

# Table of Contents

Chapter 1 - Introduction.....	1
1.1 Historical background.....	1
1.2 The structure of the thesis.....	5
1.3 References.....	9
Chapter 2 Fundamental principles.....	17
2.1 The laser diode.....	17
2.1.1 Radiative transitions.....	18
2.1.2 Population inversion.....	19
2.1.3 The resonant cavity.....	21
2.2 Separate confinement layers.....	24
2.3 Fundamentals of quantum wells.....	26
2.3.1 Quantum wells and Schrödinger's equation.....	26
2.3.2 3D and 2D k-space.....	31
2.4 Lasing threshold.....	33
2.5 Dark recombination processes.....	35
2.6 Laser structures.....	36
2.6.1 Ridge waveguide structures.....	36
2.6.2 Tapered laser structures.....	37
2.6.3 Vertical Cavity Surface-Emitting Lasers (VCSELs).....	39
2.6.4 Other laser structures.....	39

2.7 Lifetime, degradation and heat.....	40
2.8 References.....	40
Chapter 3 Device characterization.....	45
3.1 Introduction.....	45
3.2 The devices.....	46
3.3 Direct measurement of gain.....	48
3.4 Indirect measurement of gain.....	48
3.4.1 The Hakki-Paoli method.....	49
3.4.2 Cassidy's improvement on the Hakki-Paoli method.....	51
3.4.3 The least-squares fitting method.....	53
3.4.4 True unamplified spontaneous emission.....	55
3.4.5 Segmented contact method.....	55
3.4.6 Choice of Cassidy's method.....	56
3.5 Description of experimental setup.....	56
3.5.1 Overview.....	56
3.5.2 The devices and sub-mounts.....	57
3.5.3 The temperature controlled heat sink.....	59
3.5.4 Delivery of driving current.....	59
3.5.5 Manual positioning and alignment of the fibre.....	61
3.5.6 Generation of IV curves.....	62
3.5.7 Automation.....	62
3.5.8 Automatic positioning and alignment of the fibre.....	63
3.6 Measurements.....	64

3.7 Post processing - Peak and trough finding.....	64
3.8 Calculation of modal gain and loss.....	65
3.9.1 Calculation of quasi-Fermi level separation.....	66
3.9.2 Other methods for the calculation of the quasi-Fermi level separation....	67
3.10 Extraction of effective group index and alpha factor.....	69
3.10.1 Calculation of effective group index.....	69
3.10.2 Extraction of the peak position.....	71
3.10.3 Extraction of shift of effective index ( $\Delta n_{eff}$ ).....	72
3.10.4 The Kramer's-Kronig relations and the extraction of the alpha factor....	73
3.10.5 Thermal and electrical shifts in effective index.....	75
3.11 Errors in the measured signal.....	76
3.11.1 Verification of the waveguide integrity.....	76
3.11.2 A method for group index extraction.....	78
3.11.2 Deconvolution and estimation of system response.....	78
3.11.3 Estimation of error in the measured data.....	82
3.12 Experimental results and analysis.....	87
3.12.1 Gain measurement.....	87
3.12.2 The full width half maxima of the gain spectra.....	90
3.12.3 Lasing wavelength.....	91
3.12.4 Extraction of effect group index and shift in effective index.....	96
3.12.5 Calculation of the alpha factor.....	100
3.12.6 Comparison of gain data against known gain spectra.....	102
3.13 Summary.....	106

3.14 Further work and improvements in the measurement system.....	108
3.14.1 The optical spectrum analyser.....	108
3.14.2 The devices.....	109
3.14.3 The laboratory.....	110
3.14.4 Improvements in the software.....	110
3.14.5 The measurement technique.....	110
3.15 References.....	111
<b>Chapter 4 Thermal measurements.....</b>	<b>116</b>
4.1 Introduction.....	116
4.2 Thermographic imagery.....	116
4.3 Thermography with a thermal camera.....	118
4.3.1 Experimental setup.....	118
4.3.2 Measurement procedure.....	121
4.3.3 Data extraction.....	122
4.3.4 Front facet, back facet and top contact temperature.....	123
4.3.5 Device heating as a function of length.....	126
4.3.6 Evidence for cooling through the bonding wire.....	128
4.3.7 The transient thermal response of the laser.....	131
4.4 Limitations of direct thermal imaging.....	134
4.5 Spectral measurements.....	136
4.5.1 Active region temperature.....	136
4.5.2 Results.....	137
4.5.3 Error in estimation of QW temperature.....	140

