

Contents

Preface *XIII*

1	General Properties of Nitrides	1
1.1	Crystal Structure of Nitrides	1
1.2	Gallium Nitride	5
1.3	Aluminum Nitride	6
1.4	Indium Nitride	10
1.5	AlGaN Alloy	13
1.6	InGaN Alloy	14
1.7	AlInN Alloy	14
1.8	InAlGaN Quaternary Alloy	15
1.9	Electronic Band Structure and Polarization Effects	18
1.9.1	Introduction	18
1.9.2	General Strain Considerations	22
1.9.3	k-p Theory and the Quasicubic Model	23
1.9.4	Temperature Dependence of Wurtzite GaN Bandgap	26
1.9.5	Sphalerite (Zincblende) GaN	26
1.9.6	AlN	28
1.9.6.1	Wurtzite AlN	28
1.9.6.2	Zincblende AlN	28
1.9.7	InN	29
1.10	Polarization Effects	31
1.10.1	Piezoelectric Polarization	32
1.10.2	Spontaneous Polarization	35
1.10.3	Nonlinearity of Polarization	35
1.10.3.1	Nonlinearities in Piezoelectric Polarization	42
1.10.4	Polarization in Heterostructures	46
1.10.4.1	Ga-Polarity Single AlGa _n -Ga _n Interface	51
1.10.4.2	Polarization in Quantum Wells	56
1.11	Nonpolar and Semipolar Orientations	59
	Further Reading	61

2	Doping: Determination of Impurity and Carrier Concentrations	63
2.1	Introduction	63
2.2	Doping	63
2.3	Formation Energy of Defects	65
2.3.1	Hydrogen and Impurity Trapping at Extended Defects	67
2.4	Doping Candidates	69
2.5	Free Carriers	70
2.6	Binding Energy	70
2.7	Conductivity Type: Hot Probe and Hall Measurements	71
2.8	Measurement of Mobility	71
2.9	Semiconductor Statistics, Density of States, and Carrier Concentration	74
2.10	Charge Balance Equation and Carrier Concentration	78
2.10.1	n-Type Semiconductor	79
2.10.2	p-Type Semiconductor	84
2.11	Capacitance–Voltage Measurements	87
	Appendix 2.A. Fermi Integral	94
	Further Reading	95
3	Metal Contacts	97
3.1	Metal–Semiconductor Band Alignment	97
3.2	Current Flow in Metal–Semiconductor Junctions	101
3.3	Ohmic Contact Resistance	107
3.3.1	Specific Contact Resistivity	107
3.4	Semiconductor Resistance	108
3.4.1	Determination of the Contact Resistivity	109
	Further Reading	113
4	Carrier Transport	115
4.1	Introduction	115
4.2	Carrier Scattering	117
4.2.1	Impurity Scattering	118
4.2.2	Acoustic Phonon Scattering	120
4.2.2.1	Deformation Potential Scattering	121
4.2.2.2	Piezoelectric Scattering	124
4.2.3	Optical Phonon Scattering	126
4.2.3.1	Nonpolar Optical Phonon Scattering	126
4.2.3.2	Polar Optical Phonon Scattering	127
4.2.4	Alloy Scattering and Dislocation Scattering	134
4.3	Calculated Mobility of GaN	143
4.4	Scattering at High Fields	147
4.4.1	Transport at High Fields: Energy and Momentum Relaxation Times	152
4.4.2	Energy-Dependent Relaxation Time and Large B	153
4.4.3	Hall Factor	155
4.5	Delineation of Multiple Conduction Layer Mobilities	156

4.6	Carrier Transport in InN	158
4.7	Carrier Transport in AlN	159
4.8	Carrier Transport in Alloys	161
4.9	Two-Dimensional Transport in n-Type GaN	164
4.9.1	Scattering in 2D Systems	166
4.9.1.1	Electron Mobility in AlGaIn/GaN 2D System	168
4.9.1.2	Numerical Two-Dimensional Electron Gas Mobility Calculations	170
4.9.1.3	Magnetotransport and Mobility Spectrum	173
	Further Reading	174
5	The p–n Junction	177
5.1	Introduction	177
5.2	Band Alignment	177
5.3	Electrostatic Characteristics of p–n Heterojunctions	179
5.4	Current–Voltage Characteristics of p–n Junctions	185
5.4.1	Diode Current under Reverse Bias	186
5.4.1.1	Poole–Frenkel and Schottky Effects	187
5.4.1.2	Avalanching	188
5.4.2	Diffusion Current	189
5.4.2.1	Diffusion Current under Reverse Bias	190
5.4.2.2	Diffusion Current under Forward Bias	190
	Further Reading	191
6	Optical Processes	193
6.1	Introduction	193
6.2	Einstein’s <i>A</i> and <i>B</i> Coefficients	194
6.3	Absorption and Emission	196
6.4	Band-to-Band Transitions and Efficiency	198
6.5	Optical Transitions in GaN	200
6.5.1	Excitonic Transitions in GaN	200
6.5.1.1	Strain Effects	203
6.5.1.2	Bound Excitons	204
6.6	Free-to-Bound Transitions	205
6.7	Donor–Acceptor Transitions	206
	Further Reading	207
7	Light-Emitting Diodes and Lighting	209
7.1	Introduction	209
7.2	Current Conduction Mechanism in LED-Like Structures	211
7.3	Optical Output Power and Efficiency	214
7.3.1	Efficiency and Other LED Relevant Terms	215
7.3.2	Optical Power and External Efficiency	217
7.3.3	Internal Quantum Efficiency	218
7.3.3.1	Auger Recombination	219
7.3.3.2	SRH Recombination	220

