Introduction Chapter 1

1.1 Historical background

The concept of the laser (Light Amplification by Stimulated Emission of Radiation) was first proposed by Albert Einstein in his paper *Zur Quantentheorie der Strahlung* in 1917 [1]. It was not until much later in 1960 [2], when the concept was put to use with the operation of the first Ruby laser. During this early period, the possibility of lasing in semiconductor materials was also considered [3]. In 1962, several research groups independently achieved lasing action in semiconductor materials [4-6]. These early devices consisted of a GaAs p-n junction, with radiative recombination taking place in the depletion region. A resonant cavity was formed by polishing the facets perpendicular to the junction. These early devices were limited by very high threshold currents J_{th}>50kA/cm^2 [7]. The high current and associated high self-heating meant continuous wave (CW) operation at room temperature was not possible. These early devices were broad area devices - there was no lateral confinement. In 1967, the etching of a stripe was proposed to limit the injection of carriers to a thin 5μm stripe [8].

In 1963, the concept of the double heterostructure (DH) laser was proposed [9]. In 1970, the first double heterostructure laser operating at room temperature was demonstrated [10]. By 1975, AlGaAs lasers with a threshold current density as low as 0.5kA/cm^2 were reported. In these double heterostructure lasers, the active region was surrounded by two confinement layers of larger band gap. This had two advantages. Firstly, it provided electrical confinement for the carriers. Secondly, because the confinement layer has a lower optical index, it confined the light as well. By significantly reducing the width of the active region, quantum well (QW) lasers were developed. These devices have threshold current densities an order of magnitude lower than the DH structures [11].

The early GaAs-based lasers operated between 800nm-900nm and were responsible for the existence of the first telecommunications window [7]. However, the large absorption of the optical fibre at these wavelengths limited their usefulness for telecommunication systems. A great deal of effort was expended in the search for a material system, which would allow emission in the low loss region between 1.1-1.6μm. Due to the good lattice matching to InP, $In_{1-x}Ga_xAs_yP_{1-y}$ was found to be the best material system. The first pulsed room temperature operation of a 1.1μm InP-based laser was reported in 1975 [12]. By 1979, emission was reported at both 1.3μm and 1.55μm [7]. These efforts made long-haul fibre telecommunication systems a reality. By 1986 [13], most US telephone companies were either planning the deployment of single-mode fibre systems or were already using them. Today, all traffic (including that from mobile phones) is transmitted over fibre optic networks, often using tens of wavelengths of light in a single fibre. This technology is called dense wavelength division multiplexing (DWDM).

The wide choice of semiconductor alloys available today, makes almost any lasing wavelength attainable. From ultraviolet (376nm) [14] through blue (405nm) [15] to 1-

2μm in the infra-red (IR) spectrum [16]. However, there is a notable lack of direct sources in the 450-630nm wavelength range [17,18]. These wavelengths are however achievable using frequency doubling and more recently through the use of pressure tuning [19]. The ability to generate coherent light at practically any desired wavelength has led to the use of lasers in nearly every aspect of life, from low power telecommunication systems [20,21], to printing [22], medical applications [23,24], direct cutting of steel [25], and pump sources for solid-state lasers [26-27].

Although laser diodes have come a long way since their conception, a great deal of effort is being expended in the search for higher performance devices. Higher brightness, modulation performance, efficiency and reliability are all sought. Simulation tools are playing key role in the rapid development of laser diodes [28]. These tools offer the device designer the ability to firstly understand the operation of a device, then optimise the design, all without the need to perform expensive epitaxial regrowths [28]. Early tools consisted of simple rate equation models [29] and were used to predict (with some success) the dynamic response of devices. Today, a range of design tools are used, from simple coupled Poisson-Schrödinger solvers[30] and purely 3D-optical solvers [31] to full state-of-the-art electro-optical-thermal simulation tools. Modern state-of-the-art tools solve Possion's equation, the lattice heat equation, photon rate equations and drift diffusion equations. Some tools also solve the carrier energy conservation equations [32].

Reliable simulation parameters are required for the development of accurate simulation tools. One of the most important parameters is the optical gain spectrum [33]. Many models have been proposed [34] for the calculation of gain in optoelectronic devices. However, the best way to determine the gain spectrum is to measure it. Hakki and Paoli [33] first proposed a method for the indirect measurement of optical gain from the amplified spontaneous emission spectra. The Hakki-Paoli method will be discussed in Chapter 3. In recent years, more complex effects have been incorporated into device simulators. For example, the ability to model the LO-phonon bottleneck in the QW [35]. With one notable exception [32], this effect has mainly been studied using a simple rate equation approach, and not within a full device simulator [35]. This will be discussed in Chapter 7. Thermal measurements have shown a strong link between device self heating and degradation [36-38], underlining the need for not only optical and electronic optimisation of devices but also for their thermal optimisation.

This work focuses on the measurement, design and optimisation of 1.3μm dilute nitride double quantum well edge emitting lasers. The devices have been shown to be capable of 10Gb/s modulation at a heat sink temperature of 110^{O}C [40,41]. These devices are designed for 10Gb/s Ethernet, high performance computer clusters, storage area networks and low-cost transmission of data in access networks [39]. Due to their large conduction band offset, which results in good thermal stability, no active cooling is required. Thus, these devices offer a low cost alternative to their InP-based counterparts [43]. To this end, we perform detailed performance measurements on devices as a function of temperature and injection current [42]. Nottingham's isothermal electro-optical solver is extended to include thermal effects, and the device designs are optimised using the simulation tool. A series of recommendations are made, both in terms of the models needed to simulate these devices and as to the design of the devices themselves. The improvements made in the thermal simulation tools are also used to investigate self-heating in 980nm devices typically used for pumping Erbium Doped Fibre Amplifier (EDFAs).

