André Raymond who managed to interest me in semiconductor physics and tipped me on a placement at the ATI which later led to this PhD.

Finally, det bästa till sist: Emma, a lovely distraction from work, tack älskling.
Publications


7. "Band gap dependence of the recombination processes in InAs/GaAs quantum dots studied using hydrostatic pressure" I. P. Marko, A. R. Adams, S. J. Sweeney, N. F. Massé,
Contribution to conference presentations


7. "Experimental study of the pressure dependence of Auger recombination in InGaAs/InP 1.5 μm quantum-well lasers at room temperature", N. F. Massé, S. J. Sweeney, A. R. Adams. HPSP, poster presentation (presented by S. Sweeney), Barcelona (Spain), 31/07-03/08/2006


Contents

Publications iv

Contribution to conference presentations vi

1 Introduction 1
   1.1 Background and motivation ................................. 1
      1.1.1 A brief history of lasers ............................... 1
      1.1.2 Lasers for telecommunication applications ......... 2
      1.1.3 Quantum dot lasers ................................... 3
      1.1.4 Motivation and objectives ............................ 5
   1.2 Outline ......................................................... 8

2 Theory and characterisation 9
   2.1 Quantum dots ................................................... 10
      2.1.1 Effect of quantisation ................................ 10
      2.1.2 Growth of quantum dot lasers ...................... 11
      2.1.3 Homogeneous and inhomogeneous broadening .... 12
   2.2 Recombination processes .................................... 13
      2.2.1 Radiative recombination processes .................. 13
      2.2.2 Gain, optical feedback and threshold condition ... 15
2.3 Device designs and characteristics ................................................................. 21
  2.3.1 Carrier confinement ..................................................................................... 21
  2.3.2 Optical confinement .................................................................................... 22
  2.3.3 Current confinement .................................................................................... 23
  2.3.4 Carrier leakage ........................................................................................... 24
  2.3.5 Threshold current and characteristic temperature ................................... 24
  2.3.6 Characteristic temperature ($T_0$) .......................................................... 26
  2.3.7 Efficiency .................................................................................................. 27

2.4 Effect of hydrostatic pressure on semiconductor lasers .................................. 27

3 Experimental procedures ...................................................................................... 30
  3.1 Basic laser characterisation set-up ............................................................... 30
  3.2 Light-current characteristics ......................................................................... 31
    3.2.1 Measurements from the facet ............................................................... 32
    3.2.2 Measurements from the window ......................................................... 32
  3.3 Temperature dependence measurements ..................................................... 35
    3.3.1 Cryostats ............................................................................................... 35
  3.4 Pressure measurements .................................................................................. 38
    3.4.1 Liquid pressure system ........................................................................ 38
    3.4.2 Gas pressure system ............................................................................. 40
  3.5 Gain measurements ...................................................................................... 40
    3.5.1 Hakki-Paoli gain measurements ........................................................... 40
    3.5.2 Gain set-up ........................................................................................... 42
  3.6 Photo-current measurements ....................................................................... 45
4 Temperature dependent measurements

4.1 1.3 μm InAs/GaAs undoped quantum dot lasers

4.1.1 Temperature dependence of the threshold current

4.1.2 Temperature dependence of the radiative current

4.1.3 Temperature dependence of the carrier transport

4.1.4 Temperature dependence of the non-radiative current

4.2 1.3 μm InAs/GaAs p-doped quantum dot lasers

4.2.1 Temperature dependence of the threshold current

4.2.2 Temperature dependence of the radiative current and of the carrier transport

4.2.3 Temperature dependence of the non-radiative current

4.3 1.5 μm InAs/InP (311)B quantum dot lasers

4.3.1 Temperature dependence of the threshold current

4.3.2 Temperature dependence of the radiative current

4.3.3 Temperature dependence of the non-radiative current

4.4 Summary

5 Gain measurements

5.1 Gain measurements at 293 K

5.2 Gain measurements at 350 K

5.3 Summary

6 High pressure studies

6.1 1.5 μm InGaAs/InP quantum well lasers

6.1.1 Pressure dependence of the threshold current

6.1.2 Pressure dependence of the radiative current
6.1.3 Pressure dependence of the non-radiative current .... 95
6.2 1.3 μm undoped InAs/GaAs quantum dots lasers ........ 98
   6.2.1 Pressure dependence of the lasing energy ............. 98
   6.2.2 Pressure dependence of the threshold current .......... 99
   6.2.3 Pressure dependence of the radiative current .......... 100
   6.2.4 Pressure dependence of the non-radiative current .... 101
6.3 1.3 μm p-doped InAs/GaAs quantum dots lasers .......... 103
   6.3.1 Pressure dependence of the lasing energy ............. 103
   6.3.2 Pressure dependence of the threshold current .......... 104
   6.3.3 Pressure dependence of the radiative current .......... 105
   6.3.4 Pressure dependence of the non-radiative current .... 106
6.4 1.5 μm InAs/InP quantum dots lasers .................... 108
   6.4.1 Pressure dependence of the lasing energy ............. 108
   6.4.2 Pressure dependence of the threshold current .......... 108
6.5 Pressure dependence of the photo-current ............... 110
   6.5.1 Pressure dependence of the optical transition energies 110
6.6 Summary ................................................................. 112

7 Conclusions and future work .................................. 115
   7.1 Conclusions ........................................................... 115
   7.2 Future work .......................................................... 118

A Details about the devices ........................................ 120
Chapter 1

Introduction

1.1 Background and motivation

1.1.1 A brief history of lasers

In less than a lifetime information technology has dramatically changed our society. This revolution is largely due to the advent of semiconductor physics and technology and more specifically to the invention of the transistor (Shockley, Bardeen and Brattain, Nobel Prize in 1956) and semiconductor lasers (Alferov and Kroemer, Nobel Prize in 2000).

In his paper "Strahlungs-Emission und -Absorption nach der Quantentheorie" [1] where he defines the coefficients for absorption, spontaneous emission and stimulated emission, Einstein lay the foundations for the invention of the laser. In 1953 Townes (Nobel Prize in 1964) and his group developed the first maser which works on the same principles as a laser but emits microwaves instead of optical radiation. From then on researchers tried to apply the principle used in masers to optical radiation. The first working laser was built in 1960 by Mainman [2]. The concept of a semiconductor-based laser was proposed by Basov (Nobel Prize in 1964) and Javan and the first semiconductor laser was made in 1962 by Hall. It was a GaAs homojunction which could only work pulsed and at liquid nitrogen temperatures. In 1970 Alferov demonstrated the first room temperature continuously-operating semiconductor laser [3]. Since then major improvements were made thanks to the introduction of quantum-wells and strain [4] in the active region of semiconductor lasers. Nowadays laser
diodes are used in numerous applications such as telecommunications, rangefinders, barcode readers, laser pointers, printers, scanners, CD players, CD-ROMs, DVD, HD-DVD, heat treating, seam welding, for pumping other lasers, surgery, etc... In 2004, 733 million semiconductor lasers were sold corresponding to an estimated value of $3.2 billion dollars [5].

1.1.2 Lasers for telecommunication applications

Since laser diodes can emit at wavelengths that suit standard silica optical fibres, there is a special interest in laser diodes for applications in telecommunications. Indeed standard silica fibres exhibit a zero dispersion at 1.31 µm and a minimum of absorption at 1.55 µm [6]. 1.31 µm lasers are therefore used for ultra-fast/short-distance telecommunication such as Local Area Networks (LAN) and Metro Area Networks (MAN) while 1.55 µm lasers are used for long haul telecommunications. The incumbent system used for these applications is based on InGaAs(P)/InP quantum well lasers. Although these lasers exhibit generally good performance (low threshold currents, relatively high efficiency, good lifetime etc...), they suffer from poor temperature stability as shown in Fig. 1.1.

On this graph it can be seen that for a given current injection, the output power of the laser varies significantly with temperature. At high temperatures the laser could even stop lasing if the fixed current becomes less than the threshold current. Temperature controllers are used to offset this effect but they are relatively expensive and typically consume more power than the lasers (≈ watts) hence this solution is therefore not desirable for widespread implementation. The increasing demand for bandwidth for the World Wide Web requires an upgrade of the current system (1Gbit/s) to faster emitters and receivers (10 Gbit/s) especially for LAN and MAN applications. As a result a lot of research is being undertaken to develop a new generation of ultra-fast and temperature insensitive semiconductor lasers emitting at 1.31 and 1.55 µm.
In 1982 Arakawa calculated that lasers in which the carriers are confined in three dimensions in the active region would have temperature insensitive threshold currents [7]. These types of lasers are called quantum dot (QD) or quantum box lasers. Later, in 1986, Asada calculated that QD lasers would exhibit an exceptionally large gain (about 10 times larger than in bulk materials) and a large differential gain [8]. This would lead to almost "perfect" laser diodes with very small and temperature insensitive threshold currents and very high bandwidths. This promoted quantum dot lasers to the status of ideal contenders for telecommunication applications. The first QD laser was fabricated by Ledenstov’s group at the Ioffe Institute in 1994 [9] followed by many groups worldwide.

The temperature sensitivity of the threshold current of a laser is usually described by the \( T_0 \) parameter, also called characteristic temperature, defined as the temperature range over which the threshold current increases by a factor "e" \( (1/T_0 = d\ln(I_{th})/dT) \). High \( T_0 \)s
(infinite) are desirable since they relate to high temperature stability. A $T_0$ more than 150 K is regarded by many as a sign of a fairly good temperature sensitivity. The literature shows that although some good results have been demonstrated, the general trend is that in undoped quantum dot lasers, fairly high characteristic temperatures can be achieved (up to $\sim$ 150 K) but at the expense of a large threshold current density compared to the lowest obtainable $J_{th}$. Conversely, low threshold current density devices tend to have a low characteristic temperature. This is illustrated in Fig. 1.2 where the characteristic temperature of 1.3 $\mu$m InAs/GaAs quantum dot lasers is plotted as a function of their threshold current density. The threshold current density is used for comparison since the design (length and ridge width) of the devices affect the threshold current. However, in QD lasers, because of the relatively low gain [10–13] a low threshold current density is not always an indication of low threshold current as measurements are often conducted on very long cavity devices.

![Figure 1.2: Plot of the $T_0$ parameter as a function of threshold current density for 1.3 $\mu$m quantum dot lasers at room temperature. One can see that the trend is that high $T_0$ can be achieved only if the threshold current density is high. 15 actually has a slightly decreasing threshold current with increasing temperature which gives rise to an almost infinite negative $T_0$.](image-url)

1 : [14], 2 : [12], 3 : [15], 4 : [16], 5 : [17], 6 : [18], 7 : [19], 8 : [20], 9 : [21], 10 : [22], 11 : [23], 12 : [24], 13 : [25], 14 : [26], 15 : [27], 16 : [28], 17 : [29]. The red symbols are for the devices studied in this thesis.
Miyamoto and later Deppe [30, 31] proposed that p-doping quantum dots would greatly improve the gain and differential gain of quantum dot lasers allowing for larger modulation bandwidths, smaller threshold currents and higher temperature stability. Excellent performance has been reported from p-doped quantum dot lasers which can exhibit temperature stable threshold currents around room temperature and high modulation bandwidths [26]. However the literature shows that temperature insensitive threshold currents are usually achieved in p-doped quantum dot lasers at the expense of relatively large threshold currents densities (Fig. 1.2) compared to what can be achieved in undoped devices. In spite of this, in [26] Fujitsu achieved 10 Gb/s operation from 20 to 70 C with a threshold current of only 6 mA (Jth = 280 A/cm²) over this temperature range which is thought to be satisfactory for commercial devices. The literature also shows that at more than ~ 330 K typically, p-doped devices are just as temperature sensitive as undoped devices.

The lowest threshold current density reported so far for 1.3 µm InAs/GaAs quantum dot lasers at room temperature is 17 A/cm² [32] (continuous wave operation, 3 layers of dots, 2 mm long and high-reflectivity coated facets). An interesting result is published in [33] where a threshold current of 1.2 mA (threshold current density = 28 A/cm²) is achieved using continuous wave injection and anti-reflection coatings at room temperature in 1.3 µm InAs/GaAs quantum dot lasers. Excellent results have recently been published in [27] where a low threshold current density (50 A/cm²) together with a very high negative characteristic temperature around room temperature have been realised. Both p-doping and High Growth Temperature Spacer Layers (HGTSL) technique [34] were used. The HGTSL technique consists of growing GaAs spacer layers at high temperature. It is thought to reduce the defect related recombination by inhibiting threading dislocation formation.

1.1.4 Motivation and objectives

There is interest in determining which recombination processes dominate the threshold current of quantum dot lasers. Some processes such as leakage and/or recombination through defects can be suppressed by improving the growth and design of the devices while some others such as Auger recombination are intrinsic to the material. It is thus important to
know if there is room for improvement, or if these devices are intrinsically limited. A num-
ber of processes have been proposed as the cause of the poor temperature stability and high
threshold currents in quantum dot lasers, namely:

• Carrier escape from the dots to the wetting layer and/or confinement layers followed
  by radiative and/or non-radiative recombination [35, 36]

• Strongly temperature sensitive radiative current [37]

• Carrier excitation into excited states [38]

• Gain saturation [21]

• Photon coupling between the ground state and the excited state (absorption) and
  leakage [39]

• Non-radiative Auger recombination [40-42]

The disagreement goes even further: In [28, 43] it is calculated that the Auger recombi-
nation rate decreases with increasing temperature while in [42, 44] Auger increases with
temperature. Several groups working on quantum dot lasers argue that leakage into the
wetting layer is the main loss process in these devices [27, 45, 46], while groups working on
semiconductor optical amplifiers and/or ultra-fast measurements based on self assembled
quantum dot devices argue that Auger recombination is very important in these devices
which operate at very high injection conditions [47–49]. It is suggested in [11] that different
recombination processes dominate in different devices due to the large range of threshold
current densities measured.

Motivated by the promising properties of 1.3 μm InAs/GaAs quantum dot lasers, several
groups [50–55] work on extending the lasing wavelength of quantum dot lasers to the 1.55
μm range. To reach 1.55 μm, one has to grow larger dots than that needed for 1.3 μm lasing
emission. This is difficult on GaAs because of the large strain induced by the large lattice
mismatch between InAs and GaAs (7%). In spite of this, excellent results have recently
been published on 1.55 μm InAs/GaAs p-doped quantum dot lasers [55]. In this paper the combination of p-doping and tunnel injection of the carriers allows for low threshold current density (≤ 70 A/cm²) and very high characteristic temperature around room temperature (558 K). Several other groups [50–54] use a different approach and grow InAs dots on InP which has a smaller lattice mismatch with InAs (3%) [56]. Growing InAs on InP can lead to the growth of either quantum dashes [57] or quantum dots [54]. To favour the growth of dots over dashes the LENS-FOTON group in Rennes grows 1.5 μm InAs/InP lasers on (311)B oriented substrates. They achieved the first single mode Fabry-Perot quantum dot laser emitting at ~ 1.5 μm under continuous wave operation and at room temperature on InP [58].

Because we do not have the facilities to grow quantum dot lasers at the University of Surrey, the lasers used for this thesis were provided by various groups: Fujitsu and the University of Sheffield provided us with two sets of undoped and p-doped 1.3 μm InAs/GaAs quantum-dot lasers. LENS-FOTON in Rennes provided us with 1.5 μm InAs/InP (311)B quantum dot lasers.

This is the framework of the work presented in this thesis. The goals were:

- To understand the relationship between the characteristic temperature and threshold current density in undoped and p-doped InAs/GaAs quantum dot lasers by determining how the various recombination processes vary with temperature using low temperature and high pressure techniques.

- To understand how the doping influences the thermal properties of 1.3 μm InAs/GaAs quantum dot lasers.

- To determine which recombination processes dominate the threshold current of 1.5 μm InAs/InP (311)B quantum dot lasers.

Because of the complexity and the uncertainty in the numerous parameters required for simulating the properties of the quantum-dot lasers, an experimental approach was preferred.
CHAPTER 1. INTRODUCTION

1.2 Outline

The work presented in this thesis is organised in chapters as follow:

- Chapter 2 gives a brief overview of the basic theory necessary to understand the work discussed in this thesis as well as some elements of device characterisation.

- Chapter 3 describes the experimental apparatus used in this work. Experimental techniques and procedures are also discussed.

- Chapter 4 is dedicated to the experimental study of the temperature dependence of the threshold, radiative and non-radiative currents of various types of quantum dot laser. These measurements allow for a detailed understanding of the physical processes which explain the temperature sensitivity of the threshold current in QD lasers.

- Chapter 5 discusses gain measurements performed on undoped and p-doped 1.3 μm InAs/GaAs quantum dot lasers at two temperatures. This gives further understanding of the temperature dependence of the radiative current and some indication on the influence of p-doping on the laser performance.

- Chapter 6 is about the investigation of the pressure dependence of the different current paths in InGaAs/InP 1.5 μm quantum well lasers and various types of 1.3 and 1.5 μm quantum dot lasers. These results, together with the results presented in Chapter 4 allow for the determination of the dominating non-radiative recombination process in each device type.

- Chapter 7 is a summary of the different conclusions reached in each previous chapter and gives suggestions for future work.
Chapter 2

Quantum dot lasers: Principles and characterisation

This chapter presents the basic knowledge necessary to understand the work discussed in the subsequent chapters. Comprehensive studies of semiconductor lasers can be found in [6] and more specifically in [59] for quantum dot lasers. Detailed calculations of the properties of quantum dot lasers are complicated due to the numerous processes that have to be taken into account. Even calculating the band structure is highly sensitive to the shape and composition of the dots. Furthermore, the contribution of the different processes involved in quantum dot lasers, such as Auger recombination, is still the subject of much debate in the community. This lack of consensus means that there is no definite theory describing the temperature dependence of the various recombination processes (radiative, Auger etc...) some of which do not seem to be clearly understood and/or described in the literature.

Only basic concepts related to quantum dot lasers, laser principles and characterisation will be discussed in this chapter. Note that some of the theory discussed here assumes that the electrons and the holes are in thermal equilibrium which is generally not the case in quantum dot lasers. The ideal case is an useful starting point and will be contrasted with the real effects which take place in quantum dot lasers in the subsequent result chapters.
2.1 Quantum dots

2.1.1 Effect of quantisation

Quantum dots (QD) are nano-islands which can be made of III/V semiconductors such as InAs, GaAs, InGaAs, InP etc. These materials are usually preferred for optoelectronic applications since they have direct band-gaps and are prone to strong light-matter interaction. Semiconductor materials are characterised by a valence band fully occupied by electrons and a conduction band empty of electrons at 0 K. These two bands are separated by the band gap, $E_g$. In quantum dots because of the small size of the dots (less than the de Broglie wavelength of the electron) there is a quantisation of the energy. As a result, instead of having a continuum of states in both conduction and valence bands, like in bulk materials, single quantum dots exhibit atomic-like discrete energy levels. The quantisation modifies the density of states of the material which goes from a square-root dependence on the energy in bulk materials to a Dirac delta distribution in ideal quantum dots [8] as shown in Fig. 2.1.