7.3.3.3	Radiative Recombination	222
7.3.3.4	Continuity or Rate Equations as Pertained to Efficiency	223
7.3.3.5	Carrier Overflow (Spillover, Flyover, Leakage)	231
7.4	Effect of Surface Recombination	244
7.5	Effect of Threading Dislocation on LEDs	247
7.6	Current Crowding	247
7.7	Perception of Color	250
7.8	Chromaticity Coordinates and Color Temperature	251
7.9	LED Degradation	253
7.10	Packaging	255
7.11	Luminescence Conversion and White Light Generation	257
7.11.1	Color-Rendering Index	258
7.11.2	White Light from Multichip LEDs	259
7.11.3	Combining LEDs and Phosphor(s)	262
	Further Reading	266
8	Semiconductor Lasers: Light Amplification by Stimulated Emission of Radiation	267
8.1	Introduction	267
8.2	A Primer to the Principles of Lasers	268
8.2.1	Waveguiding	270
8.2.2	Analytical Solution to the Waveguide Problem	273
8.2.2.1	TE Mode	274
8.2.2.2	TM Mode	276
8.2.3	Far-Field Pattern	280
8.3	Loss, Threshold, and Cavity Modes	281
8.4	Optical Gain	283
8.5	A Glossary for Semiconductor Lasers	286
8.5.1	Optical Gain in Bulk Layers: a Semiconductor Approach	289
8.5.1.1	Relating Absorption Rate to Absorption Coefficient	290
8.5.1.2	Relating Stimulated Emission Rate to Absorption Coefficient	290
8.5.1.3	Relating Spontaneous Emission Rate to Absorption Coefficient	290
8.5.2	Semiconductor Realm	291
8.5.3	Gain in Quantum Wells	299
8.5.3.1	Optical Gain	302
8.5.3.2	Measurement of Gain in Nitride Lasers	304
8.5.4	Gain Measurement via Optical Pumping	304
8.6	Threshold Current	306
8.7	Analysis of Injection Lasers with Simplifying Assumptions	307
8.7.1	Recombination Lifetime	309
8.7.2	Quantum Efficiency	311
8.8	GaN-Based LD Design and Performance	312
8.8.1	Gain Spectra of InGaN Injection Lasers	317
8.8.2	Mode Hopping	321
8.9	Thermal Resistance	322

8.10	Nonpolar and Semipolar Orientations	323
8.11	Vertical Cavity Surface-Emitting Lasers (VCSELs)	325
8.11.1	Microcavity Fundamentals	328
8.11.2	Polariton Lasers	333
8.12	Degradation	337
	Appendix 8.A: Determination of the Photon Density and Photon Energy Density in a Cavity	343
	Further Reading	348
9	Field Effect Transistors	349
9.1	Introduction	349
9.2	Operation Principles of Heterojunction Field Effect Transistors	350
9.2.1	Heterointerface Charge	350
9.2.2	Analytical Description of HFETs	358
9.3	GaN and InGaN Channel HFETs	364
9.4	Equivalent Circuit Models: De-embedding and Cutoff Frequency	366
9.4.1	Small-Signal Equivalent Circuit Modeling	367
9.4.2	Cutoff Frequency	370
9.5	HFET Amplifier Classification and Efficiency	373
9.6	Drain Voltage and Drain Breakdown Mechanisms	378
9.7	Field Plate for Spreading Electric Field for Increasing Breakdown Voltage	383
9.8	Anomalies in GaN MESFETs and AlGaN/GaN HFETs	384
9.8.1	Effect of the Traps in the Buffer Layer	386
9.8.2	Effect of Barrier States	392
9.8.3	Correlation between Current Collapse and Surface Charging	393
9.9	Electronic Noise	396
9.9.1	FET Equivalent Circuit with Noise	398
9.9.2	High-Frequency Noise in Conjunction with GaN FETs	402
9.10	Self-Heating and Phonon Effects	405
9.10.1	Heat Dissipation and Junction Temperature	406
9.10.2	Hot Phonon Effects	409
9.10.2.1	Phonon Decay Channels and Decay Time	411
9.10.2.2	Implications for FETs	416
9.10.2.3	Heat Removal in View of Hot Phonons	418
9.10.2.4	Tuning of the Hot Phonon Lifetime	421
9.11	HFET Degradation	427
9.11.1	Gated Structures: Reliability	434
9.11.2	Reliability Tests	438
9.12	HFETs for High-Power Switching	440
	Appendix 9.A. Sheet Charge Calculation in AlGaN/GaN Structures with AlN Interface Layer (AlGaN/AlN/GaN)	444
	Further Reading	446