4.5.3.1 Red shift due to band gap re-normalisation.....	140
4.5.3.2 Blue shift with increased carrier density – Band filling.....	141
4.5.3.3 A combination of the effects.....	142
4.6 Summary.....	143
4.7 Further work – improvements to the measurement system.....	144
4.8 References.....	145
<b>Chapter 5 A laser heat model.....</b>	<b>149</b>
5.1 Introduction.....	149
5.2 The lattice heat equation.....	150
5.3 Thermal boundary conditions.....	151
5.3.1 Neumann boundary conditions.....	152
5.3.2 Dirichlet boundary conditions.....	153
5.3.3 Mixed boundary conditions.....	153
5.4 Discretisation of the thermal problem.....	155
5.5 Coupled iterative solution of the electrical and thermal problem.....	156
5.5.1 The 1D problem.....	156
5.5.2 The 2D problem.....	157
5.6 Solving the 2D thermal problem.....	158
5.6.1 Alternating Direction Implicit methods (ADI).....	158
5.6.2 Gaussian elimination.....	158
5.6.3 Newton's method.....	159
5.6.4 Solving the 1D heat equation using Newton's method.....	160
5.6.5 Solving the 2D heat equation .....	162

5.7 Meshing.....	163
5.7.1 Interpolating between the electrical and thermal meshes.....	163
5.7.2 Using the same electrical and thermal mesh.....	165
5.8 The materials database.....	165
5.9 Material models.....	167
5.9.1 Bulk carrier densities.....	167
5.9.2 Confined carriers.....	168
5.9.3 The intrinsic carrier density.....	169
5.9.4 Low-field mobility model.....	169
5.9.5 Lattice thermal conductivity.....	170
5.9.6 Specific heat capacity.....	172
5.9.7 Material density.....	173
5.9.8 Elastic constants (C11,C12,C44).....	173
5.9.9 Other parameters.....	174
5.9.10 Bulk spontaneous emission.....	174
5.9.11 Bulk Shockley-Read-Hall (SRH) recombination.....	175
5.9.12 Bulk Auger recombination.....	176
5.9.13 Auger and SRH recombination in the GaInNAs quantum well .....	177
5.9.14 Maximum temperature.....	178
5.10 The carrier transport model.....	178
5.10.1 Thermodynamic treatments and hydrodynamic models.....	178
5.10.2 The Drift Diffusion (DD) and Energy Balance (EB) models.....	179
5.10.3 Scharfetter-Gummel discretisation of the drift diffusion equations.....	183

5.11 Gain.....	187
5.11.1 Calculation of transition rate.....	187
5.11.2 Calculation of material gain.....	189
5.11.3 Spontaneous emission.....	190
5.12 Bulk heat generation.....	191
5.12.1 Average separation of carriers.....	191
5.12.2 Free carrier absorption.....	193
5.13 Heating in the quantum well.....	195
5.13.1 Capture heating.....	195
5.13.2 Stimulated emission.....	196
5.13.3 Spontaneous emission.....	197
5.13.4 Lateral Joule heating.....	197
5.13.5 Shockley-Read-Hall (SRH) heating.....	197
5.13.6 Free carrier absorption.....	198
5.14 Total lattice heat.....	198
5.15 Contact heating.....	198
5.16 Stability of the electrical model.....	202
5.16.1 Matrix normalisation.....	203
5.16.2 Iterative improvement of the solution.....	204
5.16.3 Clamping and back tracking algorithms for fast global convergence....	205
5.16.4 Bi-CGSTAB.....	208
5.17 Summary.....	208
5.18 References.....	209

Chapter 6 Thermal Optimisation of 1.3um dilute nitride lasers.....	217
6.1 Introduction.....	217
6.2 The device and its thermal performance.....	217
6.3 Comparison with experiment.....	220
6.4 Thermal comparison of the mesa and ordinary RW structures.....	222
6.5 Filled etched trenches with gold straight across.....	223
6.5.1 Variation of gold on the side of ridge.....	223
6.5.2 Variation of gold on the bottom of trench.....	225
6.5.3 Variation of gold thickness on the top of the device.....	226
6.6 Mounting the device p-side up or p-side down.....	226
6.7 Mesa p-side up/down mounting at elevated temperatures.....	229
6.8 Impact of substrate height on maximum temperature.....	232
6.9 Etch depth of large area mesa structure in the high modulation frequency device.....	233
6.10 Thermal conductivity of the etched trench.....	234
6.11 Using a small stub to extract heat from the top of the ridge.....	236
6.12 The effect of p-contact resistance.....	239
6.13 Variation of ridge width.....	241
6.14 Optimisation of the doping of the p-type cladding.....	242
6.15 Graded doping in the p-type cladding region.....	245
6.16 Summary.....	248
6.17 References.....	250
Chapter 7 Dilute nitride lasers and non-equilibrium carrier temperatures.....	252