![Figure 2.1: Schematic of the effect of the confinement on the Density Of States (DOS) in bulk, quantum well (2D), quantum wire (1D) and quantum dots (0D).](image)

These properties of QD drew attention for laser applications since it was thought that in QD all the injected carriers would lie at a fixed energy, determined by the material and
the dimensions of the system. Due to the density of states, one electron-hole pair would be sufficient to reach transparency in a dot.

2.1.2 growth of quantum dot lasers

To fabricate quantum dot lasers, dots are self-assembled following the Stranski-Krastanov growth process [59]. In this process a material with a large lattice constant like InAs (6.0584 Å) or InGaAs is deposited on a buffer layer that has a smaller lattice constant such as GaAs (5.6533 Å) or InP (5.8686 Å). At the beginning the growth is two-dimensional and compressive strain builds up as successive atomic layers are deposited. If the thickness of the deposited layer is larger than the critical thickness, the strain relaxes and quantum dots are formed on top of a wetting layer, as illustrated in Fig. 2.2. This technique allows for the growth of $\approx 10$ billion quantum dots per square centimetre in one step only.

![Figure 2.2: Schematic of the Stranski-Krastanov growth process which leads to the formation of quantum dots and a wetting layer.](image)

The size, shape, composition and density of such quantum dot systems greatly depend on the growth condition and materials used. However self-assembled dots can be made small enough to allow for confinement of the carriers in 3 dimensions. The confinement and strain energies are enough to make InAs/GaAs quantum dots have ground state transitions at around 0.95 eV (which corresponds to a wavelength of 1300 nm) while the band gap of bulk InAs is 0.354 eV at 300 K.

The presence of the wetting layer, intrinsic to the Stranski-Krastanov growth, is an important factor which was not anticipated in Arakawa’s [7] and Asada’s [8] papers. The wetting layer can be compared to a quantum well with a relatively large density of states compared
to that of the dots at energies just above that of the dots. It plays a fundamental role in
the physics and properties of quantum dot lasers by allowing for the coupling between the
different dots. The effect of the wetting layer will be described in detail in the following
results chapters.

2.1.3 Homogeneous and inhomogeneous broadening

In [7, 8] it is assumed that the linewidth of quantum dots is comparable to that of atoms.
In reality individual dots have a much larger linewidth due to thermal broadening and the
dots have to treated as an ensemble of inhomogeneously broadened quantum dots due to
their size, shape and composition fluctuations.

Homogeneous broadening

Measurements of the homogeneous linewidth performed as a function of temperature show
that the homogeneous broadening can be as small as a few hundreds of μeV at cryogenic
temperatures which is similar to what is observed in atoms [60] but it increases dramat­
ically with increasing temperature up to ~ 10 - 12 meV around room temperature in
InGaAs/GaAs quantum dots [61, 62]. This homogeneous broadening is a first intrinsic lim­
itation to the properties of quantum dot lasers which had not been taken into account in
Arakawa’s and Asada’s papers [7, 8].

Inhomogeneous broadening

Another consequence of the self-assembly is that there is some variation in the size, shape
and composition of the quantum dots. This results in a distribution in the confinement
energy which further broadens the linewidth of the dots and will limit the properties of
quantum dot lasers. This size distribution of the dots, referred to as inhomogeneous broad­
ening, is measured to be typically of about 50 meV. This can be directly observed by photo­
luminescence and electro-luminescence measurements at low temperature where emission is
observed from an ensemble of lines at various energies [63]. This can also be observed from
lasing spectra where at low temperatures, the dots are decoupled and can lase independently at different energies [64].

2.2 Recombination processes

2.2.1 Radiative recombination processes

The electronic structure of semiconductor quantum dots is defined by valence states fully occupied by electrons and empty conduction states at 0 K. As the temperature is increased the electrons can gain enough energy to get promoted to the conduction states. The empty valence states are known as holes. The distribution of the electrons and holes is given by the Fermi-Dirac distribution at a given temperature, T:

$$f_{Ce}(E) = \frac{1}{e^{[(E - E_{fC})/k_bT]} + 1} \quad (2.1)$$

$$f_{Ve}(E) = \frac{1}{e^{[(E - E_{fV})/k_bT]} + 1} \quad (2.2)$$

where E is the energy considered, $E_{fC}$ and $E_{fV}$ are the quasi-fermi-levels for the electrons in the conduction and valence band respectively and k$_b$ is the Boltzmann constant. At thermal equilibrium $f_{Ce} = f_{Ve}$ (the quasi Fermi levels are aligned), but lasers are not operated at thermal equilibrium, this is why two quasi-Fermi-levels are used. In quantum dots in particular due to the non-uniformity of the size, shape and composition of the dots, the electrons and holes are not always in thermal equilibrium with themselves, as discussed later. The Fermi-Dirac statistic can therefore not be used. Given a carrier distribution, the electrons and holes can recombine and/or interact with photons in different ways. These transitions are called radiative and can be separated in 3 different processes: absorption, spontaneous emission and stimulated emission (Fig. 2.8).
Chapter 2. Theory and Characterisation

Absorption

Absorption occurs when a photon of energy $h\nu$ is absorbed by an electron. The energy of the photon is transferred from the photon to the electron which will transit from a state of low energy $E$ to a state of higher energy $E + h\nu$. The absorption is therefore dependent on the electron density in the low energy state, the density of empty states at the energy $E + h\nu$, and the photon density. The absorption rate can therefore be written:

$$ r_{abs} = B_{abs} \rho_V(E) f_{Vc}(E) (1 - f_{Cc}(E + h\nu)) \rho_C(E + h\nu) P(E_{h\nu}) $$ \hspace{1cm} (2.3)

where $P(E_{h\nu})$ is the density of photons with an energy $h\nu$, $\rho_C$ and $\rho_V$ are the densities of states and $B_{abs}$ is the Einstein coefficient for absorption.

In quantum dot lasers, this transition mainly happens between the valence and conduction states. Other types of transition might also be possible such as absorption between two valence and/or conduction states. These are called Inter-Valence Band Absorption (IVBA) and free carrier absorption [65]. Both IVBA and free carrier absorption are detrimental to the laser performance and are part of the internal loss, $\alpha_i$ as discussed later.

Figure 2.3: Schematic of the three radiative processes: Absorption (left), spontaneous emission (middle) and stimulated emission (right).
Spontaneous emission

The spontaneous emission of a photon occurs when an electron spontaneously recombines from a high energy level $E + h\nu$ to a low energy level $E$. A photon of energy $h\nu$ is created with random phase and direction. The spontaneous emission rate is proportional to the density of electrons at the energy $E + h\nu$ and the density of holes at energy $E$.

$$r_{spon} = A_{spon} \rho_C(E + h\nu) f_{Ce}(E + h\nu) (1 - f_{Ve}(E)) \rho_V(E) \quad (2.4)$$

where $A_{spon}$ is the Einstein coefficient for spontaneous emission.

Stimulated emission

Under certain conditions detailed in the next section, when a photon travels across the gain medium of the laser, it can stimulate the recombination of an electron with a hole creating a photon identical in energy, phase and direction to the original incoming photon. This process is known as stimulated emission and is proportional to the density of electrons in the conduction states, holes in the valence states and photons in the cavity.

$$r_{stim} = B_{stim} \rho_C(E + h\nu) f_{Ce}(E + h\nu)(1 - f_{Ve}(E)) \rho_V(E) P(E_{hv}) \quad (2.5)$$

where $B_{stim}$ is the Einstein coefficient for stimulated emission and can be shown to be equal to $B_{abs}$.

2.2.2 Gain, optical feedback and threshold condition

Gain and losses

To achieve lasing, it is required that the stimulated emission rate is higher than the absorption rate. By substituting 2.3 and 2.5 in $r_{abs} < r_{stim}$ and using $B_{abs} = B_{stim}$ and the expressions for $f_{Ce}$ and $f_{Ve}$, it can be shown that the condition for net gain is:

$$E_{fc} - E_{fV} > E_{photon} > E_g \quad (2.6)$$
This is known as the Bernard-Duraffourg condition for population inversion [66]. This equation shows that if:

- $E_{fc} - E_{fv} < E_{\text{photon}}$: Absorption is more likely than emission, the material absorbs light. This is the lossy regime.

- $E_{fc} - E_{fv} = E_{\text{photon}}$: The absorption and emission rates are equal. The light travels through the material without being amplified or absorbed. This is transparency.

- $E_{fc} - E_{fv} > E_{\text{photon}}$: Stimulated emission is more likely than absorption, the material amplifies the light. This is the gain regime.

At room temperature without external excitation of the material the probability of finding an electron in the conduction band is less than the probability of finding an electron in the valence band; Absorption in the dots is therefore more likely than stimulated emission. In order to reach the gain regime needed for lasing emission, electrons need to be injected in the conduction states in order to reach population inversion. This can be achieved by optical excitation: Light is shone on the sample which absorbs the photons. The electrons are excited to high energy levels and subsequently thermalise to the lowest available state. Another way to achieve population inversion is by injecting carriers with an electrical current. This is known as electrical pumping. The latter technique is used for practical devices and was used for the devices presented in this thesis. A typical gain spectrum for a quantum dot laser is shown in Fig. 2.4. Below the band gap $E_g$, there is no state and therefore no net gain. Light with an energy larger than $E_g$ is amplified providing that its energy is less than the Fermi level splitting but more than the band gap. Light that has an energy larger than the Fermi level splitting is absorbed.

**Optical feedback**

Although gain is needed, it is not enough for sustained lasing to occur. Optical feedback is also required in a laser to "feed" the cavity back with the photons needed for simulated emission. In Fabry-Perot or edge emitting lasers, the optical feedback is provided by cleaving
CHAPTER 2. THEORY AND CHARACTERISATION

Energy (eV)

Figure 2.4: Gain spectrum of a quantum dot laser. The spectrum shows two peaks which correspond to the ground state (GS) and first excited state (1ES) transitions. Below the band gap ($E_g$) the light experiences losses due to the internal loss of the cavity ($\alpha_i$). Above $E_g$ the light is amplified until it reaches the quasi-Fermi-level splitting. Light emitted at energies above $E_{fc} - E_{fV}$ will experience losses because of the predominantly empty electronic states at these energies. This graph is discussed in more detail in chapter 5.

The structure of these devices gives rise to Fabry-Perot modes in the output spectrum. The

Figure 2.5: Schematic of a Fabry-Perot cavity with a gain medium and two mirrors of reflectivity $R_1$ and $R_2$.

The material perpendicularly to the axis of the cavity along a crystalline orientation. Because of the difference in refractive indices between the semiconductor and the surrounding media (air), a resonant cavity is created and the light emitted from the active region can therefore be partially reflected and amplified in the active region (Fig. 2.5).
mode spacing $\Delta \lambda$ is determined by both the material and the design of the device:

$$\Delta \lambda = \frac{\lambda^2}{2\mu L}$$  \hspace{1cm} (2.7)

where $\lambda$ is the wavelength, $\mu$ the effective refractive index experienced by the optical field and $L$ the length of the cavity.

Threshold condition

The threshold condition can also be derived from the standing waves in the cavity. As the light travels along the cavity it experiences gain but also losses due to free carrier absorption, inter-valence band absorption or scattering, but also from transmission through the partially reflecting mirrors. Indeed some of the light has to escape from the cavity for the device to be effective. Threshold is reached when the gain equals the losses and is given by:

$$G_{th} = \frac{1}{\Gamma} \left[ \alpha_i + \frac{1}{2L_{cav}} \ln \frac{1}{R_1 R_2} \right]$$ \hspace{1cm} (2.8)

$G_{th}$ is the material net gain at threshold, $\Gamma$ the confinement factor takes into account the overlap of the optical field over the active region (the quantum dots), $\alpha_i$ the internal loss takes into account the losses due to scattering, absorption etc, $L_{cav}$ is the cavity length, $R_1$ and $R_2$ are the reflectivities of the facets. $1/(2L_{cav}) \times ln(1/R_1 R_2)$ is commonly referred to as the mirror loss ($\alpha_m$).

2.2.3 Non-radiative recombination processes

When carriers are injected into the active region of a laser, they may not necessarily recombine radiatively. Other processes called non-radiative processes can occur and even dominate in semiconductor lasers. These processes are known as Auger and defect related recombination.
Auger recombination

Auger recombination results from a Coulombic interaction whereby the energy released from an electron-hole recombination is transferred to a third carrier (electron or hole) which is promoted to a higher energy state. This hot carrier will relax back to lower energies via phonon emission. It was first thought that Auger recombination would be limited in quantum-dot lasers due to the limited number of final states (from the discrete energy levels of quantum dots) satisfying the energy conservation rule. However, because of the non-dispersion of the electronic levels in quantum-dots, the k-selection rule is relaxed. This results in an ambiguous case where it is not clear how Auger recombination should be affected by the 3D confinement. There is evidence for Auger recombination taking place in single quantum-dots in a colloidal solution [67] where the dots are not coupled to a wetting layer.

An ensemble of self assembled quantum-dots with a wetting-layer is very different to single uncoupled quantum-dots. The high density of states of the wetting-layer should allow many more transitions. As a result, although Auger recombination might be present but limited within an isolated dot, hot electrons can be excited to (or from) the states of the wetting layer [42]. Many Auger processes should thus be allowed in self-assembled quantum-dot lasers. Fig. 2.6 shows only two of them.

![Figure 2.6: Schematic of two different types of Auger recombination processes. In the process shown on the left an electron recombines with a hole and an electron from the conduction ground state of the dots is excited to the conduction band of the wetting layer. In the process on the right, after the electron-hole recombination, an electron from the light hole band of the wetting layer is excited to an empty hole state of the dots.](image-url)
Although Auger recombination is well understood in quantum well and bulk materials, its
collection, band gap and temperature dependencies have yet to be clearly determined
in QD structures. There have been some attempts to simulate Auger recombination in
self-assembled quantum dots [48,68] and self-assembled quantum dot lasers [28,41,42] and
some experimental papers show that Auger recombination is important in quantum-dot
lasers [28,41–44,69]. However there is still much discussion as to how Auger recombination
varies with temperature and its role in the thermal properties of QD lasers. Also, the Auger
coefficient, \( C \), depends on the overlap integrals of the wavefunctions of the states involve
in the process. These wavefunctions, and thus the Auger coefficient, strongly depend on the
shape, size and composition of the dots which is likely to vary from sample to sample.

In bulk and quantum well lasers the Auger recombination current is proportional to \( Cp^2n \)
or \( Cnp^2 \) with \( C \) the Auger coefficient, \( n \) and \( p \) the electron hole concentrations in the active
region, respectively. In these materials, Auger recombination is temperature dependent
because both the Auger coefficient and the carrier concentration are temperature dependent
[6]. Auger recombination is also band-gap dependent in quantum-wells because of the
momentum conservation rule: As the band gap is increased the transitions are pushed away
from \( \Gamma \), the centre of the Brillouin zone, where the carrier occupancy becomes less. As a
result Auger recombination is less in large band gap materials [70].

In quantum-dot lasers, the carrier concentrations (\( n \) and \( p \)) are more difficult to define than
in quantum well or bulk devices. Indeed, as it is explained in the results chapters, not all of
the injected carriers are in the ground state of the dots (the active region). Moreover, some
carriers are likely to be in the wetting layer and are therefore spatially separated from the
dots. The carrier concentration within a dot can be large at threshold, especially in doped
devices where there can be a large number of holes. This suggests that Auger recombination
could be important in these devices if it was found to be strongly carrier-density dependent.
Because of the non-dispersion of the QD states, it is not clear why the Auger coefficient
should be temperature dependent. Experimental results in [28] are interpreted as showing
that the Auger current could decrease with increasing temperature while in [42] the opposite
is suggested.
Defects-related recombination

When the dots are grown to form the active region, defects in the lattice (dislocations, impurities, vacancies etc...) can create states in the band gap. These states can capture electrons or holes which can thereafter recombine (radiatively or non-radiatively). Loose bonds at surfaces can also act as defects. The monomolecular current is given by:

\[ I_{\text{mono}} = eVAn \]  

with \( e \) the charge of an electron, \( V \) the volume of the active region, \( A \) the monomolecular recombination rate and \( n \) the carrier concentration. Good material and growth quality usually lead to negligible defect-related recombination.

2.3 Device designs and characteristics

2.3.1 Carrier confinement

In 1962 the first lasers were simple p-n homojunctions where the light was emitted from a depletion region between the p-doped and n-doped layers [71–73]. In this type of device the carriers are spatially distributed in the different regions; As a result they could not operate at room temperature and their threshold current densities were very large (typically 5700 A/cm\(^2\) at 77 K). Heterojunctions were developed in the early seventies. In double heterostructure lasers, a material that has a smaller band gap is grown between the p-doped and n-doped layers. As a result the carriers are mainly in the region with smaller gap and threshold currents were decreased by two orders of magnitude as compared to homojunction lasers meaning that these lasers could work at room temperature [3,74,75]. Further improvement was made with the introduction of quantum wells (QW) in the heterojunction [76]. The first obvious advantage is that it reduces the volume of the active region and the carriers are trapped in a tightly confined space. If the thickness of the layer grown in the double heterostructure is less than the de Broglie wavelength of the carriers, quantum confinement of the carrier will further improve the characteristics of the device.
because of the increased density of states at the band edge thus increasing the gain and reducing the carrier density required to reach threshold. The latest development in carrier confinement in semiconductor laser structures consists of growing layers of quantum dots in quantum wells. These are called dots in a well or DWELL. Ideally in this type of device the carriers are spatially confined in three dimensions within quantum dots approximately 8 nm high and 20 nm across. However, the presence of the wetting layer, intrinsic to the Stranski-Krastanov growth process, reduces the expected confinement in real quantum dot lasers. This will be discussed in detail in the next chapters.

2.3.2 Optical confinement

The stimulated emission rate is proportional to the photon density, as shown in section 2.2.1. In order to increase the photon density but also the overlap between the optical field and the active region, it is important to confine the light. This is made possible by surrounding the active region with a material that has a smaller refractive index. In fact
semiconductors that have small refractive indices at the wavelength corresponding to the band gap of the active region also have large band gaps. As a result confining the carriers, as explained in the previous section, conveniently also confines the optical field.

![Optical field confinement](image)

**Figure 2.9:** Effect of the optical confinement induced by the index-guiding of the optical field.

### 2.3.3 Current confinement

Low threshold currents are desirable for commercial applications. A way to reduce the threshold current is to reduce the pumped volume of the active region by laterally confining the current. There are several ways of doing this. The most basic method consists of using a stripe in the p-side contact of the device using a dielectric (patterned area in schematic a) in Fig. 2.10). The current is channelled through the contact toward the active region (red). This method weakly guides the optical field around the current path. A stripe was used in the 1.5 μm InAs/InP quantum dot lasers studied in this thesis. A more elaborate solution is the growth of a ridge as in Fig. 2.10b). The ridge is etched and the top contact is surrounded by a dielectric material. In this case the current is more efficiently channelled toward the active region and the optical field is guided using the large difference in refractive index between the semiconductor and the air surrounding the device. This design was used in the 1.3 μm InAs/GaAs devices from Sheffield. A slightly different version of a ridge lasers was used in the 1.3 μm InAs/GaAs lasers from Fujitsu (Fig. 2.10c). In these devices the ridge was etched through the active region providing a better current confinement.