1.2 The structure of the thesis

In the next chapter, the basic theory and operation of laser diodes is outlined. The concepts of the resonant cavity, the active region and the double-heterostructure are reviewed. In Chapter 3, the amplified spontaneous emission spectra of state-of-the-art 1.3μm double quantum well dilute nitride lasers is measured below threshold. From these measurements, the optical gain, effective group index and linewidth enhancement factor are extracted. These measurements are performed over a wide range of temperatures (300-380K) and injection currents. Cavity loss and quasi-Fermi level separation are also extracted. The devices are shown to have excellent thermal stability and a high T_0 of 282K.

Chapter 4 experimentally investigates self-heating effects in the 1.3μm dilute nitride lasers for the first time. Thermal imaging at a wavelength of 8-9μm is used to investigate relative changes in the temperatures of the front/back facets and the top contact. Evidence for significant heat loss through the wire bond is found. The average active region temperature is estimated by examining the red shift in the lasing wavelength and comparing it to the emission wavelength shift as a function of heat sink temperature. Errors in these measurements are examined and estimated using numerical modelling. It is shown that the active region can reach up to 440K with the device still operating.

Chapter 5 introduces the theory of thermal modelling in optoelectronic devices. The drift diffusion (DD) equations incorporating all thermal driving terms (derived from the Boltzmann Transport Equation – see appendix A) are discussed and discretised in a robust manner for incorporation into our device simulator. Thermally dependent material parameters (including, thermal conductivity, carrier mobility and gain) are then introduced into the laser simulator to produce a fully thermal device simulation tool. The often neglected carrier capture heating (the energy the carriers release as they relax down the QW from the bulk states to the bound lasing states), is included and found to be of significant importance in device heating. Numerical stabilisation and meshing is investigated and it is found that an identical electrical and thermal mesh is essential for accurate simulation results.

Chapter 6 contains a full electrical-thermal optimisation of a 1.3μm edge-emitting laser diode. Ridge width, substrate thickness, contact resistance, etch trench width, p-side up/down mounting are examined, as are trench filling and different depositions of gold on the top of the device. The doping profile is examined to minimise the sum of Joule and free carrier absorption (FCA) heating. Operation at elevated heat sink temperatures and meshing of the electrical/thermal problem are also studied.

In Chapter 7, a model is derived that includes hot phonons generated by the relaxation of carriers in semiconductor devices. The model solves the lattice heat equation in 2D along with an electron/hole/LO-phonon energy balance equation to obtain a four-temperature model of the QW. Due to the large conduction band offset in the dilute nitride devices, it is shown that a large non-equilibrium LO-phonon population is generated around the QW. This large non-equilibrium LO-phonon population heats the carriers and reduces material gain. The model eliminates many of the assumptions made by earlier hot carrier models whilst holding on to their numerical attractiveness. It is found that in the roll-over region of a 300μm dilute nitride device, the hot carrier effects can cause a loss of up to 4mW of peak optical power and add up to 20K to the carrier gas temperatures.

In Chapter 8, the impact of phonon reflection at epitaxial interfaces is examined for the first time in a full device simulator. As heat flows across an epitaxial interface, a small, but measurable, temperature step is produced due to phonon reflection. The reflection occurs because of the acoustic mismatch of the two materials (analogous to total internal reflection in optics) and the scattering of phonons off of interface defects. This temperature discontinuity can be represented as a thermal boundary resistance (TBR). The impact of TBR is found to slow the progress of heat out of a device. This effect is examined for both a low power 1.3μm device and a 980nm high power ridge waveguide laser. An increase in the QW temperature by up to 0.5K is predicted. A slight reduction in the front facet output power is also predicted. The investigation is made possible due the derivation of a numerically stable discretisation scheme, able to include both the impact of TBR at epitaxial interfaces and the solution of the bulk lattice heat equation. Finally, using a fully hydrodynamic model, the interaction of carrier heat and a TBR is examined around an epitaxial interface.

Chapter 9 discusses the main conclusions and contributions to knowledge drawn from this body of work. This work has made contributions to knowledge in the following areas:

- A detailed knowledge has been obtained of the gain spectra and effective group index in high performance 1.3μm edge-emitting dilute nitride ridge waveguide lasers [44,45].
- For the first time, the front facet and quantum well temperatures of high performance dilute nitride devices were measured [46].
- A thermal model including capture heating into the QW has been developed. This model was used to suggest design improvements for the dilute nitride devices studied in this work [47].
- The impact of phonon reflection at epitaxial interfaces on the transport of lattice heat out of laser diodes was examined for the first time. This effect was investigated in both low power 1.3μm devices and high power 980nm devices. To robustly include the reflection of phonons off of epitaxial interfaces in a device simulator, a finite-difference scheme has been adapted from electromagnetic modelling [48,49]. The model was then extended to include carrier heat transport effects, and used to study the interaction of carrier heat flux and

TBR for the first time.

- The thermal model was extended to study the hot phonon population in dilute nitride devices. The effect was found to be very important for both the prediction of LI-curves and modulation response [50]. The non-equilibrium LO-phonon population was found to increase and decrease in temperature by up to 2K even when modulated as fast as 10Gb/s.

1.3 References

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