7.1 Introduction.....	252
7.2 The LO-phonon bottleneck.....	252
7.3 Hot phonon models in the literature.....	254
7.4 The model.....	256
7.5 A numerical overview.....	258
7.6 Preliminaries.....	260
7.6.1 Carrier densities.....	260
7.6.2 Carrier energy density.....	261
7.6.3 Average carrier energy.....	261
7.6.4 Average lasing energies.....	261
7.6.5 Average carrier energies taking place in spontaneous emission.....	262
7.6.6 Heat capacities.....	262
7.6.7 The effective band gap.....	263
7.7 Electron/hole rate equations.....	263
7.8 Heating and cooling mechanisms.....	264
7.8.1 Heat capacity.....	264
7.8.2 Free carrier absorption.....	265
7.8.3 Energy loss via stimulated emission.....	265
7.8.4 Optical phonon emission.....	266
7.8.5 Acoustic phonon emission.....	266
7.8.6 Shockley-Read-Hall recombination.....	267
7.8.7 Auger recombination in the QW.....	267
7.8.8 Final electron/hole rate equations.....	268

7.9 The hot LO-phonon population.....	269
7.9.1 The LO-phonon rate equation.....	269
7.9.2 The hot phonon energy density.....	271
7.9.3 Lattice heat flux.....	275
7.10 Relaxation times used.....	276
7.11 A simplified model.....	277
7.12 Solution of the problem.....	277
7.12.1 Lattice equation derivatives.....	279
7.12.2 Electron energy conservation equation.....	280
7.12.3 Hole energy conservation equation.....	280
7.12.4 LO-phonon energy conservation equation.....	281
7.12.5 Evaluation of the derivatives.....	281
7.13 The 1.3 $\mu$ m dilute nitride device.....	282
7.13.1 The structure.....	282
7.13.2 Simulation results for the low power 1.3 $\mu$ m device – Steady state.....	283
7.13.3 Simulation results for the low power 1.3 $\mu$ m device – Time domain.....	288
7.14 Summary.....	291
7.15 References.....	293
Chapter 8 Thermal boundary resistance.....	295
8.1 Introduction.....	295
8.2 Chapter outline.....	296
8.3 The magnitude of TBR.....	297
8.3.1 Models for the calculation of TBR.....	298

8.3.2 The Acoustic Mismatch Model (AMM).....	299
8.3.3 The Diffuse Mismatch Model (DMM).....	303
8.4 Values of TBR from the literature and DMM.....	306
8.5 Inclusion of thermal boundary resistance in device simulators.....	307
8.6 Validation of numerical scheme.....	317
8.7 The impact of TBR on a device with multiple epitaxial layers.....	319
8.8 Inclusion of the impact of TBR within a full device simulator.....	323
8.9 The impact of TBR on high power high brightness 980nm ridge waveguide lasers.....	330
8.10 Carrier heat flux and TBR.....	338
8.10.1 Introduction.....	338
8.10.2 The model.....	339
8.10.3 Newton's method.....	341
8.10.4 Jacobian elements.....	341
8.10.5 Carrier relaxation times.....	342
8.10.6 Results for a simple slab of GaAs with a layer of defects.....	343
8.10.7 Summary and further work on the transfer of heat due to carriers over thermal boundary resistances.....	347
8.11 Summary - Overview.....	348
8.11.1 Summary - Edge emitting lasers.....	348
8.11.2 Summary - VCSELs.....	348
8.11.3 Summary – Carrier/lattice heat flux.....	349
8.11.4 Concluding remarks and further work.....	349

8.12 References.....	349
Chapter 9 Conclusions.....	355
9.1 Introduction.....	355
9.2 Measurement of gain.....	357
9.3 Thermal measurements.....	357
9.4 Development of a temperature dependent laser simulation tool.....	358
9.5 Thermal optimisation of $1.3\mu\text{m}$ dilute nitride laser diodes.....	359
9.6 Impact of LO-phonon population in $1.3\mu\text{m}$ dilute nitride lasers.....	361
9.7 Thermal boundary resistance.....	362
9.8 Concluding remarks.....	362
9.9 References.....	363
Appendix A The derivation of the drift diffusion and hydrodynamic model.....	365
A.1 Introduction.....	365
A.2 Band structure.....	365
A.3 The Boltzmann Transport Equation (BTE).....	365
A.4 The method of moments.....	367
A.5 Fundamentals.....	368
A.6 The method of moments.....	370
A.7 Derivation of the momentum conservation equation.....	370
A.8 References.....	375