Finally, in Semi-Insulating Planar Buried Heterostructure (Fig. 2.10d), as used in the 1.55 μm InGaAs/InP quantum well lasers used in this thesis, the current is confined by a semi-insulating layer (Fe-doped in the devices studied here) which strongly confines both the current and the optical field.
Figure 2.10: Schematic of a stripe, a), a ridge, b) and c), and a semi-insulating planar buried heterostructure, d) structure. The red area symbolises the active region, the yellow area is for the contact, the patterned area is for the dielectric, and the black region is the semi-insulating layer.

2.3.4 Carrier leakage

In an ideal case all of the carriers are confined within the active region (the dots), but if the temperature is high enough the carriers can gain enough thermal energy to escape from the active region as shown in Fig. 2.11. Leakage into the wetting layer and/or into the barrier layers is often thought to be responsible for the poor thermal properties of quantum dot lasers [27,45,46]. Since this is a thermally activated process, it increases exponentially with temperature. Once the carriers have escaped they can recombine radiatively or non-radiatively, in which case they are lost with respect to the gain process.

2.3.5 Threshold current and characteristic temperature

The threshold condition was described in section 2.2.2 as being the point at which the gain equals the losses. Electrical current is injected in the laser to increase the gain of the device. It is therefore possible to measure a threshold current ($I_{th}$) defined as being the current at which the device starts lasing. In real devices all of the current does not
Figure 2.11: Schematic of the leakage process in a quantum dot laser. The electrons are injected from the n-doped side of the device and "drop" to the quantum dots which have lower energies. Leakage occurs if the electrons can escape from the dot and diffuse toward the p-doped side of the device. Conversely, the holes are injected from the p side into the dots. Leakage occurs if the holes escape from the dots and go into the n-side of the device. The red arrows symbolise the recombination (radiative or not) from the wetting layer and the waveguide.

participate in the lasing process: Some of the carriers can leak outside of the active region (section 2.3.4), and/or some carriers can recombine non-radiatively via Auger recombination (section 2.2.3) or defect-related recombination (section 2.2.3). As a result, the threshold current can be written as the sum of the different radiative, leakage and non-radiative recombination currents:

$$I_{th} = I_{rad} + I_{nonrad} + I_{leak}$$ (2.10)

where $I_{th}$ is the threshold current, $I_{rad}$ is the radiative current, $I_{nonrad}$ is the non-radiative current and $I_{leak}$ is the leakage current. Below threshold the device behaves like a light emitting diode, and it is only above threshold that stimulated emission dominates the emission from the facet of the device. The threshold current is experimentally determined by measuring the light emitted from the facet of the device as a function of the injected current as shown in Fig. 2.12.
2.3.6 Characteristic temperature ($T_0$)

Because the various recombination processes which contribute to the threshold current have different temperature dependencies, the threshold current of a laser can vary dramatically with temperature as shown in Fig. 1.1. The characteristic temperature, or $T_0$ parameter, of a laser is a figure of merit of the temperature stability of the threshold current of a laser. It is given by the following equation:

$$T_0 = \left[ \frac{d\ln(I_{th})}{dT} \right]^{-1} \quad (2.11)$$

A high $T_0$ is desirable since it corresponds to a high temperature stability of the threshold current.
2.3.7 Efficiency

The internal quantum efficiency $\eta_i$ is the number of photons created per injected electron-hole pair above threshold. In an ideal semiconductor laser all of the carriers injected in excess to those necessary to reach threshold are used for stimulated emission. As a result the carrier concentration pins and above threshold, $\eta_i = 1$. The differential quantum efficiency $\eta_d$ is defined as the fraction of photons emerging from the facets per injected electron-hole pair above threshold. In the case of an ideal laser diode, it is equal to the ratio of the number of photons emerging from the cavity to the number of created photons since $\eta_i = 1$. One can therefore write that:

$$\eta_d = \eta_i \left( \frac{\alpha_m}{\alpha_m + \alpha_i} \right) \quad (2.12)$$

where $\alpha_m$ is the mirror loss (described in section 2.2.2) and $\alpha_i$ is the internal loss. The internal loss results from scattering and absorption due to IVBA and free carrier absorption (described in section 2.2.1). The differential quantum efficiency can be measured by calculating the slope of the $LI$ characteristic above threshold and using the following equation:

$$\eta_d = \frac{q\lambda}{h c} \left( \frac{dL}{dI} \right) \quad (2.13)$$

where $q$ is the charge of an electron, $\lambda$ is the wavelength, $h$ is the Planck constant, $c$ is the velocity of light, $L$ is the cavity length and $I$ the injected current. In quantum dot lasers, because of various effects which will be discussed in detail later, the carrier concentration does not always pin above threshold. This makes the interpretation of efficiency measurements more complicated. More details about efficiency measurements are given in [77].

2.4 Effect of hydrostatic pressure on semiconductor lasers

When high hydrostatic pressure is applied to a crystal, it squeezes the material and decreases the lattice constant without changing its symmetry. In most III/V semiconductors this results in a modification of the band structure of the material. This manifests itself as an
increase of the band-gap of the material with increasing pressure, typically at a rate of ~7 to 14 meV/kbar depending on the material. The L and X minima are also modified with pressure with respect to the Γ maximum of the valence band, which is the main point of interest for optoelectronic studies. With respect to the Γ maximum of the valence band, the L minimum of the conduction band increases with pressure at a lower rate than the Γ minimum of the conduction band (about 4 meV/kbar) while the X minimum decreases slowly with increasing pressure (about 1 meV/kbar) [78]. This is illustrated in Fig. 2.13 where the data are given in meV/GPa (1 GPa = 10 kbar).

![Figure 2.13: Schematic of the band structure of a typical III/V semiconductor. When high hydrostatic pressure is applied, the Γ and L minimum (red and blue respectively) increase while the X minimum (green) decreases in energy [78].](image)

Pressure measurements allow one to study the effect of the band gap on the laser characteristics without having to grow numerous devices with different active layer compositions. Beside the cost effectiveness of the process, different growths may lead to some inhomogeneity in the structures (thickness, composition, doping etc...) which would make the interpretation of the results difficult.

Because the different recombination processes have different band gap dependencies, applying hydrostatic pressure is a useful tool to study the recombination processes that take place in semiconductor lasers, where:

- Defect related recombination is usually pressure independent [41].
• Leakage toward the cladding layers usually increases with increasing pressure if it is indirect (into X or L) [79].

• Leakage toward the wetting layer and subsequent recombination from the wetting layer is thought to be pressure independent as the confinement energy of the carriers is not thought to vary significantly with pressure. Photo-current measurements carried out under pressure will be discussed further in section 6.5.

• Auger recombination is thought to decrease with increasing pressure. In quantum-well lasers, Auger recombination decreases with increasing band-gap because as the energy increases, the transitions are pushed away from the Brillouin zone centre where the carrier occupation becomes less [70]. In quantum-dots, the non-dispersion of the energy levels makes this effect irrelevant. However it is calculated in [41] that the Auger coefficient also decreases with increasing band-gap in quantum-dots. This is because as the transition energy increases, the wave-function of the final state of the excited electron becomes more oscillatory in space while the wave function of the fundamental state (in the dot) does not change much as the band gap is increased. The overlap integral between the initial and the final states of the excited electron therefore decreases as the band-gap is increased.
Chapter 3

Experimental procedures

This chapter is dedicated to the description of the experimental techniques and apparatus used in this work. A basic laser characterisation setup is described first. This basic setup allows for the measurement of light-current characteristics from the facet as well as from a window milled in the n-contact of the device. The technique used for radiative current measurements is described and discussed. The basic laser characterisation setup was used in conjunction with more elaborate systems such as cryostats and high-pressure rigs which will be described. Details of setups using spectrometric techniques used for gain and photocurrent are also given.

3.1 Basic laser characterisation set-up

The basic laser characterisation setup is used to measure the output power of the laser as a function of the injected current. It consists of a voltage source (AVTECH 1011B1, HP 8112A) used with a current probe and an oscilloscope (TEKTRONIX TDS3052) to read the corresponding current, or directly a current source (KEITHLEY 2400) to electrically pump the laser. InGaAs detectors (ILX OMM-6810B, ANRITSU ML910B, ANDO AQ2140) were used to measure the light output power, an optical spectrum analyser (ANDO AQ6315A) was used to measure emission spectra and Peltier thermoelectric heater/cooler to regulate the temperature of the sample. This basic setup was used to characterise the devices at
room temperature and could then be used in conjunction with other more advanced systems like a cryostat or a pressure cell which will be described later in this chapter. A schematic of this basic setup is shown in Fig. 3.1.

![Schematic of basic setup](image)

**Figure 3.1:** Schematic of the basic set-up used for laser characterisation

Under pulsed operation, a 47 Ω resistor was used in series with the laser to match the impedance of the BNC cables. The whole setup was controlled using a computer equipped with a GPIB IEEE488 interface bus and the routines were run using Labview programs. To ensure that the lasers did not suffer from internal heating, 500 ns 10 kHz current pulses were usually used to study 1.3 μm InAs/GaAs quantum dot lasers and 1.5 μm InGaAs/InP quantum well lasers. 100 ns 2 kHz current pulses were used for measurements on 1.5 μm InAs/InP (311)B quantum dot lasers.

### 3.2 Light-current characteristics

Light-current characteristics (LIs) are the most basic measurements performed in this work. They consist in measuring the light emitted as a function of the current. Two different types of LIs were performed in this work. They are described in the following sections.
3.2.1 Measurements from the facet

By measuring the light emitted from the facet of the laser as a function of the injected current it is possible to measure the threshold current and the differential efficiency of the device. To perform these measurements the devices are placed in a clip designed by Sweeney in [80].

![Figure 3.2: Schematic of a clip used for light-current characteristics](image)

Fig. 3.2 is a schematic of a clip where A is a copper clip used to contact the p-side of the laser, B is a brass-copper base used as a heat-sink and also to contact the n-side of the device, C is an electrical insulator separating the parts A and B. D symbolises a laser diode held between A and B, E is a lever to hold or release the laser and finally, F is an optical fibre used for spontaneous emission measurements which will be discussed in the next section. This fibre goes through B to emerge on the top side of the base. The threshold current was determined by the intersection of the tangents plotted on either side of the threshold as illustrated in Fig. 2.12. It is possible to calculate the differential quantum efficiency by measuring the slope above threshold and substituting its value in equation 2.13. These basic LI characteristics can be performed under various conditions of temperature and pressure as discussed later in this chapter.

3.2.2 Measurements from the window

To measure the radiative current we used the fact that it is proportional to the spontaneous emission rate which itself is proportional to the integrated pure spontaneous emission:

\[ R_{\text{spont}} \propto \int \lambda P(\lambda) d\lambda \quad (3.1) \]
where the spontaneous emission spectrum $P(\lambda)$ is integrated over the corresponding wavelength range. The wavelength $\lambda$ appears in the integral because to convert the optical power into a rate the optical power has to be divided by the energy of the photons $\hbar c/\lambda$, with $\hbar$ the Planck constant and $c$ the velocity of light. Constants were not taken into account since measurements were performed in arbitrary units, as explained later.

To measure the radiative current one has to make sure that one collects pure spontaneous emission that has not been affected by the gain and/or losses in the cavity. In order to do so, the light cannot be collected from the same axis as the cavity of the laser using a normal laser cavity. Three possibilities are therefore possible:

- One can measure the light emitted from the side of the device, parallel to the plane of the dot layers. This solution is not always possible depending on the design of the laser. In a simple ridge device for example, there is a significant volume of the active region that is not pumped and which can absorb the light emitted along this plane. This solution was therefore not used in this work.

- One can also collect the light emitted perpendicularly to the growth layers. It is made possible by milling a small window in the n-side contact of the device. The window has to be small enough so that the current flow across the active region is not altered. This method is only possible if the TM polarisation is weak which was calculated [41] and measured (from the facets) to be true in the 1.3 \( \mu \text{m} \) devices studied in this work. This method was used for this work.

- Another technique, called the segmented contact technique, was not used in this thesis but is routinely used by other groups to study quantum dot lasers [81]. In this technique pure spontaneous emission and gain spectra can be determined in absolute units by measuring the light emitted directly from the facet of the device. Although this is a very powerful technique it was not used because it requires complicated preparation of the devices (anti-reflection-coating deposition, milling of the stripes etc...).
The windows were milled using either a focused ion beam or an argon beam miller. A Scanning-Electron-Microscope image of a window milled across the contact of a laser is shown in Fig. 3.3. The windows were circular with a 100 μm diameter. The threshold current was measured before and after the milling process to make sure that it did not affect the properties of the laser.

![Figure 3.3: Left: SEM picture of a window milled in a device. Right: Integrated pure spontaneous emission spectra give access to a fraction of the radiative current.](image)

The pure spontaneous emission emitted through the window was collected by an optical fibre as shown on Fig. 3.2 and the signal was sent to an Optical Spectrum Analyzer (OSA) Ando AQ6315A. A typical spectrum is shown on the right side of Fig. 3.3. The measurement can be repeated for various currents and the spectra can be integrated to obtain a measure of the radiative current using equation 3.1. This allows one to plot the variation of the spontaneously emitted light (which is proportional to the radiative current) as a function of the injected current. Since an unknown fraction of the total spontaneous emission is measured, these measurements can ultimately only give a measurement of a fraction of the total radiative current in arbitrary units.

The radiative current density at threshold \((J_{\text{rad}})\) was determined in arbitrary units as shown in Fig. 3.4.
 CHAPTER 3. EXPERIMENTAL PROCEDURES

3.3 Temperature dependence measurements

To measure the threshold and radiative currents as a function of temperature below and above 290K, two different types of cryostat were used. In both closed cycle helium and gas exchange cryostat setups, the basic set up described in 3.1 and clips similar to that described in sections 3.2.1 were used. These different cryostats are described in the two following sections.

3.3.1 Cryostats

Closed cycle helium cryostat

A schematic of the closed cycle helium cryostat is shown in Fig. 3.5. It is composed of a clip (A) mounted on a cold finger (B). The cold finger is cooled down by a compressor (C) which compresses helium gas. The helium gas is subsequently pumped into the cooling head (D) where it expands and cools down the cold finger. Then the gas goes back to the compressor
where it loses its heat via a water cooling system. By adjusting the current flowing in a coil (E), the temperature can be adjusted from about 10K to 300K. The temperature is measured by a silicon diode positioned close to the clip on the cold finger. To avoid condensation at low temperature, a rotary pump followed by a turbo molecular pump (F) were used to create a vacuum of about $10^{-6}$ mbar around the cold finger. Electrical wires (G) for contacting the device and optical fibres for facet (H) and window (I) measurements go through sealed feedthroughs. The whole cold finger is surrounded by a removable sealed lid (J).

In this setup both facet and window measurements were carried out by collecting the light with optical fibres. The output power was measured from the facet for LI measurements by an ANDO AQ2140 optical power meter while spontaneous emission spectra were measured
using an optical spectrum analyser ANDO AQ6315A.

Gas exchange cryostat

![Figure 3.6: Schematic of a gas exchange cryostat.](image)

Fig. 3.6 is a schematic of a gas exchange cryostat. The sample is mounted in a clip (A) which is positioned in a sample exchange gas space (D). This space is evacuated and then filled with helium gas via the valve (E) to avoid condensation. Liquid nitrogen is poured through G to fill the liquid nitrogen reservoir (B). The nitrogen flows by gravity to the heat exchanger (C) surrounding the the sample volume (D). The resulting gas exits through the needle valve (F). The whole volume surrounding the cryostat is evacuated through H. The facet of the lasers faced towards a quartz window so that measurements could be performed outside of the cryostat. This cryostat allows the measurement of both window and facet
LiS over an 80 to 360 K temperature range. In this case a fibre was used to collect the spontaneous emission emitted through the window and the facet emission was measured through the quartz window by an InGaAs detector head on an Anritsu ML910B optical power meter.

3.4 Pressure measurements

3.4.1 Liquid pressure system

A piston-in-cylinder system was used for high-hydrostatic-pressure measurements of the lasing wavelength, threshold and radiative currents. This system offers a large pressure cell volume allowing the insertion of a piston in a hardened-steel double cylinder. Two different pistons were used for the measurements:

- On the first piston, the laser facet placed in the clip faced a 100 μm core optical fibre. The signal travelling via this fibre was used to determine the threshold current using an optical power-meter and also to determine the pressure dependence of the lasing energy using an Optical Spectrum Analyzer.

- On the second piston, the device faced a broad area germanium detector to measure the threshold current, and a fibre was positioned in the clip underneath the laser for spontaneous emission measurements as in Fig. 3.2.

A schematic of the pressure cell and second piston is shown in Fig. 3.7.

The piston was placed in the pressure cell which was filled with a liquid called Essence F. The refractive index of this pressure transmitting liquid is ≈ 1.4 at room temperature, atmospheric pressure and at a wavelength of 1300 nm as determined by ellipsometry measurements. Its transmission spectrum shows two absorption bands around 1200 and 1500 nm. This was not a problem for threshold current and lasing wavelength measurements since enough signal was collected. However it could be more problematic for spontaneous emission measurements. Indeed, because of the broad SE spectra encountered in QD lasers,
the collection efficiency is expected to vary differently in different part of the emission spectrum due to the pressure dependence of the transmission spectrum of the essence F. However we assumed that the clip pressed the device against the base of the clip and therefore the amount of essence F between the device and the clip is negligibly small. The wavelength dependence of the pressure transmitting medium is thus considered to be negligible in our measurements. In fact if there was some liquid between the laser and the clip, there would not be any electrical contact as the essence F is an electrical insulator. The pistons are sealed using a nylon ring for low pressures (≤ 4 kbar) and/or a copper ring for high pressure measurements (≥ 4 kbar). The pressure was generated using a hydraulic ram capable of generating a load up to 120 tons. The pressure was measured using a manganin coil whose resistivity varies with pressure as follows:

\[ R(P) = R_0 \exp \left( 2.3 \times 10^{-3} P \right) \] (3.2)

where P is in kbar. The procedure was to increase the pressure by steps of 2 kbar up to 8 kbar and then decrease the pressure to 7, 5, 3, 1 and 0 kbar. Because of the adiabatic
compression of the essence F, the temperature of the liquid increases when the pressure
is increased. It is therefore necessary to wait for at least 40 minutes after changing the
pressure before taking a measurement. To make sure that the properties of the devices
were not altered or that the light collection for spontaneous emission measurements had
not changed during the measurement, threshold and radiative currents were measured at
0 kbar both at the beginning and at the end of the experiment. If the value of \( I_{rad} \) was
not the same, it was a sign that the device had moved during the experiment, changing
the collection efficiency. In this case the measurement of \( I_{rad} \) would not be reliable. The
measurements were only considered valid if \( I_{rad} \) and \( I_{th} \) changed in a reversible manner.

3.4.2 Gas pressure system

High hydrostatic pressure can also be applied on the device using a gas pressure system. In
this system, helium is compressed using a 3 stage compressor to pressures up to 12 kbar.
This system offers several advantages over the liquid system since the refractive index of
the gas helium is almost identical to that of the air which is the medium in which the lasers
are usually used. In this set-up the pressure cell (Fig. 3.8) can be cooled down to liquid
nitrogen temperatures. Despite these advantages, the liquid pressure system was mostly
used since it allows for the measurements of the pure spontaneous emission. Further details
of the gas pressure set-up can be found in [82].

The device is mounted in a clip facing a sapphire window which allows for light collection
outside of the pressure cell.

3.5 Gain measurements

3.5.1 Hakki-Paoli gain measurements

The method chosen to measure the gain of the laser diodes is the one described by Hakki
and Paoli in [83]. In this method, the gain is calculated by extracting the peaks and the
troughs of the Fabry-Perot modes of the amplified spontaneous emission spectra as shown
in Fig. 3.9.
CHAPTER 3. EXPERIMENTAL PROCEDURES

Figure 3.8: Schematic of the pressure-cell used in the gas pressure system. Drawing by S. Jin. Only electrical contacts are made to the device.

Figure 3.9: Left: Amplified spontaneous emission spectrum of an undoped quantum dot laser (uncalibrated for the system response) measured at 293K and J=1300A/cm². Right: Zoom into the spectra to show the Fabry-Perot modes.

The height of the peaks $P_i$ and $P_{i+1}$ and of the trough $V_i$ are then substituted in the following equation:

$$-\Gamma G = \frac{1}{L} \ln \left( \frac{P_i + P_{i+1}}{2V_i} \right) + \frac{1}{L} \ln R$$

where $R$ is the reflectivity of the facets and $L$ is the length of the cavity. $R$ was determined by measuring the mode spacing of the Fabry-Perot modes on the spectra and then determining
the effective refractive index, defined as the average refractive index as seen by the optical mode, using the following equation (from equation 2.7):

$$\mu = \frac{\lambda^2}{2L\Delta \lambda}$$

(3.4)

where $\mu$ is the effective refractive index, $\lambda$ the wavelength, $L$ the length of the cavity, and $\Delta \lambda$ the mode spacing. $\mu$ was measured as a function of the wavelength and was found to be approximately constant over the whole spectral range. An average value was therefore used to decrease the scattering of the data. The value of $R$ can then be determined using the calculated value of $\mu$ in:

$$R = \left(\frac{\mu_{\text{air}} - \mu}{\mu_{\text{air}} + \mu}\right)^2$$

(3.5)

where $\mu_{\text{air}}$ is the refractive index of the surrounding medium (usually air).

This method allows one to measure the modal net gain defined as being the modal gain minus the internal losses ($G - \alpha_i$). Once the ASE spectrum shown in 3.9 is processed, one can measure the peak modal net gain defined as the modal net gain at the peak for a given injection. This is illustrated in Fig. 3.10.

It is also possible to measure the internal losses by measuring the gain below the band edge. In the example shown in Fig. 3.10 they are of about 7 cm$^{-1}$ (average value of the loss below the band gap) but there is a very large experimental uncertainty on this measurement.

### 3.5.2 Gain set-up

To accurately measure the gain using the Hakki-Paoli method, one has to resolve the peaks and troughs with accuracy (ie make sure that the peaks and trough measured are the actual peaks and troughs). A 1m long SPEX 1000 single-grating monochromator was used in order to obtain the resolution needed. The slit width was adjusted depending on the resolution needed, which itself depends on the device length. Typically the slit width was of about 20 microns giving a resolution of about 0.05 nm. The signal was then detected using a nitrogen-
cooled germanium detector. The lasers, placed in a clip, were temperature-controlled using a Peltier thermoelectric heater/cooler and an ILX LDT-5910B temperature controller. The clip was positioned on a X, Y, Z, θ micro-positioner to optimise the alignment and the signal. The beam was collimated through a first lens, passed through a Glan-Thomson polariser to separate the TE to the TM polarised light and finally focused down onto the entrance of the slit of the monochromator as shown in Fig. 3.11.
Despite the use of a polariser to discriminate TE over TM modes, a small amount of polarisation cross-talk was sometimes observed in the measurements contributing to the experimental error. Because the TE and TM modes have different mode spacing, a beating of the modes could be observed generating a modulation of the signal. We find that its influence can be relatively important close to transparency but is negligible when the gain is $\approx 2$ cm$^{-1}$.

Since the gain spectra were obtained by calculating the ratio of the successive peaks over the following troughs of the Fabry-Perot modes, the system response does not play a significant role in the determination of the gain spectra and was not taken into account. Nonetheless, the system response was measured using a calibrated lamp. Working on the first order of the gratings allowed higher signals due to a higher response, as shown in Figure 3.12, but the decrease in the response at around 1250 nm in TE polarisation can limit the accuracy of the data around these wavelengths. This low response happened to correspond roughly to the minimum between the ground-state and the excited-state emissions which explains
the peculiar shape of the spectrum shown in Fig. 3.9. In this graph there is a surprisingly
pronounced dip between the ground state and the excited state transitions compared to
what is usually observed in electro-luminescence measurements. Because this dip happens
to be precisely between the peak GS and 1ES, the peak net gain could still be determined
accurately without affecting our interpretation.

3.6 Photo-current measurements

Basic photo-current measurements were performed to identify the position of the different
transitions observed in the electro-luminescence spectra. The light emitted by a broad-
spectrum white lamp (A) was sent to a SPEX 1681 monochromator (B) with a resolution
of \( \approx 4 \) nm. The light was then collimated (C), filtered by an 850 nm high-pass filter (D),
modulated by a mechanical chopper (E) and focused onto the facet of the lasers (I) by a
microscope objective. A beam splitter was used to align the beam with the laser using a
CCD camera (G) plugged into a monitor (H). The signal was converted into a voltage using
resistors (K) and demodulated by a Stanford sr830 lock-in amplifier (L). The laser tem­
perature was controlled using a ILX LDT-5910B temperature controller (L) and a Peltier
thermoelectric heater/cooler. If needed, the lasers could also be reverse biased using a CW
voltage source (J). The entire set-up was controlled by Labview routines written by James
Chamings installed on a computer (M).
Figure 3.13: Schematic of the photo-current measurement setup.
Chapter 4

Temperature dependent measurements

This chapter focuses on the thermal properties of various types of quantum dot lasers emitting at the telecommunication wavelengths (1.3 and 1.5 μm). The temperature dependence of the different recombination process of 1.3 μm InAs/GaAs quantum dot lasers is studied using two sets of both undoped and p-doped lasers grown by Fujitsu and University Sheffield. Some of the results shown in sections 4.1 and 4.2 are published in [84,85]. The temperature dependence of the threshold, radiative and non-radiative currents of 1.5 μm InAs/InP (311)B quantum dot lasers provided by the LENS group at the INSA in Rennes is also studied and these results are published in [69].

4.1 1.3 μm InAs/GaAs undoped quantum dot lasers

4.1.1 Temperature dependence of the threshold current

The temperature dependence of the threshold current of 1.3 μm undoped InAs/GaAs quantum dot lasers was measured experimentally. The results are plotted in Figure 4.1.

Two different structures grown by Fujitsu (black squares) and the University of Sheffield (red triangles) were studied. Details about the structure of these devices can be found in the
both device types exhibit a very similar behaviour over the whole temperature range. The temperature variation of the threshold current can be split into two separate parts:

- Below 200 K the threshold current densities decrease with increasing temperature giving rise to a negative $T_0$. This peculiar behaviour is characteristic of quantum dot lasers and was first observed by Zhukov in [86] and subsequently by many other groups. An explanation for this behaviour is given in the following paragraphs.

- Above 200 K the threshold current increases quasi-exponentially with increasing temperature comparably to what is observed in quantum well lasers emitting at 1.3 μm. This dramatic increase gives rise to relatively high threshold currents and poor characteristic temperatures around room temperature. The threshold current density of the devices from Fujitsu is of $\sim 200$ A/cm² at room temperature (5.3 mA) and their $T_0$ is of $\sim 50$ K for temperatures ranging from 280 K to 360 K. The samples from Sheffield had a threshold current density of $\sim 115$ A/cm² at room temperature (230
mA) and a $T_0$ of about 60 K at temperatures ranging from 260 K to 310 K. The difference in the absolute values of $J_{th}$ can be explained by the different structures (more details are given in Appendix A) and the difference in gain and losses in either type of devices.

Figure 4.2: Temperature dependence of the differential quantum efficiency of undoped InAs/GaAs quantum dot lasers normalised to its absolute value at room temperature (50%).

The differential quantum efficiency ($\eta_d$) of the lasers from Fujitsu was measured as a function of the temperature in arbitrary units with a broad area detector and was then normalised to its absolute value at 300 K which is 50 % at room temperature as determined from light-current characteristics measured in absolute units, using an integrating sphere as explained page 26-27. The results, shown in Fig. 4.2, exhibit a peculiar behaviour of $\eta_d$ with temperature: it increases with temperature for temperatures $\leq$ 260 K and then becomes approximately temperature stable around room temperature before slightly decreasing at the highest temperature (above 340 K). This result is in good agreement with the improvement in the carrier distribution model discussed later in this chapter.

As shown in eq. 2.10 the threshold current is the sum of the contribution of different
radiative and non-radiative recombination processes. It is the temperature dependence of these different recombination paths that explains how the total threshold current varies with temperature. This is studied in the following sections.

4.1.2 Temperature dependence of the radiative current

To determine whether radiative recombination is responsible for the temperature sensitivity of the threshold current as suggested in [37], radiative current measurements were performed using the method described in section 3.2.2. The temperature dependence of the radiative current density at threshold ($J_{rad}$) is plotted in Fig. 4.3 (open symbols) together with the temperature dependence of the threshold current density (solid symbols).

![Figure 4.3: Variation of threshold current densities and normalised radiative current densities with temperature in undoped InAs/GaAs quantum dot lasers. The black squares and red triangles show results obtained on lasers from Fujitsu and Sheffield respectively.]

As discussed in section 3.2.2, in this work the radiative current is measured in arbitrary units because only an unknown fraction of the total spontaneous emission is collected. $J_{rad}$ was then normalised using the argument proposed in [41, 84], as follows:

Since the radiative current density at threshold cannot be more than the total threshold
current density, a maximum value of $J_{rad}$ is fixed by $J_{th}$. It can also be seen that both radiative and threshold currents follow one another very closely especially in the devices from Fujitsu. This suggests that non-radiative recombination is negligible at low temperatures and that close to 100% of the injected current goes into radiative recombination. To confirm this assumption, the integrated spontaneous emission ($L$) was measured at a fixed current below threshold (2 mA) as a function of temperature using the devices from Fujitsu (Fig. 4.4). Below 200 K $L$ remains constant. Above 200 K $L$ decreases showing the onset of a loss process at this temperature which is consistent with what is observed in Fig. 4.3. Assuming that there is no non-radiative recombination at low temperatures is consistent with previous observations in quantum well lasers where non-radiative recombination is negligible at low temperatures (typically below 150 K as seen in Fig. 6.4) [80]. In quantum well lasers emitting around 1.3 µm Auger recombination is known to be important and can be described as an thermally activated process. However, if Auger recombination was the main non-radiative process in quantum dot lasers too, there is no clear reason why
the Auger coefficient (C) should be governed by a thermally activated process because of the non-dispersion of the the electronic states of the dots in k-space.

The apparent negligible amount of non-radiative recombination at low temperature allows for the confident normalisation of $J_{\text{rad}}$ to the value of $J_{\text{th}}$ at low temperatures as shown in Fig. 4.3.

Comparing the variations of both threshold and radiative current densities shows that the decrease in $J_{\text{th}}$ with increasing temperature below 200 K is consistent with a decrease in $J_{\text{rad}}$. This suggests that the decrease in threshold current is driven by a decrease in the radiative current at temperatures less than 200 K. An explanation for the decrease in $J_{\text{rad}}$ with increasing temperature is discussed in details in the following section. Between about 200 K and 300 K the radiative current remains roughly constant as expected by Arakawa in his early calculations [7]. However it is unlikely to be due to the reason evoked in [7]. In this paper it is thought that all of the injected carriers are at the same energy and all can contribute to the lasing process. It is clear from our spontaneous emission spectra measurements that all the carriers are not at the same energy.

While $J_{\text{rad}}$ is approximately constant between 200 K and 300 K, the threshold current increases strongly with the onset of a strongly temperature dependent non-radiative recombination process. At room temperature the radiative current forms a maximum of only 30% of the total threshold current. At high temperatures (typically more than 300 K) the radiative current density increases. There are several possible explanations for this:

- The first possible explanation is that the gain might be reduced when the temperature is increased. The homogeneous broadening might become relatively significant at these temperatures. It is measured to increase from 1 meV or less below 50 K to about 12 meV at room temperature in InGaAs quantum dots [61,62]. The peak gain being inversely proportional to the broadening [41], the radiative current should increase with increasing homogeneous broadening. This is providing that the inhomogeneous broadening does not decrease over the same temperatures, which seems to be the case as discussed in the following section. The temperature dependence of the gain is
studied experimentally in Chapter 5.

- It might also be that excited states become increasingly populated, especially in the hole levels which have closely spaced energy levels [31]. Unfortunately too much scatter in the measurements of the full width at half maximum of the GS spontaneous emission in Fig. 4.7 (see later) makes any conclusion difficult.

- The third possibility is that the internal loss increases over this temperature range. Processes such as inter-valence band absorption [65] or free carrier absorption are known to be important at high temperatures and high injections in various types of semiconductor lasers [6]. If the losses are increased the carrier injection required to reach threshold is consequently increased, and because we measured the radiative current density at threshold, \( J_{\text{rad}} \), this would increase with increasing loss. In [87] it is calculated that internal losses may play an important role in quantum dot lasers due to absorption in the cladding and/or optical confinement layers. It could also be possible to determine whether this effect can explain the increase in \( J_{\text{rad}} \) by systematically measuring the internal loss as a function of both temperature and injection. In [88], it is measured that the internal loss remains small (about 1 cm\(^{-1}\)) with temperature which goes against this argument. However these measurements are performed on InGaAs QD lasers by extracting the value from measurements of the differential quantum efficiency for various cavity lengths which are not correct if the spontaneous emission does not pin properly [77]. Net gain measurements performed as a function of the temperature would be ideal to determine the temperature dependence of the loss.

From this measurement it is clear that although the radiative current density is temperature sensitive at low temperatures, it is relatively temperature stable from 200 K up to \( \sim 320 \) K. The poor characteristic temperature of the threshold current density and the relatively high threshold current densities measured in these type of devices cannot therefore be explained by the temperature dependence of \( J_{\text{rad}} \). Non-radiative and/or leakage currents are thought to be responsible for the temperature dependence of the threshold current density around room temperature.
4.1.3 Temperature dependence of the carrier transport

To further study the temperature behaviour of the radiative current, pure spontaneous emission spectra measured at a fixed current current below threshold (2 mA) are compared at different temperatures in Fig. 4.5.

The pure spontaneous emission spectra show at least two transitions: The ground state (GS) positioned at 1.048 eV at room temperature with a full width at half maximum (FWHM) of 40 meV at 300 K and the first excited state (1ES) at 1.117 eV. Both transitions are present at all temperatures. Below 200 K the intensity of light emitted from the 1ES decreases slowly while the intensity from the GS increases slightly with increasing temperature. The net result is that the total amount of spontaneously emitted light remains roughly constant as observed in Fig. 4.4. This is a sign that the carrier occupation of the dots changes with temperature: when the carriers are injected in the active region they randomly populate the dots. Because of the size distribution of the dots, different dots have different GS and 1ES energies: The larger dots which have less confinement energy will have shallower energy levels than the smaller dots. At low temperatures, the electrons in the smaller dots are not
able to move to the larger dots because of the relatively large confining potential. These electrons will recombine either via spontaneous emission or stimulated emission. It has been measured that at low temperatures quantum dot lasers lase at a multitude of wavelengths related to the different dot sizes and the non thermal distribution of the carriers amongst the inhomogeneously broadened dots [64].

The energy difference between the GS of the dots and the GS of the wetting layer is approximately 300 meV as shown in Fig. 4.6. This graph compares a pure spontaneous emission spectra measured for 1 mm long 1.3 μm undoped quantum dot laser at 290 K and 3.2 mA (black line) and an unbiased photo-current measurement performed on the same material (red line). A spontaneous emission spectrum from a 0.5 mm long InAs/GaAs undoped laser from Fujitsu at 360K and pumped at 1340 A/cm² (grey dotted line), where more optical transitions are visible, is also plotted. Four different features are clearly visible on the dotted curve: the ground-state emission (GS) at 0.956 eV, the first and second excited state emissions (1ES and 2ES respectively) at 1.039 and 1.096 eV respectively and the wetting
layer (WL) at 1.25 eV. The confining potential (difference in energy between the GS of the dots and the GS of the wetting layer) is 300 meV. Although the photo-current spectra are not calibrated, there is a good agreement between the photo-current and the spontaneous emission spectra.

The decrease in $J_{\text{rad}}$ in Fig. 4.3 can be explained by the following: when the temperature is increased, the carriers gain more thermal energy and have a higher probability to transport from one dot to the other via the wetting layer states. This is made more likely by the fact that the density of states of the wetting layer is large compared to that of the dots as observed in the photo-current measurements. Once the carriers are in the wetting layer they will preferably thermalise to the largest dots which have lower ground state energies. This results in a decrease of the broadening which will increase the peak gain of the material for a given injection. This in turn will decrease the radiative current when the temperature is increased. This process can be illustrated by looking at the variation of the Full Width at Half Maximum (FWHM) of the ground state emission measured at 2 mA (Fig. 4.7). The FWHM is calculated by fitting the ground state emission with a Gaussian curve.

![Graph showing FWHM vs Temperature](image)

**Figure 4.7:** Temperature dependence of the full width at half maximum of the ground state spontaneous emission of undoped InAs/GaAs 1.3 µm quantum dot lasers measured at 2 mA.
It is clear that below 200 K the FWHM decreases with increasing temperature. This is a sign of an improvement in the thermal distribution the carriers among the inhomogeneously broadened dots. Above 200 K the radiative current at threshold (Fig. 4.3) and the FWHM at 2 mA reach their minimum and become more-or-less constant with temperature. We know from [61, 62] that the homogeneous broadening is likely to increase over the whole temperature range. This may suggest that the increase in the homogeneous broadening is compensated by a slowly decreasing inhomogeneous broadening above 200 K. The minimum value of the FWHM (~ 40 meV) above 200 K is a sign that the gain is optimised with respect to the broadening above this temperature. There is a large scatter at T > 270 K (the error is estimated to be ± 2 meV above 300 K). Thus it is difficult to discuss the temperature dependence of the FWHM with accuracy above 270 K. If the FWHM increases slightly over this temperature range this could explain why the radiative current increases above 300 K.

![Figure 4.8: Total integrated spontaneous emission (solid symbols) and ground state spontaneous emission measured at 80, 300 and 350 K. The total integrated spontaneous emission is integrated to its value at threshold. The integrated ground state emission is normalised to the value of the total integrated spontaneous emission at threshold for comparison.](image-url)
A consequence of the improvement in the thermal distribution is also observed in the pinning of the spontaneous emission above threshold. In an ideal laser the spontaneous emission pins above threshold because all of the carriers injected in excess of those needed to reach the threshold condition are used for stimulated emission. The variation of the integrated spontaneous emission (solid symbols) and the integrated spontaneous emission from the GS only (open symbols) with current are plotted in Fig. 4.8 for three different temperatures corresponding to the three different regimes of $J_{\text{rad}}$ (decrease, constant or increase with temperature). The integrated spontaneous emission is normalised to the value of $J_{\text{rad}}$ at threshold, as is the spontaneous emission from the ground state, to make the pinning comparison easier. These measurements are consistent with the carrier redistribution induced by the improvement in the carrier transport. At low temperature (80 K), the GS emission pins slightly, but the total emission does not pin. As the temperature is increased, the spontaneous emission pins better and there is no difference between the degree of pinning of the GS and the pinning of the total emission as you would expect in thermal equilibrium conditions where the electrons occupy mainly the GS of the larger dots. The difference between the pinning of the GS emission and the total spontaneous emission suggests that the population of the higher excited state is important at low temperatures. A possible reason for this is that the thermalisation of the carriers to the GS of the lasing dots is poor at low temperatures which reduces the peak gain from the ground state. Hence there is some spontaneous emission from the excited states which prevents the spontaneous emission from pinning.

The improvement of the pinning of the integrated spontaneous emission with increasing temperature explains the increase of the differential quantum efficiency with increasing above 260 K shown in Fig. 4.2. As the carrier distribution improves with increasing temperature, more of the injected carriers can couple to the lasing process leading to an increase in $\eta_{\mu}$. Once thermal equilibrium is reached, the differential quantum efficiency becomes approximately constant.

Below threshold (clearly evident at 350 K) there is a significant difference between the curvature of the light-current characteristic of the GS and total emission. This is attributed to gain saturation of the ground state which is discussed in detail in the next chapter.
Figure 4.9: Spontaneous emission spectra measured at threshold (black) and stimulated emission spectra (red) measured for various temperatures of 1.3 μm InAs/GaAs undoped lasers from Fujitsu.

The spontaneous emission spectra at threshold and lasing spectra measured at 1.3 times $I_{th}$ are plotted for various temperatures (100 K to 320 K) in Figure 4.9. Over this temperature range a linear increase of the lasing wavelength at 0.35 meV/K is observed. This is slightly
more than the temperature dependence of the bulk band-gap of InAs as given by the Varshni equation (0.24 meV/K assuming a simple linear dependence) [89,90]. It is clear that these devices lase on the GS at all temperatures measured. It can also be seen that the shape of the pure spontaneous emission spectra varies greatly with temperature and that the lasing linewidth becomes narrower as shown in Fig. 4.10 and observed elsewhere [91]. The narrowing of the lasing linewidth is also a consequence of the improvement in the carrier distribution with increasing temperature [91]. The scatter in the data comes from the fact that these devices are multi-mode, as seen in Fig. 4.9.

![Figure 4.10: Temperature dependence of the lasing linewidth of 1.3 μm InAs/GaAs undoped lasers from Fujitsu (left). Comparison between the temperature dependence of the lasing energy measured experimentally and the temperature dependence of the band gap of bulk InAs determined using Varshni equation.](image)

### 4.1.4 Temperature dependence of the non-radiative current

The results discussed in section 4.1.2 show that the temperature dependence of the threshold current around room temperature cannot be attributed to radiative recombination only and that a strongly temperature dependent non-radiative recombination process is present in these devices. This non-radiative current is measured to account for at least 70 % of the total threshold current at room temperature as determined from Fig. 4.3. The temperature dependence of the total non-radiative current density at threshold ($J_{\text{nonrad}} = J_{\text{th}} - J_{\text{rad}}$) is plotted in Fig. 4.11.

Different recombination processes were considered: defect related recombination, Auger recombination and carrier leakage toward the wetting layer and/or the cladding layer and
CHAPTER 4. TEMPERATURE DEPENDENT MEASUREMENTS

Figure 4.11: Variation of the non-radiative current densities and normalised radiative current densities with temperature in undoped InAs/GaAs quantum dot lasers. The black squares and red triangles show results obtained on lasers from Fujitsu and Sheffield respectively.

subsequent radiative and/or non-radiative recombination. Inter-Valence Band Absorption (IVBA) was also considered, however IVBA would increase the radiative current, which we do not observe and hence cannot explain the increase of the non-radiative current.

Defect-related recombination usually is usually less carrier dependent than radiative recombination. If defect-related recombination were the dominant process, the spontaneous emission characteristics would be super-linear below threshold, which is not what is observed in Fig. 4.8. Recombination at defects is thus not thought to be the main non-radiative process taking place in these 1.3 μm quantum dot lasers.

Leakage toward the cladding layer also seems unlikely since in these devices the band gap difference between the dots and the cladding is large.

Several groups [35,39,46] suggest that at these relatively high injections, leakage of the carriers from the dots towards the wetting layer or even towards the barriers is the main loss process in 1.3 μm InAs/GaAs quantum dot lasers. The transport mechanism involved in self-assembled quantum dots, where the dots are coupled via the wetting layer, implies that
there are carriers in the wetting layer. However there is little experimental evidence proving that carrier leakage and recombination from the wetting layer dominates the threshold current around room temperature. In the two sets of devices studied in this work, no emission from the wetting layer was observed below 340 K. A small amount of spontaneous emission was observed only above 340 K and at very high current densities (well above the threshold current) in 0.3 mm long devices. This does not corroborate the leakage argument as the dominating process around room temperature: If carrier excitation into the wetting layer and subsequent recombination was dominating, we would reasonably expect to measure some emission from the wetting layer even if there were some non-radiative recombination from the wetting layer.

This leaves Auger recombination as the probable main recombination process in these devices at room temperature. It is difficult to gain direct experimental evidence for Auger recombination. However the efficiency measurements, shown in Fig. 4.2, increase and then level-out with increasing temperature which suggests that Auger recombination rather than leakage dominates in these devices at most temperatures. If drift related leakage was important, the differential quantum efficiency should decrease steeply with increasing temperature; note that diffusion-related leakage would leave the differential quantum efficiency unchanged. Above 340 K, $\eta_d$ decreases slightly which may indicate that leakage is a factor at these very high temperatures. Pressure measurements discussed in Chapter 6 also support Auger recombination as the dominating recombination process at room temperature.

4.2 1.3 $\mu$m InAs/GaAs p-doped quantum dot lasers

The experimental procedure used in section 4.1 is used to study 1.3 $\mu$m InAs/GaAs p-doped quantum dot lasers. p-doping was initially thought to reduce the threshold current by increasing the gain of the lasers. Although the threshold current is not usually less in doped devices than in undoped quantum dot lasers, p-doped lasers can exhibit temperature insensitive threshold currents over a limited temperature range around room temperature. This is a very desirable property for commercial devices and the physics of this is studied in this section.
Note that beside the doping, the p-doped and undoped devices were identical allowing for a direct comparison of the results.

4.2.1 Temperature dependence of the threshold current

The variation of the temperature dependence of the threshold current density of 1.3 \( \mu \text{m} \) InAs/GaAs p-doped devices is plotted in Fig. 4.12. It can be seen immediately that the shape of the curves is different to what was observed in the undoped devices. Also the different sets of p-doped devices showed different threshold current variations with temperature. Comparing Fig. 4.12 and Fig. 4.1 shows that at room temperature the threshold current density is higher in the p-doped devices than in the undoped devices, as it is usually observed in the literature (Fig. 1.2). \( J_{th} \) is \( \approx 300 \text{ A/cm}^2 \) at 300 K in both p-doped devices compared to 115 and 200 A/cm\(^2\) in the undoped devices. The threshold currents are \( \approx 9 \text{ mA} \) and \( \approx 300 \text{ mA} \) for the devices from Fujitsu and Sheffield respectively. This is because the lasers from Fujitsu are ridge devices while those from the University of Sheffield are broad area lasers.

In the devices from Fujitsu, \( J_{th} \) first increases before decreasing and increasing again with increasing temperature. The transition between the decrease and the increase takes place around room temperature which leads to a temperature stable threshold current, or in other words an infinite \( T_0 \) over a limited range of temperatures around room temperature (from approximately 270 to 300 K in these devices). Above this temperature range, the \( T_0 \) of these lasers from Fujitsu drops to \( \approx 50 \text{ K} \) similar to what is observed in undoped devices. The devices from Sheffield exhibit a different behaviour: their threshold current increases continually over the wide temperature range studied here. The characteristic temperature of the devices from Sheffield (\( \approx 87 \text{ K} \) between 250 and 300 K) is thus less than that of the devices from Fujitsu which is consistent with the trend observed in the literature (Fig. 1.2) where devices with lower \( J_{th} \) tend to have a lower \( T_0 \). Above 300 K both device sets show similar behaviour.

There is a significant improvement in the temperature stability of the p-doped devices from Fujitsu when compared to similar undoped devices, however there is a corresponding
increase in the threshold current density. It is also interesting to notice that the differential quantum efficiency of the doped devices (black squares in Fig. 4.13) is relatively temperature stable from 270 to 350 K (Fig. 4.2) which is very desirable for uncooled operation.

However its absolute value is less in the p-doped devices (~ 42% versus ~ 50% in the undoped lasers). This difference could be attributed to the increased temperature at which thermal equilibrium is reached in the doped devices compared to that of the undoped devices, as discussed in the next section.

4.2.2 Temperature dependence of the radiative current and of the carrier transport

The temperature dependence of the integrated spontaneous emission at threshold (open symbols) is plotted together with the variation of the threshold current density (solid symbols) in Fig. 4.14.
The normalisation technique used for the undoped devices in section 4.1.2 is also used for the doped devices. The integrated spontaneous emission \( (L) \) measured below threshold at 2 mA is measured (Fig. 4.15) to verify if the same normalisation procedure as in [41] can be applied. \( L \) remains approximately constant up to about 60 K. At higher temperatures it decreases because of the onset of a non-radiative recombination process. This is in perfect agreement with what is seen in Fig. 4.14 where the threshold current closely follows the radiative current up to only 60 K. The radiative current is therefore normalised to the value of the threshold current at low temperatures.

Unlike in the undoped devices where non radiative recombination was negligible at temperatures below 200 K, non-radiative recombination is present in the doped devices from ~ 60 K. The temperature sensitivity of \( J_{th} \) and \( J_{rad} \) of the doped devices therefore becomes different above this temperature:

- In the devices from Fujitsu (black symbols) the radiative current increases with increasing temperature up to ~ 170 K. This might be attributed to the thermal broad-
CHAPTER 4. TEMPERATURE DEPENDENT MEASUREMENTS

Figure 4.14: Variation of threshold current densities and normalised radiative current densities with temperature in P-doped InAs/GaAs quantum dot lasers. The black and red symbols show results obtained on lasers from Fujitsu and Sheffield respectively.

Enlarging of the confined states and to the thermal excitation of the carriers to higher energy states which will reduce the gain for a given injection. Above ~ 180 K the radiative current starts decreasing due to the improved inter-dot transport as explained in section 4.1.3 of this chapter. This is illustrated in Fig. 4.16 where the Full Width at Half Maximum (FWHM) of pure spontaneous emission spectra measured at 2 mA (below threshold) is plotted as a function of temperature.

The FWHM is larger than that of the undoped device at all but the highest temperatures at the same injection. It increases for T ≤ 150 K and then starts decreasing with increasing temperature showing that there is an improvement in the carrier transport among the inhomogeneously broadened dots, as explained in details in section 4.1.3. This result is in good agreement with what is observed in Fig. 4.14 where the radiative current density at threshold increases up to 170K before decreasing until 320K and stabilising. At around 350 K the FWHM of both undoped and p-doped lasers are approximately equal suggesting that the carriers are distributed thermally in the
doped devices and that the effect of the doping becomes less important.

The main difference between the undoped and the p-doped devices is that the decreases in the FWHM and consequently in $I_{rad}$ takes place around room temperature. This means that thermal equilibrium is not reached until higher temperatures in the doped devices. Because the undoped and the doped devices are nominally identical apart from the doping, the difference in the carrier transport is consistent with the introduction of excess holes introduced by the doping: The Coulombic attraction of the excess holes increases the confining potential for the electrons (Fig. 4.18). The carriers therefore need more energy to escape and transport from one dot to the other via the wetting layer. This results in the observed shift in the decrease of the FWHM and $I_{rad}$ from below 200 K in the undoped lasers to around room temperature in the p-doped lasers. P-doping had already been proposed to reduce the leakage current in semiconductor lasers diodes [30] using the same idea of an increased confining potential for the electrons.

Although we could not measure the confining potential directly, a consequence of the
Figure 4.16: Variation of full width at half maximum of the ground state spontaneous emission with temperature in P-doped InAs/GaAs quantum dot lasers. The spontaneous emission spectra were fitted with a Gaussian function.

Increased confining potential might be observed in unbiased photo-current measurements performed at room temperature. It can be seen in Fig. 4.17 that the energy of the quantum dot confined states is slightly higher (few tens of meV) in the p-doped devices than in the undoped devices. This could be due to the larger energy separation between the electronic states induced by the larger confinement. However, other effects like size or composition fluctuations etc could also have the same effect.

Consequences of the Coulombic attraction of the excess holes on the improvement in the carrier distribution is clearly observed on the pinning of the integrated spontaneous emission. At 80 K the pinning of the doped devices is as poor as in the undoped devices. However, while the total integrated spontaneous emission and the ground state emission pins identically well at 300 K and 350 K in the undoped devices, the pinning is still poor at 300 K in the p-doped lasers. At 370 K, the pinning has improved but is still not perfect, as seen in Fig. 4.19.

The poor pinning also has consequences on the temperature dependence of the differ-
Figure 4.17: Unbiased photo-current spectra of undoped and p-doped InAs/GaAs quantum dot lasers from Fujitsu at room temperature.

Figure 4.18: Illustration of the effect of the p-type doping on the band offset.

ential quantum efficiency. It can be seen in Fig. 4.13 that the increase in $\eta_{pd}$ is shifted towards higher temperatures.

Although the radiative current decreases with increasing temperature around room temperature, the non-radiative current increases over the same temperature range (Fig 4.20). Clearly, the interplay between the decreasing radiative current and the increasing non-radiative current happens to give rise to the temperature-stable threshold current around room temperature in the p-doped devices from Fujitsu.
The devices from Sheffield exhibit a different behaviour. The bump in the radiative current is not as pronounced as in the devices from Fujitsu and the radiative current increases around room temperature. The main difference between the devices from Sheffield and those from Fujitsu is the doping: In the lasers from Sheffield there are 30 acceptors per dot while there are only 10 acceptors per dot in the lasers from Fujitsu. The same observation has recently been published in [27] where the bump in $J_{th}$ leading to an infinite characteristic temperature around room temperature is only observed for low doping concentrations (15 acceptors per dot). This bump disappears at higher doping concentration (50 acceptors per dot). It is not clear why the bump in the threshold and radiative currents is not present at high doping concentrations. We also observed that the temperature dependence of the full width at half maximum is different in the devices from Sheffield compared to that of the devices from Fujitsu. Because the radiative current does not decrease around room temperature, it does
not compensate for the increase in the non-radiative current and the threshold current increases continuously leading to a poor characteristic temperature (87 K) but a relatively small threshold current density at room temperature compared to the devices from Fujitsu.

### 4.2.3 Temperature dependence of the non-radiative current

There is some non-radiative recombination in the p-doped devices from 80 K and 100 K in the devices from Fujitsu and Sheffield respectively (Fig. 4.20). The amount of non-radiative recombination is typically higher in the doped devices than in the undoped devices for $T \leq 300$ K in the lasers coming both from Fujitsu and Sheffield. Above 300 K the effect of doping becomes less and the amount of non-radiative recombination becomes similar to that in the undoped devices.

At first, both Auger and leakage current toward the wetting layer are suspected to be important in these devices. It is likely that there is some leakage into the wetting layer, a
consequence of which is thought to be observed in the improvement in the carrier inter-dot transport. However because of the excess holes introduced by the p-doping, the confinement potential is more in the doped devices than in the undoped devices. If leakage was dominating, the non-radiative current density would be less in the doped devices especially at low temperatures, but this is not what is measured in devices from both Fujitsu and Sheffield. This suggests that although leakage might be present, Auger recombination is most probably the dominant non-radiative recombination process in the doped devices. This is further supported by the fact that Auger is known to be strongly dependent on the hole concentration in quantum well lasers emitting in this wavelength range [80] \( I_{\text{Aug}} \propto p^2n \) and the hole concentration in the dot is large in p-doped quantum dot devices. Assuming a dot volume of 1300 nm³ [92] and 5 holes per dot (some papers refer to 50 holes per dot or even more [16, 31, 93]), the hole concentration is of the order of \( 4 \times 10^{18} \) holes/cm³ which is comparable to quantum well lasers (typically \( \sim 10^{18} \) holes/cm³) where Auger recombination is known to dominate at these wavelengths. Auger recombination is therefore very likely to be an important non-radiative recombination process in these p-doped quantum dot lasers. This is also confirmed by the temperature dependence of the differential quantum efficiency which is found to either remain constant or increase up to 360 K while leakage is known to lead to a dramatic decrease of \( \eta_d \) with increasing temperature. A decrease in \( \eta_d \) takes place at higher temperatures than in undoped lasers, as one would expect from the increased potential for the electrons in the doped devices. At high temperatures (from 320 K) the temperature dependence of the threshold current density of the undoped and p-doped devices from Fujitsu become similar. This confirms that Auger recombination also dominates in the undoped devices. Above 350 K, where the effect of doping becomes less, the differential-efficiency measurements suggest that leakage into the wetting layer might become significant in both undoped and p-doped lasers. However the decrease in the differential quantum efficiency takes place at higher temperature in the doped devices, as one would expected from the increased confining potential in the doped lasers. Further evidence is found when the threshold and radiative currents are studied as a function of high hydrostatic pressure. This is discussed in Chapter 6.
4.3 1.5 μm InAs/InP (311)B quantum dot lasers

In this section, the threshold and radiative current densities of undoped 1.5 μm InAs/InP (311)B quantum dot lasers were studied experimentally as a function of the temperature using the same techniques as in the previous sections of this chapter. Unlike the lasers emitting at 1.3 μm which are grown on GaAs, these 1.5 μm lasers are grown on InP. This substrate is preferred because its smaller lattice mismatch with InAs allows for an easier growth of long-wavelengths lasers. Details about the devices, provided by LENS-FOTON at the INSA-Rennes, are given in Appendix A. These results are published in [69].

4.3.1 Temperature dependence of the threshold current

The temperature dependence of the threshold current density of 1.5 μm InAs/InP (311)B quantum dot lasers is plotted in Fig. 4.21.

Unlike what is observed in undoped 1.3 μm InAs/GaAs QD lasers, the threshold current of 1.5 μm InAs/InP (311)B quantum dot lasers increases continually with increasing tem-
perature. No decrease in the threshold current was observed in any of the devices studied with increasing temperature. The threshold current density was typically 50 A/cm² at 20 K and increased to ≈ 450 A/cm² at room temperature with a rather low characteristic temperature of about 55 K around room temperature.

4.3.2 Temperature dependence of the radiative current

The radiative current density at threshold was determined as previously described and normalised to the value of the threshold current at the lowest temperature as shown in Fig. 4.21. However, unlike the 1.3 μm undoped and p-doped devices, there is no evidence that there is no non-radiative recombination at the lowest temperature measured here (20 K) since $J_{\text{rad}}$ does not follow $J_{\text{th}}$ over any temperature range. This is confirmed by plotting the integrated spontaneous emission at 80 mA (below threshold) over the entire temperature range (Fig. 4.22).

![Figure 4.22](image)

**Figure 4.22:** Variation of the integrated spontaneous emission measured at 80 mA of 1.5 μm InAs/InP (311)B quantum dot lasers measured as a function of temperature.

It can be seen that the spontaneous emission efficiency decreases with increasing temperature which is a sign that some non-radiative recombination process and/or leakage occurs...
over this temperature range. Normalising $J_{rad}$ to $J_{th}$ therefore corresponds to a maximum possible value of $J_{rad}$. It is interesting to note that compared to the threshold current density, the radiative current density is relatively constant over the entire temperature range. Plotting the radiative current density separately on a more appropriate scale (Fig. 4.21) reveals that it increases slightly with increasing temperature above 100 K. This suggests that the carriers could be coming into thermal equilibrium below 100 K where $I_{rad}$ is constant, and that thermal broadening starts decreasing the gain and consequently increasing the radiative current above 100 K. The characteristic temperature of the radiative current is $\sim 1500$ K around room temperature.

![Figure 4.23: Variation of the normalised radiative current density at threshold as a function of temperature for 1.5 µm InAs/InP (311)B quantum dot lasers. The error bars decrease with increasing temperature because the threshold current becomes better defined, reducing the experimental uncertainty.](image)

The temperature dependence of the radiative current can be understood when one examines the material used for these devices. These devices are grown on InP instead of GaAs which is usually used for QD lasers. This is because to reach a lasing wavelength of 1.5 µm with InAs dots, one has to increase the size of the dots relatively to that needed for 1.3 µm emission. As the dots grow larger, the strain increases and can compensate for the decrease
in the confinement energy which makes growing 1.5 μm InAs/GaAs difficult (although not impossible [55]). To overcome this, the group in Rennes grows InAs dots on InP which has a lower lattice mismatch: InAs/InP (3.2%) versus InAs/GaAs (7%). This smaller lattice mismatch results in the formation of larger quantum dots but also in a thicker wetting layer. The total confining energy (difference in energy between the ground state transition of the dots and the transition in the wetting layer, $\Delta E$) is therefore less in InAs/InP than in InAs/GaAs self assembled QD lasers. Photo-current measurements carried-out on 1.3 μm (Fig. 4.6) and on 1.5 μm QD lasers (Fig. 4.24) shows that $\Delta E \approx 300$ meV and $\approx 110$ meV in undoped 1.3 μm InAs/GaAs quantum dot lasers and 1.5 μm quantum dot lasers respectively.

Evidence is given in Section 4.1 showing that the carriers come into thermal equilibrium around 200 K in undoped 1.3 μm InAs/GaAs QD lasers. It can therefore be expected that in 1.5 μm InAs/InP QD lasers the carriers are thermally distributed at temperatures less than 200 K due to the smaller total confining energy explaining why the radiative current is constant with temperature below 100 K and increases at higher temperatures. It is also
thought that tunnelling via the excited states enhances the inter-dot transport in these devices [94].

Evidence of the good inter-dot carrier transport is observed in the pinning of the spontaneous emission light-current characteristics. The pinning is already good below 140 K and the spontaneous L–1s pin very well above 140 K which is in consistent with the temperature dependence of $J_{rad}$.

There is some evidence of interference effects in the pure spontaneous emission spectra (Fig. 4.26): the position of the peaks and troughs of the spontaneous emission remain fairly constant with changing temperature (compared to the shift of the lasing energy which shifts by 0.5 meV/K). Also, in Fig 4.24 there is a weak shoulder at 0.78 eV and what looks like a first excited state in the spontaneous emission spectra at ~ 0.88 eV but there is no feature in the photo-current spectrum at this energy. These are due to the partial reflection of the spontaneous emission at the interface of the different layers of the heterostructure. Although this does not change the integrated value of $L$, it modifies the shape of the spectra.

Fig 4.23 shows that the radiative current is very temperature stable and also that at least 90
% of the threshold current at room temperature is formed by non-radiative recombination. The temperature sensitivity of the threshold current is thus largely due to the temperature sensitivity of a dominant non-radiative recombination process.
4.3.3 Temperature dependence of the non-radiative current

The small energy difference between the quantum dot ground state and the wetting layer transitions (110 meV) suggests that leakage toward the wetting layer and subsequent radiative and/or non-radiative recombination might be an issue in these devices. Indeed spontaneous emission from the wetting layer was observed at room temperature as shown in Fig. 4.24 where the spontaneous emission spectrum was measured at 290 K and 860 A/cm². However, despite the interference in the spontaneous emission spectra, the radiative current obtained from the emission from the wetting layer seems negligible compared to the total threshold current assuming that re-absorption in the relatively thin wetting layer is negligible. This suggests that, even if there is some leakage in these devices, it is unlikely to dominate at room temperature. Auger recombination is known to be important at these wavelengths in quantum well lasers and is also thought to dominate the threshold current of 1.3 μm InAs/GaAs QD lasers [41,84] as discussed earlier in this chapter. Further investigation on the dominating non-radiative process is discussed in chapter 6 confirming

Figure 4.27: Variation of the nonradiative current density at threshold as a function of temperature calculated assuming that 90% of the threshold current is nonradiative at room temperature (see Fig. 4.21).
that Auger recombination is the main recombination process in 1.5 \( \mu \text{m} \) InAs/InP quantum dot lasers.

### 4.4 Summary

In this chapter it is shown that although \( J_{\text{rad}} \) can be relatively temperature stable around room temperature in 1.3 and 1.5 \( \mu \text{m} \) undoped quantum dot lasers, the threshold current is dominated by a strongly temperature dependent non-radiative recombination process. As a result the threshold current is temperature sensitive in these devices. Temperature-dependent measurements suggest that leakage into the wetting layer is present to some extent in both 1.3 \( \mu \text{m} \) InAs/GaAs and 1.5 \( \mu \text{m} \) InAs/InP (311)\( B \) quantum dot lasers. However leakage makes a negligible contribution to the threshold current around room temperature in these devices. Auger recombination seems to be the main recombination process involved in both undoped 1.3 \( \mu \text{m} \) InAs/GaAs and 1.5 \( \mu \text{m} \) InAs/InP quantum dot lasers. We measured that \( \sim 70 \% \) of the threshold current is formed of non-radiative recombination in 1.3 \( \mu \text{m} \) lasers while at least \( 90 \% \) of \( I_{\text{th}} \) is non-radiative in the 1.5 \( \mu \text{m} \) devices.

Several pieces of experimental evidence are found to explain the unusual decrease of the radiative current with increasing temperature in these quantum dot devices. This is attributed to an improvement of the carrier transport in the inhomogeneously broadened dots.

Measurements on p-doped 1.3 \( \mu \text{m} \) InAs/GaAs quantum dot lasers show that both threshold current and differential quantum efficiency can be temperature insensitive if the acceptor concentration is carefully chosen. It is thought that the holes introduced by p-doping increase the confinement potential for the electrons. This results in a decreasing radiative current around room temperature which compensates for the increase in non-radiative Auger recombination over a small temperature range around room temperature. These are very interesting characteristics for commercial devices. However the threshold current can be constant only over a limited temperature range and the threshold current density of p-doped quantum dot lasers is relatively high compared to undoped quantum dot lasers (300 versus 200 A/cm\(^2\) in the devices from Fujitsu). Also the differential quantum efficiency is
larger in the undoped devices than in the p-doped devices (~ 50 % versus ~ 43 %) at room temperature. Overall, the properties of the lasers are found to be highly sensitive to the growth parameters as shown in the literature and in the results presented in this thesis.

Our radiative current measurements show that the radiative current at threshold is higher in the 1.3 μm doped devices than in comparable undoped lasers. This suggests that contrary to what was calculated in the literature [16, 21, 31], the differential gain of doped devices is less than that of undoped lasers. The gain of both undoped and p-doped quantum dot lasers is studied in the next chapter.
Chapter 5

Gain measurements

In the previous chapter it was found that, in some cases, p-doping can greatly improve the temperature stability of the threshold current of 1.3 μm quantum dot lasers. However the measurements do not suggest a clear increase in the differential gain as originally suggested in [16, 21, 31] compared with undoped devices. Indeed, it was measured in chapter 4 that at room temperature the radiative current at threshold, $J_{rad}$, is twice as much in the p-doped devices as that in the undoped suggesting that the peak gain is less in the doped samples for the same current.

Furthermore it was measured that $J_{rad}$ increases slightly with increasing temperature above $\sim 300$ K suggesting that gain saturation could play a role in these quantum dot devices above room temperature.

This motivated a comparative study of the gain in both undoped and p-doped InAs/GaAs quantum dot lasers from Fujitsu. Measurements were performed at room temperature and at 350 K to determine if gain saturation could explain the increase in $J_{rad}(T)$ observed at high temperatures in Fig. 4.3 and 4.14.

The Hakki-Paoli technique [83] was used as described in section 3.5. The results discussed in this chapter are published in [10].
5.1 Gain measurements at 293 K

Amplified spontaneous emission spectra were measured at 293 K using 1.3 μm InAs/GaAs undoped and p-doped quantum dot devices from Fujitsu and the technique described by Hakki and Paoli in [83]. Modal net gain spectra \( g = \Gamma G - \alpha_i \) of undoped (top) and p-doped (bottom) quantum dot lasers are shown in Fig. 5.1. \( \Gamma \) is the confinement factor, \( G \) is the material gain, and \( \alpha_i \) is the internal loss. The measurements were performed at various injections below threshold using uncoated 0.5 mm long devices to measure the gain at low injections \( (g < 20 \text{ cm}^{-1}) \) and 0.3 mm long cavities for \( g > 13 \text{ cm}^{-1} \). Where the results overlap (same \( J \) value) in Fig. 5.2 the measurements show an excellent agreement.

Fig. 5.1 clearly shows that p-doping greatly changes the gain properties of InAs/GaAs QD lasers. It is obvious that gain saturation is not as strong in the doped samples where the first excited state does not reach transparency even for the highest injections. This is clearer in Fig. 5.2 where the peak modal net gain is plotted as a function of the current density. The measurements show that the peak net modal gain of the p-doped quantum dot lasers is less than that of the undoped devices for current densities less than \( \sim 1300 \text{ A/cm}^2 \). This is clearly illustrated by the injection needed to reach transparency \( (g=0 \text{ cm}^{-1}) \): it is more than twice as much in the p-doped devices compared to the undoped lasers \( (J \sim 200 \text{ and } \sim 450 \text{ A/cm}^2 \) respectively). In chapter 4 we found that unlike in undoped devices, in the p-doped lasers the carriers have still not reached thermal equilibrium at room temperature. The inhomogeneous broadening is thus slightly larger in the doped devices as shown in Fig. 5.3. This results in a broader gain spectrum with a lower peak which could partially explain the lower peak gain and the higher value of \( J_{rad} \) observed in the doped devices.

The differential peak gain with respect to current density \( (dg/dJ) \) is further lowered in the doped devices by the increased non-radiative component of the threshold current. Indeed it was shown in Chapter 4 that at room temperature \( J_{nonrad} \) is about twice as high in the p-doped compared to the undoped devices. Although this would not decrease the gain for a given \( J_{rad} \) as the broadening does, non-radiative recombination decreases the gain for a given current density, or in other words the differential gain. This is confirmed in [93] where it is measured that doping increases the gain at a fixed quasi-Fermi-level separation, but
Figure 5.1: Modal net gain spectra measured at various current injections below threshold in undoped (top) and p-doped (bottom) 1.3 µm InAs/GaAs quantum dot lasers at room temperature (293 K) obtained for two different length devices (0.3 and 0.5mm).
also increases the non-radiative current. So overall the differential gain of p-doped lasers is not increased compared to that of the undoped devices.

More recent results demonstrated that p-type impurities can be incorporated without increasing the non-radiative recombination, resulting in a lower threshold current density in the doped lasers. In this case the peak gain was measured to be larger in the doped sample for any given injection [29]. These devices, grown by Sheffield did not exhibit a negative characteristic temperature nor an infinite $T_0$ around RT similarly to what we observed on our samples from Sheffield. This is consistent with our conclusions in Chapter 4.

In chapter 4, 1 mm long cavities were used for the measurements. Such devices have mirror losses $\alpha_m = 11 \text{ cm}^{-1}$. Looking at Fig. 5.2 and comparing the values of the current density at $g = 11 \text{ cm}^{-1}$ (which is threshold for 1 mm long cavities since this graph shows the modal net gain) shows that $J_{th}$ is expected to be about 2.5 times as much in the doped devices as in the undoped devices. This is in excellent agreement with what was measured in the temperature dependence measurements. However there is a significant discrepancy in the
absolute values of $J_{th}$. This might be attributed to the effect of internal heating: The temperature dependent measurements were performed using 500 ns pulses at a frequency of 10 kHz which prevented effects of internal heating while the gain measurements were performed quasi-CW using 1ms pulses at a repetition rate of 50% because of the time response of the detector and to avoid transient mode hopping. For 1 mm long cavities, the value of the threshold current density at room temperature is $\sim 270$ A/cm$^2$ as determined from Fig. 5.2, while in Fig. 4.1 it is measured to be $\sim 197$ A/cm$^2$ for a 1 mm long laser at the same temperature but using short pulses. Using Eq. 2.11 and the measured value of the characteristic temperature (60 K, as measured in Chapter 4), it is found that the threshold current density measured from the gain measurements corresponds to a temperature of $\sim 312$ K on Fig. 2.11 where internal heating is negligible. This corresponds to a temperature rise of $\sim 19$ K due to internal heating. This is comparable to what was observed in broad area quantum well lasers [95].

Whilst doping is detrimental to the gain at low injections, it is found to reduce the effect of
gain saturation at high injections: While the ground state transition (GS) of the undoped devices (solid red symbols) saturates at a value of ~ 26 cm⁻¹, the GS of the doped devices did not completely saturate in the whole range measured in this work (Fig. 5.2). This is supported by the presence of the first excited state (1ES) in the undoped devices which reach transparency at ~ 600 A/cm² when the GS starts saturating, while the contribution from the 1ES of the p-doped devices was negligible. As a result, even if the gain is generally more in undoped devices, above 1300 A/cm² the GS of the p-doped lasers can achieve higher gain at high injections thanks to the reduced gain saturation. The reason for this is given in [93] where it is calculated that using p-type impurities reduces the probability of occupation of electrons in both the valence and conduction excited states.

5.2 Gain measurements at 350 K

Following the gain measurements performed at room temperature (293 K), gain measurements were performed at 350 K using the same technique and the same devices (0.3 mm long p-doped and undoped InAs quantum dot lasers from Fujitsu). The results are shown in Fig. 5.4 where the variation of g is plotted as a function of the current density (J). The red symbols correspond to the undoped devices, the black symbols are for the doped devices and the solid and open symbols are for the ground state and first excited states respectively. Fig. 5.4 shows 4 major differences when compared to Fig. 5.2 where g was measured at room temperature:

- Transparency and gain saturation are still reached at lower injection in the undoped devices but the difference is less than at 293 K. This is because at 350 K the effect of the doping becomes less significant. This is illustrated in Fig. 5.3 where the full width at half maximum becomes more similar in both device types because of the improved carrier thermalisation. This also suggests that the carriers in the p-doped devices may still not be at thermal equilibrium at 350 K since p-doped lasers should have a lower carrier density at transparency providing that the non-radiative current has not increased too much [31,37,93].
Comparing the values of \( I_{th} \) and \( I_{rad} \) in Fig. 5.5 further confirms the idea that the effect of the doping becomes less at 350 K since the threshold current and the radiative current tend toward the same values for the doped and undoped devices. It is therefore expected that the modal peak net gain (\( g \)) of undoped and p-doped lasers varies in a more similar way with the current density at 350 K than at 293 K.

- As measured in Chapter 4, the non-radiative current increases steeply with increasing temperature. As a result the differential gain \( \frac{dg}{dJ} \) is decreased compared to that at room temperature because of the increased fraction of carriers involved in non-radiative recombination relative to the number of carriers involved in producing gain from the GS. This also explains why transparency is reached at higher injections at 350 K.

- \( g \) saturates at lower values at 350 K than at 293 K. This might be attributed to an increase in the thermal broadening of the confined levels in the dots [61,62] which would reduce the peak gain. Another explanation is that electrons are excited to higher
energy states which would reduce the gain, as explained in [93]. It is said in [88] that the internal loss does not increase much with temperature, and is therefore unlikely to play an important role. Homogeneous broadening and carrier excitation into higher energy levels might therefore be responsible for the decrease in the value at which the gain saturates. This in turn explains the increase in the radiative current at threshold observed at high temperatures in Fig. 5.5.

• Finally, the role played by the first excited state becomes more important at 350 K than at 293 K. This is clearly illustrated by the fact that at room temperature in the p-doped device, the 1ES does not reach transparency even when the GS generates a gain > 30 cm\(^{-1}\) (see Fig. 5.2 and 5.1), while at 350 K the 1ES reaches transparency while the gain of the ground state is only \(~17\) cm\(^{-1}\) (see Fig. 5.4).
CHAPTER 5. GAIN MEASUREMENTS

5.3 Summary

At room temperature gain measurements show that p-doping in InAs/GaAs lasers successfully reduces the gain saturation. However, the non-thermal distribution of the electrons due to the increased confining potential for the electrons and the increase in the non-radiative current decrease both the peak gain and the differential gain of p-doped devices. This results in a regime ($J<1300 \text{ A/cm}^2$) where undoped samples achieve more gain than p-doped devices. Above this current density, reduced gain saturation allows for a larger gain in the doped devices. These results are consistent with the work described in [11, 93]. We clearly measured that at room temperature the first excited state would take over in these devices if the mirror loss is more than $\sim 25 \text{ cm}^{-1}$. In other words these devices (as-cleaved) should be more than 0.44 mm long if ground state emission is desired.

At 350 K, the effect of p-doping is reduced as the influence of the excess holes becomes less. The behaviour of both devices thus becomes more similar. The peak modal net gain of the doped samples is still slightly less at low injections than in the undoped devices. Because of the increased $J_{\text{non-rad}}$ at 350 K, the differential gain is less than at room temperature. Gain saturation is also dramatically increased suggesting that homogeneous broadening and/or population of excited energy states might become significant at high temperatures in these doped quantum dot lasers. This explains the increase in the $J_{\text{rad}}$ observed above 300 K in Chapter 4.
Chapter 6

High pressure studies

In this chapter the pressure dependence of the threshold current and radiative current at threshold are measured and analysed. 1.5 µm InGaAs/InP quantum well lasers, which have previously been studied in detail were first measured and analysed. The pressure dependence of the threshold and radiative current was used to determine the pressure dependence of the Auger coefficient. Similar measurements were then performed on 1.3 µm InAs/GaAs undoped and p-doped quantum dot lasers and 1.5 µm InAs/InP quantum dot lasers. Finally initial photo-current measurements were carried under pressure to determine the pressure dependence of the ground-state/wetting-layer splitting which has an influence on leakage. So far there has been only little theoretical and experimental investigation of the effect of pressure on the recombination processes in quantum dot lasers and the interpretation of the experimental results remains speculative.

6.1 1.5 µm InGaAs/InP quantum well lasers

6.1.1 Pressure dependence of the threshold current

The pressure dependence of the threshold current is plotted on Fig. 6.1 where it can be seen that the threshold current decreases by about 24% over 8 kbar. This is consistent with what has been observed before in [80,96] and is attributed to a decrease of the non-radiative Auger recombination current with increased band gap. The pressure dependence of the Auger and
radiative recombination processes will be discussed in detail in the following sections.

![Figure 6.1: Pressure dependence of the threshold current in a 1.5 μm InGaAs/InP multi-quantum well laser.](image)

**Figure 6.1: Pressure dependence of the threshold current in a 1.5 μm InGaAs/InP multi-quantum well laser.**

### 6.1.2 Pressure dependence of the radiative current

Many publications [96–98] assume that the pressure dependence of the radiative current is proportional to the square of the band gap as calculated for ideal quantum well lasers in [99]. Since the band gap increases with increasing pressure, the radiative current at threshold increases with pressure too. Pressure measurements carried out at cryogenic temperatures, where all of the injected carriers recombine radiatively, have been performed in [100]. They show that the threshold current, which is thought to be formed of 100 % radiative current, increases with pressure close to $E_g^2$. In the work presented in this thesis the pressure dependence of the radiative current was studied experimentally at room temperature by measuring the light spontaneously emitted through a window as described in Section 3.2.2. This allows for the verification of the validity of the $I_{rad} \propto E_g^2$ relation. The results are plotted on Fig 6.2.

The measured pressure dependence of the radiative current increases by about 10 % over 8
CHAPTER 6. HIGH PRESSURE STUDIES

Figure 6.2: Pressure dependence of the radiative current in a 1.5 μm InGaAs/InP multi-quantum well laser.

Pressure (kbar) versus Normalised $I_{rad}$

The pressure dependence of the radiative current in a 1.5 μm InGaAs/InP multi-quantum well laser is shown in Figure 6.2. This increase is slightly less than that given by the simple $E_g^2$ model [70]. Detailed calculations were performed by Dr Stephen Sweeney at the University of Surrey using a code written by Silver [101] to further investigate the pressure dependence of the radiative current. A six-band k.p Hamiltonian taking into account the changes in effective masses and band gaps with pressure was used to calculate the QW band-structure. Poissons and Schrödinger's equations were solved self-consistently in the calculation of both the conduction and valence bands under injection. A five-point difference method [101] was used to account for carrier spill-over into the barrier and separate-confinement regions. The spontaneous emission rate, gain and radiative current density were calculated from these band structures for single QWs using the density matrix formulation including Lorentzian-type broadening. Further details of the modelling can be found in Ref. [101]. The wavelength of the emitted light shifts by about 7 meV/kbar as pressure is applied. However, the dimensions of the laser remain approximately constant. This induces a significant change in the confinement factor with pressure as discussed in [102]. This was accounted for in the calculations using the effective index method [101]. The results of these calculations are compared to the
experimental data on Fig. 6.3.

It was found that the variation of the calculated radiative current, taking into account the pressure dependence of the confinement factor, increases more than the experimental data. This suggests that another effect has to be accounted for. In Ref. [97] it is measured that the internal loss ($\alpha_0$) is $\sim 10$ cm$^{-1}$ at atmospheric pressure and room temperature in InGaAs/InP quantum well lasers. This was thus taken as a new pressure independent parameter in the calculations. These new calculations (dotted line in Fig. 6.3) offered a better agreement but still overestimated the experimental data.

The origin of the internal losses in lasers operating at these wavelengths is due to the absorption of a photon by an electron in the spin-orbit band which is then excited to the top of the valence band [65]. This process is known as Inter Valence Band Absorption or IVBA. As the pressure is increased, the photon energy increases but the spin orbit splitting remains relatively constant [103]. The transitions involved in IVBA therefore have to move away from the Brillouin zone center where the hole occupation becomes less. The IVBA rate is therefore reduced when the pressure is increased. In order to take the decrease in $\alpha_i$ into account, to first approximation
a linear decrease of the losses with increasing pressure was assumed: \( \alpha_i(P) = \alpha_0 - \beta P \)
where \( \alpha_i \) is the total internal loss for a given pressure, \( \alpha_0 \) is the internal loss at atmospheric pressure, and \( \beta \) the rate of change in loss with pressure. A good agreement with the experimental data could now be found for \( \beta = 0.5 \text{ cm}^{-1}/\text{kbar} \) as shown in Fig. 6.3.

### 6.1.3 Pressure dependence of the non-radiative current

Knowing the pressure dependence of the threshold and radiative currents, it is possible to determine the pressure dependence of the non-radiative current using the relation

\[
\frac{I_{th}(P)}{I_{th}(0)} = X \frac{I_{\text{rad}}(P)}{I_{\text{rad}}(0)} + (1 - X) \frac{I_{\text{nonrad}}(P)}{I_{\text{nonrad}}(0)}
\]

This assumes that the leakage current is negligible which is shown to be true in these structures [80]. \( X \) was determined by measuring the temperature dependence of the threshold and radiative currents. The results of the temperature measurements are shown on Fig. 6.4.

![Figure 6.4: Temperature dependence of the threshold current in a 1.5 \( \mu \text{m} \) InGaAs/InP multiple-quantum well laser. \( I_{\text{rad}} = 20\% I_{th} \) at room temperature](image)

To determine \( X \) it was assumed that at low temperature all of the current was radiative [80]. By linearly extrapolating the radiative current toward high temperatures (red line) it is
found that at room temperature $I_{rad}$ forms 20% of $I_{th}$, giving $X = 0.2$. It is now possible to experimentally determine the pressure dependence of the non-radiative current which is shown in Fig. 6.5.

![Figure 6.5: Pressure dependence of the radiative current (Open circles), threshold current (solid squares) and non-radiative current (Open triangles) in a 1.5 μm InGaAs/InP multi-quantum well laser.](image)

The non-radiative current decreases with increasing pressure as it is usually observed in this type of device. This is because as hydrostatic pressure is applied, the band gap of the material increases. In order to fulfil the energy and momentum conservation laws and because of the k-dependence of the bands, the transitions involved in Auger recombination are pushed away from the Γ Brillouin zone centre where the hole population is less in the valence band. As a result Auger recombination is less likely in large band gap semiconductor materials. The decrease of the non-radiative current is consistent with Auger recombination dominating the threshold current around room temperature in these devices [80,96].

It is shown in [80] that the Auger process known as CHSH dominates in these devices. In CHSH Auger recombination an electron recombines from the conduction band to the heavy hole band promoting an electron from the spin orbit band to the heavy hole band.
The pressure dependence of the Auger coefficient $C = I_{Aug} / (eVp_{th}^2n_{th})$ may therefore be calculated using the measured pressure dependence of the Auger current $I_{Aug}$ and the calculated electron and hole densities at threshold ($n_{th}$ and $p_{th}$ respectively). $V$ is the total pumped volume of the active region ($6.03 \times 10^{-12}$ cm$^3$). The pressure dependence of $C$ is shown in Fig. 6.6. The Auger coefficient $C$ is found to be $\sim 1.6 \times 10^{-29}$ cm$^6$/s at atmospheric pressure decreasing exponentially with band gap. This is in reasonable agreement with what is reported in the literature [6]. The inset in Fig. 6.6 is a semi-logarithmic plot of $C$. It is shown that by exponentially extrapolating $C$ towards 1.3 $\mu$m, the value of $C$ decreases by $\sim 50\%$. This is in excellent agreement with measurements performed on 1.3 $\mu$m lasers where $I_{Aug}$ forms 50\% of $I_{th}$ at room temperature. The calculated decrease of $C$, together with the increase in $I_{rad}$ explain why $I_{nonrad}/I_{th}$ changes from 80\% to 50\% when decreasing the wavelength from 1.5 to 1.3 $\mu$m.
6.2 1.3 μm undoped InAs/GaAs quantum dots lasers

6.2.1 Pressure dependence of the lasing energy

The pressure dependence of the ground and first excited state lasing energies of the 1.3 μm InAs/GaAs quantum dot lasers are shown in Fig. 6.7. It increases linearly with pressure at a rate of 7.0 meV/kbar on the ground state and 6.7 meV/kbar on the first excited state.

![Figure 6.7: Pressure dependence of the lasing wavelength in 1.3 μm InAs/GaAs quantum dot laser. Open symbols: first excited state, Solid symbols: ground state.](image)

Although the 0.5 mm long devices from Fujitsu usually lased from the ground state, once in the pressure liquid they lased from the first excited state. This arises from the increased refractive index of the essence F (n = 1.4) compared to that of the air (n = 1). This change in the refractive index induces an increase of the mirror losses from 23.5 cm\(^{-1}\) in the air to 34 cm\(^{-1}\) in the essence F for 0.5mm long cavities. As it can be seen on Fig. 5.2 this increase in the mirror losses will make the laser switch from the ground state to the first excited state as a consequence of the gain saturation. Illustration of this effect is shown on Fig. 6.8 where the spontaneous emission at threshold was measured at threshold both in the air (blue curve) and in the pressure liquid at various pressures (black curves) where
the gain saturation of the ground state is evident. The 1 mm long devices however always lased from the ground state as expected from the gain measurements. This allowed for the measurement of the pressure dependence of the lasing wavelength when devices lased from the ground state or from the first excited state.

![Figure 6.8: Spontaneous emission spectra measured at threshold in the air (blue curve) and in the pressure liquid (black curves) from a 0.5 mm long undoped 1.3 μm InAs/GaAs device from Fujitsu. The effect of the gain saturation of the ground state is evident from the levelling of the ground state emission and from the increased emission from the first and second excited states.](image)

**6.2.2 Pressure dependence of the threshold current**

The pressure dependence of the threshold current was measured for both 1 mm long devices which lased from the ground state and for 0.5 mm long lasers which lased from the first excited state. The results are plotted on Fig. 6.9 where the threshold current is normalised at atmospheric pressure. They show that the threshold current remains quasi pressure-independent over the 8 kbar range for both cavity lengths. It is interesting to note that the devices lased from different energy levels but still have the same pressure dependence within experimental uncertainty.
6.2.3 Pressure dependence of the radiative current

In order to further understand the pressure dependence of the threshold current, spontaneous emission measurements were performed under pressure using the same 0.5 mm and 1 mm long InAs/GaAs quantum dot lasers as in the previous section. The normalised pressure dependence of the radiative current at threshold is plotted in Fig. 6.10. The radiative current increases steeply with increasing pressure by about 40 % over the 8 kbar range. The pressure dependence of the radiative current at threshold is identical in both cavity length devices. In fact the normalised pressure dependence of \( J_{rad} \) varies similarly in all quantum dot lasers studied so far and seems to be a common property of quantum dot lasers as outlined in [104].

To date, there is no clear explanation for this strong increase of the radiative current at threshold. It can be empirically fitted with an \( E_g^5 \) pressure dependence which is large compared to the \( E_g^2 \) dependence observed in most quantum well lasers, as discussed in the previous section.
6.2.4 Pressure dependence of the non-radiative current

The temperature dependent measurements shown in Fig. 4.3 reveal that, in air, 70 % of the total threshold current is formed of non-radiative recombination while 30 % only comes from radiative recombination at room temperature and atmospheric pressure. Because we know the pressure dependence of both the threshold and its radiative component, we can determine the band-gap dependence of the non-radiative current at threshold at room temperature since $I_{\text{th}}(P)/I_{\text{th}}(0) = 0.3 I_{\text{rad}}(P)/I_{\text{rad}}(0) + 0.7 (I_{\text{nonrad}}(P)/I_{\text{nonrad}}(0))$. Because of the increase of the threshold current density due to the large effective index of the essence F compared to that of the air, $I_{\text{rad}}/I_{\text{th}}$ may be less in the liquid at room temperature than in the air. However, we cannot quantify this and assume that $I_{\text{rad}}/I_{\text{th}} = 30\%$. A smaller $I_{\text{rad}}/I_{\text{th}}$ ratio would make the pressure dependence of the non-radiative current move closer to that of the threshold current. The calculated pressure dependence of the non-radiative current at threshold is shown in Fig. 6.11.

$I_{\text{nonrad}}$ decreases by approximately 15 % over 8 kbar. In quantum well lasers a decrease
in $I_{\text{non-rad}}$ with increasing pressure is usually a sign that Auger recombination is the main non-radiative recombination process. The reason for this is explained in section 6.1. In quantum-dot lasers, because the states are $k$-independent, the momentum conservation rule is relaxed which should make Auger recombination pressure independent. However, in [41], it is shown that Auger recombination should also decrease with pressure in quantum dot lasers. This is because as the pressure is increased, the band gap is also increased. As a result the carrier excited after the electron-hole recombination gets excited to higher energy levels as the pressure increases. Because the higher energy levels have more oscillatory wave-functions, the overlap integral between the fundamental and the excited states decreases with increasing pressure leading to a decrease in Auger recombination when pressure is increased. The decrease in the non-radiative current is thus consistent with Auger recombination being the main recombination process in these 1.3 μm InAs/GaAs quantum dot lasers.

The pressure coefficient of the wetting layer is thought to be very close to that of the GS
quantum dots. Leakage toward the wetting layer would therefore be pressure independent. This is confirmed by Fig. 6.8 where the small amount of emission from the wetting layer remains approximately constant while the emission from the dots increases.

6.3 1.3 μm p-doped InAs/GaAs quantum dots lasers

6.3.1 Pressure dependence of the lasing energy

The pressure dependence of the lasing energy was measured for 1 mm and 0.5 mm long 1.3 μm p-doped InAs/GaAs quantum dot lasers. Because of the increased mirror losses induced by the pressure medium the 500 mm long cavities lased from the first excited states (cf section 6.2.1).

![Graph showing pressure dependence of lasing energy](image)

Figure 6.12: Pressure dependence of the lasing wavelength in p-doped 1.3 μm InAs/GaAs quantum dot laser. Open symbols: first excited state, Solid symbols: ground state.

The lasing energy of the ground state increases by 7.1 ± 0.1 meV/kbar and of 7.8 ± 0.5 meV/kbar for the 1 mm and 0.5 mm long devices respectively. The pressure coefficient of the ground state is identical within experimental error in both undoped and p-doped
devices. The lasing energy of the ground state is also identical at 0.974 eV. The pressure coefficient of the first excited state of the p-doped lasers (0.5 mm long laser) seems to be more than that of the undoped devices.

### 6.3.2 Pressure dependence of the threshold current

The pressure dependence of the threshold current was measured for both 0.5 and 1 mm long p-doped quantum dot lasers. $I_{th}$ is normalised to its value at atmospheric pressure.

![Figure 6.13: Pressure dependence of the threshold current of 1 mm (solid symbols) and 0.5 mm (open symbols) long p-doped 1.3 μm InAs/GaAs quantum dot laser.](image)

The experimental error is quite large in these measurements. The 1 mm long lasers, which have lower carrier concentrations at threshold, tend to be more pressure sensitive than the shorter cavity devices which is consistent with Auger recombination dominating the threshold current of these devices as discussed in Chapter 4.

The threshold current of the 1 mm long devices was also measured as a function of the pressure at 60°C where non-radiative recombination is more important than at room temperature (Fig. 6.14). At 60°C the threshold current was measured to increase slightly less
than at room temperature with increasing pressure. This consistent with a slowly decreasing non-radiative current with increasing pressure as discussed in the following sections, which again is thought to a sign of Auger recombination being the dominant non-radiative process.

6.3.3 Pressure dependence of the radiative current

The pressure dependence of the radiative current at threshold in the 1 mm long devices is measured to increase by ~ 45 % over 8 kbar (Fig. 6.15) similarly to what is observed in the undoped lasers. The 0.5 mm long devices however see their radiative current increasing slightly more than that (≈ 60 %). Although numerous experiments were performed, the radiative current increased in a reversible manner only once in each device type. This means that there is only one measurement of the pressure dependence of $I_{\text{rad}}(P)$ for each cavity length. Clearly more measurements need to be done to confirm these results and, to a first approximation, the difference between $I_{\text{rad}}(P)$ in the two cavity lengths is thought to be
negligible.

![Figure 6.15: Pressure dependence of the threshold current (red circles) and radiative current at threshold (black squares) in 1.3 μm InAs/GaAs quantum dot laser.](image)

6.3.4 Pressure dependence of the non-radiative current

The pressure dependence of the non-radiative current at threshold is measured using the pressure measurements of the threshold current and radiative current at threshold together with the temperature-dependent measurements as explained before. In Fig. 4.14 the total threshold current is measured to be formed of ~70 % non-radiative current and ~ 30 % radiative current. As explained in the previous section, $I_{\text{rad}}/I_{\text{th}}$ might be less than 30% in Essence F because of its larger refractive index compared to that of the helium used in the cryostat, but X=0.3 is used here as a maximum value to determine the pressure dependence of the non-radiative current at threshold. The results of the calculated pressure dependence of the non-radiative current at threshold are shown in Fig. 6.16 (blue triangles) with the pressure dependence of the threshold current (red circles) and radiative current at threshold (black squares).

Despite the relatively large uncertainty, the trend in these measurements is that the non-
radiative current decreases with increasing pressure. This is consistent with what is observed in the undoped devices and in other types of lasers (quantum well and bulk lasers) emitting at these wavelengths. A decrease in the non-radiative current with increasing pressure is attributed to Auger recombination being the dominant non-radiative process in these p-doped devices. In [41] Auger recombination is calculated to decrease with increasing pressure because the overlap integral of the wave functions decreases with increasing band gap. There is no obvious reason which would make this mechanism much different in the undoped devices compared to in the doped lasers. Also, because the threshold current and the radiative current at threshold vary approximately identically with increasing pressure in both undoped and p-doped devices, and because $I_{\text{rad}} / I_{\text{th}}$ is the same for both undoped and p-doped devices, the pressure dependence of the non-radiative current should thus be similar in both device types. Indeed, the pressure dependence of the non-radiative current in the undoped devices varies identically with pressure to the average value of $I_{\text{nonrad}}$ for the doped devices.
The decrease of the non-radiative current with increasing pressure seems to be more pronounced in the shorter cavity devices. Although the experimental uncertainty is large in these measurements, the larger decrease in $I_{\text{nonrad}}$ might be because of gain saturation; The shorter devices are driven at much higher current densities than the undoped devices and non-radiative recombination is likely to be more significant than in the 1 mm long devices. Since the pressure dependence of the radiative current at threshold could not be measured at 60°C, the pressure dependence of the non-radiative current at threshold cannot be determined at this temperature. However, the temperature-dependence measurements show that only ~17% of the total threshold current is formed of radiative current at 333 K in the gas system. This suggests that the normalised pressure dependence of $I_{\text{nonrad}}$ must be very close to that of $I_{\text{th}}$. Because $I_{\text{rad}}$ is most probably more pressure dependent than $I_{\text{th}}$, the non-radiative current is thought to be little more pressure dependent than the threshold current. This suggests that at 60°C also the non-radiative current decreases slightly with increasing pressure, a sign of Auger recombination dominating.

6.4 1.5 μm InAs/InP quantum dots lasers

6.4.1 Pressure dependence of the lasing energy

The lasing energy was determined as function of pressure in 1.5 μm InAs/InP (311)B quantum dot lasers. The pressure coefficient is measured to be $8.4 \pm 0.6$ meV/kbar (Fig. 6.17). This is a slightly higher than in the 1.3 μm InAs/GaAs devices studied in the two previous sections, but falls within the range of typical values.

6.4.2 Pressure dependence of the threshold current

The pressure dependence of the threshold current was measured from 0 to 8 kbar. The band gap dependence of the threshold current is plotted in Fig. 6.18.

The threshold current decreases steeply by 40% over 8 kbar (~64 meV). The pressure dependence of the radiative current could not be measured in these devices, but we note at least 90% of the threshold current at room temperature and atmospheric pressure
Figure 6.17: Pressure dependence of the lasing wavelength in 1.3 μm InAs/GaAs quantum dot laser.

Figure 6.18: Pressure dependence of the threshold current in 1.5 μm InAs/InP quantum dot laser.
is formed of non-radiative recombination. The pressure dependence of the non-radiative current must therefore be close to that of the threshold current. Furthermore, the radiative current is expected to increase as has been observed in every other quantum dot laser measured at Surrey approximately proportionally to $E_g^6$ and also increases in quantum well lasers emitting at 1.5 μm [70]. The non-radiative current is therefore expected to decrease slightly more than the threshold current with increasing pressure. This decrease of the non-radiative current is consistent with Auger recombination being the main non-radiative process as explained earlier in this chapter.

We know from the temperature-dependent measurements that there is some leakage into the wetting layer at threshold and room temperature in these lasers. This is thought to be pressure independent, however there is no clear experimental evidence proving it. Photocurrent measurements carried out under high hydrostatic pressure are discussed in the next section to determine how the confining potential of the carriers varies with pressure.

### 6.5 Pressure dependence of the photo-current

It is not clear how the confining energy of the carriers should vary with increasing pressure. Although the pressure coefficient of the ground state emission could be measured by collecting pure spontaneous emission as a function of pressure, the emission from the wetting layer is too weak to be determined with accuracy (a typical spontaneous emission spectrum is shown in Fig. 4.24). Furthermore interference effects could modify the energy at which the peak emission is observed.

Photo-current measurements were performed as a function of pressure to determine the pressure coefficient of both the quantum dot ground state and wetting layer transition energies.

#### 6.5.1 Pressure dependence of the optical transition energies

Because we suspect that there may be a small amount of leakage into the wetting layer in 1.5 μm InAs/InP (311)B quantum-dot lasers at room temperature, we used these devices to
perform pressure dependent photo-current measurements. Kristukat et al in [105] performed photo-luminescence measurements on 1.3 μm InAs/GaAs self assembled quantum dots as a function of high hydrostatic pressure. This allows for the measurement of the ground state and wetting layer pressure coefficients. They found that the energy of the wetting layer increases more than that of the ground state of the quantum dots which would make leakage current decrease with increasing pressure. This is not thought to be an issue for the interpretation of the pressure measurements of the 1.3 μm InAs/GaAs quantum devices studied earlier in this chapter since the total magnitude of the leakage current is thought to be small compared to that of the Auger recombination current. The measurements presented in this thesis were carried out using the set-up described in section 3.6 and using the high hydrostatic gas pressure system described in [100]. The photo-current spectra obtained are shown in Fig. 6.19. Because the signal was weak, there is a relatively large experimental error associated with these measurements. The energy of the ground state and wetting layer transitions are plotted in Fig. 6.20.

The energy of the dot ground-state transition increases steadily with pressure. The pressure

![Figure 6.19: Pressure dependence of the photo-current spectra in a 1.5 μm InAs/InP quantum-dot lasers.](image)
coefficient of this transition is $\frac{dE}{dP} = 7.6 \pm 2.6 \text{ meV/kbar}$. The energy of the wetting layer also increases steadily with a pressure coefficient of $\frac{dE}{dP} = 8.3 \pm 1.2 \text{ meV/kbar}$. These two pressure coefficients are equal within experimental error, which suggests that the leakage current is pressure insensitive. However the experimental error is quite large in these measurements and more work needs to be done to confirm the results presented here.

6.6 Summary

Pressure measurements of the threshold current and its radiative and non-radiative components at threshold were performed as function of high hydrostatic pressure using p-doped and undoped InAs/GaAs 1.3 µm and InAs/InP (311)B 1.5 µm quantum dot lasers. The pressure coefficients of the ground state and first excited states transition energies were also determined.

The radiative component of the threshold current is observed to increase steeply with pressure in all devices measured as discussed in [104] but there is no clear explanation for this
Fig. 6.21 shows the normalised variation of the threshold current of various types of undoped devices as a function of high hydrostatic pressure. From this graph it is clear that as the band gap of the material is decreased, the pressure dependence of the threshold current tends to decrease more with pressure: In the 980 nm devices measured in [41], the threshold current increases because leakage is the main loss process in these devices. In the 1300 nm devices the non-radiative current decreases with increasing pressure which is attributed to Auger recombination. This decrease is more pronounced in the 1500 nm devices where the band gap increases more quickly with pressure and where Auger plays an even more important role. These results are very similar to what is observed in quantum well lasers where the gradual decrease of the pressure dependence of the threshold current with increasing band gap is also attributed to a reduction in Auger recombination. This is also thought to be the case in these quantum dot lasers, but for other physical reasons as explained in [41].

Furthermore, initial photo-current measurements were performed under high hydrostatic pressure using 1.5 μm InAs/InP (311)B quantum dot lasers. Within experimental uncer-
tainty we expect the leakage current to be pressure insensitive. Clearly more measurements need to be undertaken to reduce the level of uncertainty in the pressure coefficients of the ground state and wetting layer transitions.

Pressure-dependent measurements of the threshold current and its radiative component were also performed on 1.5 μm InGaAs/InP quantum well lasers. These measurements combined with temperature-dependent measurements as well as detailed calculations of the pressure dependence of the carrier density, taking into account the pressure variation of the optical confinement factor and of the internal loss, allow for the determination of the band gap dependence of the Auger coefficient, C.
Chapter 7

Conclusions and future work

7.1 Conclusions

The recombination processes which take place in quantum dot devices have been studied experimentally. It is found that in undoped 1.3 μm InAs/GaAs quantum dot lasers the radiative current at threshold decreases with increasing temperature below 200 K. This is attributed to an improvement of the carrier transport among the inhomogeneously broadened dots. This broadening decreases with increasing temperature which in turn increases the gain and decreases the injection needed to reach the threshold condition. Various pieces of experimental evidence such as measurements of the full width at half maximum of the spontaneous emission spectra, study of the pinning of the spontaneous light-current characteristics and measurements of the differential quantum efficiency all support this argument. Above 200 K the radiative current becomes approximately temperature-insensitive but the onset of a strongly temperature dependent non-radiative current makes the total threshold current temperature sensitive leading to relatively poor characteristic temperatures, $T_0$ (typically less than 100 K). A careful study of the temperature dependence measurements confirmed by high-hydrostatic pressure measurements suggest that Auger recombination is the main loss process in these devices. Auger recombination, being an intrinsic process, is difficult to suppress in this material system, however its magnitude can be reduced if the carrier concentrations are reduced.
A similar study is performed on p-doped 1.3 μm InAs/GaAs quantum dot lasers. Two types of device with different doping concentrations were measured. The acceptor concentration is found to play a crucial role in the performance of these devices. If the doping concentration is carefully chosen (from the literature it seems that ~15 acceptors per dot is the upper limit), the threshold current can be temperature insensitive around room temperature. If too much doping is introduced, the benefit is lost and the lasers do not exhibit a negative or infinite $T_0$.

In the doped devices with an infinite characteristic temperature, the decrease of the radiative current takes place around room temperature. It is shifted towards higher temperatures because the Coulombic attraction of the excess holes increases the potential for the electrons. In the doped devices, the electrons need more energy to thermalise within the inhomogeneously broadened dots. Because the non-radiative current increases around room temperature, the interplay between the decreasing radiative current and the increasing non-radiative current gives rise to a finite temperature range over which the threshold current is temperature insensitive. Because the carriers are not in thermal equilibrium, the broadening is larger in the doped devices than in the undoped devices at room temperature. This results in a smaller peak gain for a fixed injection current in the doped lasers as observed from gain measurements. Because of the smaller peak gain, higher injections are needed to reach the threshold condition. As a result both radiative and non-radiative currents are increased. This results in a smaller differential gain and a larger threshold current in the doped devices.

The dominant non-radiative process involved in these doped devices is thought to be Auger recombination, like in the undoped devices.

In the p-doped 1.3 μm InAs/GaAs quantum dot lasers, both Auger recombination and inhomogeneous broadening which are both usually detrimental to the laser performance are combined and, counter-intuitively, result in improved device characteristics. The temperature range over which an infinite $T_0$ is achieved could possibly be extended by carefully selecting and controlling the doping concentration and the inhomogeneous broadening. However because of the numerous coupled processes involved in these devices, it is difficult to defini-
tively state how changing any of these parameters would change the device properties. For this, detailed calculations of the temperature dependence of the threshold current would prove useful. This requires calculating the band structure for realistic dot structures, calculation of the gain taking into account the variation of the broadening and implementing the evolution from a non-Fermi-Dirac distribution at low temperatures towards a Fermi-Dirac distribution when the carriers are in thermal equilibrium. Detailed calculations would also require simulating leakage and calculations of the Auger recombination taking into account different possible recombination processes.

Finally 1.5 μm InAs/InP (311)B quantum dot lasers were studied. In this material the smaller lattice mismatch between the dots and the substrate leads to the formation of a relatively thick wetting layer creating a small total band offset between the wetting layer and the dot ground state. The inter-dot transport is therefore good even at low temperature. This results in a relatively temperature stable radiative current at threshold, increasing only slightly above 100 K due an increase in homogeneous broadening and the population of the excited states. The threshold current however is very temperature sensitive because of a temperature dependent non-radiative process which accounts for at least 90% of the total threshold current at room temperature. A small amount of spontaneous emission from the wetting layer is observed at room temperatures. This suggest that there is some leakage from the dots to the wetting layer, but its total magnitude is relatively small. Temperature and pressure measurements suggest that Auger recombination is the main loss process in these devices too. Better thermal performance should be achievable in 1.5 μm quantum dot lasers by increasing the band offset (by using a larger lattice mismatch between the wafer and the active region) and utilising p-doping, thus modifying the carrier transport and reproducing the effect obtained in p-doped 1.3 μm InAs/GaAs quantum dot lasers.

Initial photo-current measurements carried-out under high hydrostatic pressure suggest that the pressure coefficient of the wetting layer is comparable to that of the ground state of the dots, however the experimental error is relatively large which makes interpreting these results difficult. Based on these data, the leakage current is considered to be pressure independent in these quantum dot lasers.
Finally pressure measurements were carried out using 1.5 μm InGaAs/InP quantum well lasers. Measurement of the radiative component of the threshold current are found to be in reasonable agreement with the simple $E_g^2$ model. However, for more accuracy, more sophisticated calculations were performed to accurately simulate the pressure dependence of the radiative current at threshold. They reveal that decreasing internal losses with increasing pressure, due to a decrease in inter-valence band absorption, influence the pressure dependence of the radiative current at threshold. In conjunction with the experimental data, these calculations also allow for the determination of the pressure dependence of the Auger coefficient. This new technique gives results which are in good agreement with the literature.

7.2 Future work

Significant progress has been made in understanding how and which recombination processes explain the thermal properties of quantum dot lasers, but there is a lot more work to be done to comprehensively characterise quantum dot lasers. A better understanding of the physics of the devices could eventually lead to improvement of the device performance.

- It would be interesting to clearly understand how the doping concentration modifies the thermal behaviour of the devices. Ideally a cooperation with growers would allow for a direct comparison of nominally identical devices with different doping concentrations. Careful photo-current measurements might be used to measure the effect of the Coulombic attraction of the excess holes on the electron confining potential.

- Further effort should be put in to understand in detail the pressure results. First, further photo-current measurements should be carried out under pressure to determine with accuracy the pressure dependence of the leakage current in different types of quantum dot lasers. It would also be useful to perform detailed calculations of the pressure dependence of the radiative and Auger currents.

- Detailed calculations of the temperature dependence of threshold current in the light of the latest results could enable improvements in the design of the lasers for lower
and more temperature stable threshold currents (the broadening might be controlled with composition, layer thicknesses and doping. The carrier concentration might be controlled by adjusting the number of dot layers, the length of the lasers etc...).

- Preliminary experiments have already been performed on 920 nm AlGaInAs/GaAs and InGaAs/GaAs quantum dot lasers. Investigating different type of quantum dot lasers could extend and deepen our understanding of their unique properties. In particular, patterned quantum dot lasers, where inhomogeneous broadening is negligible, might show some interesting properties.

Since the radiative current is temperature stable around room temperature, it would be interesting to see how devices would perform if Auger is reduced or suppressed. This might be achieved if the final excited states involved in Auger recombination involve quantised states (Auger would be limited by the energy conservation law). This might be achieved by significantly increasing the confinement of the dots, and/or by using smaller band gap materials where the band gap is much less that the electronic band offset.
Appendix A

Details about the devices

1.3 μm InAs/GaAs undoped and p-doped quantum dot lasers

Devices from Fujitsu

The set of devices provided by Fujitsu [106] consists in 0.3, 0.5 and 1 mm long InAs/GaAs quantum dot lasers. Besides the doping, the structure of both undoped and p-doped devices was identical. Their active region was formed of 10 stacked layers of InAs dots in 5 nm InGaAs quantum-wells separated by GaAs spacer layers which were either undoped or modulated p-doped with carbon at a concentration of $5 \times 10^{17}$ cm$^{-3}$ which corresponds to 10 acceptors per dot (the dot density is $5 \times 10^{10}$ cm$^{-2}$). A GaAs waveguide was sandwiched by 1.5 μm n and p type Al$_{0.35}$Ga$_{0.65}$ cladding layers. Mesa stripe structures were fabricated by photo-lithography and wet chemical etching. The p-GaAs contact layer, p-Al$_{0.35}$Ga$_{0.65}$As cladding layers and the quantum dot active layers were etched off and the mesas were ~2.8 μm wide. The contacts were processed differently in both types of lasers: In the undoped lasers, small pads on the n-side contact of the device allowed for direct measurements of the spontaneous emission while windows had to be milled in the p-doped devices.
Devices from Sheffield

Similarly to the set of lasers from Fujitsu, the devices from Sheffield were identical beside the doping allowing for a direct comparison of the effect of the doping. The design of these devices is also very similar to that of the devices from Fujitsu. The different layers of the active region were as follows:

1) p-AlGaAs cladding layer
2) GaAs waveguide
3) 6 nm InGaAs quantum well
4) InAs quantum dots
5) 2 nm InGaAs quantum well
6) 45 nm GaAs spacer layer
7) steps 3) to 6) are repeated 5 more times
8) 55 nm GaAs waveguide
9) n-type AlGaAs cladding layer

The doping was introduced in the GaAs spacer layers using Be at a concentration of 30 acceptors per dot. 2 mm long cavities were cleaved and the ridges were 30, 50 or 100 μm wide. The batch number of these sets of devices are VN9863 and VN9875 for undoped and p-doped lasers respectively.
1.5 μm InAs/InP (311)B quantum dot lasers

Unlike the 1.3 μm InAs/GaAs quantum dot lasers described above, these devices are not DWELLs (dots-in-a-well). The active region was formed of 5 layers of InAs dots grown in an In$_{0.2}$Ga$_{0.8}$As$_{0.435}$P$_{0.565}$ waveguide grown by molecular beam epitaxy. The dots were grown using the double cap procedure [107]. This technique allows one to reduced the inhomogeneous dispersion of the dots by reducing the height of the dots. Since in these devices the height is the smallest dimension of the dots, as seen from images obtained by Atomic Force Microscopy (AFM), reducing the height dispersion of the dots results in much narrower linewidth (from 120 to 50 meV [107]). Details about the growth sequence can be found in [107]. The dot density, determined by AFM measurements, is $\sim 10^{11}$ cm$^{-2}$ [108]. The cavities are 1.5 mm long with 30, 50 and 100 μm wide stripes.

![Figure A.2: Schematic of the active region of the 1.5 μm InAs/InP (311)B quantum dot lasers from LENS-FOTON, INSA Rennes. The band offsets indicated are not meant to be realistic.](image-url)
1.5 μm InGaAs/InP quantum well lasers

The active region of these lasers grown by Philips is formed of four InGaAs 0.6% compressively strained quantum well surrounded by unstrained InGaAsP barriers (λ = 1.3μm. More details about these devices are given in [80]. The sample batch number is B1145-1. These devices were 1.5 mm long with semi-insulating buried hetero-structures and have 1.68 μm wide mesas.
Bibliography


BIBLIOGRAPHY


BIBLIOGRAPHY


