

Contents

1. Introduction	1
1.1 LEDs and LDs	1
1.2 Group-III Nitride Compound Semiconductors	3
2. Background	7
2.1 Introduction	7
2.2 Applications and Markets for Gallium Nitride Light Emitting Diodes (LEDs) and Lasers	7
2.3 Who Were the Early Key Players in the Field?	10
2.4 Why InGaN/AlGaN?	11
2.5 Key Steps in the Discovery – Materials Issues	13
2.5.1 Research History of Shuji Nakamura and Selected Steps in the Development of the Commercial Blue GaN LED	15
2.6 Why Did Nichia Succeed Where Many Much Larger Multinationals and Research Groups Failed?	17
2.7 Additional Comments on Blue LED Research	20
2.8 A Short Summary of the Physics of Semiconductor Lasers and LEDs	21
2.8.1 LEDs	23
2.8.2 Lasers	24
3. Physics of Gallium Nitride and Related Compounds	29
3.1 Introduction	29
3.2 Crystal Structures	29
3.2.1 Wurtzite versus Zincblende Structure	29
3.2.2 Growth of Wurtzite GaN onto Sapphire	31
3.2.3 Growth of Cubic (Zincblende) GaN	31
3.2.4 Growth of GaN onto Other Substrates	32
3.3 Electronic Band Structure	32
3.3.1 Fundamental Optical Transitions	34
3.3.2 Band Structure Near the Fundamental Gap	35
3.3.3 Band Parameters and Band Offsets for GaN, AlN, and InN	36

3.4	Elastic Properties – Phonons	38
3.5	Other Properties of Gallium Nitride	38
3.5.1	Negative Electron Affinity (NEA)	41
3.5.2	Pyroelectricity	41
3.5.3	Transferred-Electron Effect (Gunn Effect)	41
3.6	Summary of Properties	42
4.	GaN Growth	47
4.1	Growth Methods for Crystalline GaN	47
4.2	A New Two-Flow Metalorganic Chemical Vapor Deposition System for GaN Growth (TF-MOCVD)	48
4.3	In Situ Monitoring of GaN Growth Using Interference Effects	52
4.3.1	Introduction	52
4.3.2	Experimental Details	52
4.3.3	GaN Growth Without AlN Buffer Layer	54
4.3.4	GaN Growth with AlN Buffer Layer	59
4.3.5	Summary	65
4.4	Analysis of Real-Time Monitoring Using Interference Effects	65
4.4.1	Introduction	65
4.4.2	Experimental Details	66
4.4.3	Results and Discussion	67
4.4.4	Summary	75
4.5	GaN Growth Using GaN Buffer Layer	75
4.5.1	Introduction	75
4.5.2	Experimental Details	75
4.5.3	Results and Discussion	76
4.6	In Situ Monitoring and Hall Measurements of GaN Growth with GaN Buffer Layers	79
4.6.1	Introduction	79
4.6.2	Experimental Details	80
4.6.3	Results and Discussion	80
4.6.4	Summary	88
5.	p-Type GaN Obtained by Electron Beam Irradiation	89
5.1	Highly p-Type Mg-Doped GaN Films Grown with GaN Buffer Layers	89
5.1.1	Introduction	89
5.1.2	Experimental Details	89
5.1.3	Results and Discussion	90
5.2	High-Power GaN p-n Junction Blue Light Emitting Diodes	95
5.2.1	Introduction	95
5.2.2	Experimental Details	95
5.2.3	Results and Discussion	96
5.2.4	Summary	101

6. n-Type GaN	103
6.1 Si- and Ge-Doped GaN Films Grown with GaN Buffer Layers	103
6.2 Experimental Details	104
6.3 Si Doping	104
6.4 Ge Doping	108
6.5 Mobility as a Function of the Carrier Concentration	111
6.6 Summary	112
7. p-Type GaN	113
7.1 History of p-Type GaN Research	113
7.2 Thermal Annealing Effects on p-Type Mg-Doped GaN Films .	114
7.2.1 Introduction	114
7.2.2 Experimental Details	114
7.2.3 Results and Discussion	114
7.2.4 Appendix	119
7.3 Hole Compensation Mechanism of p-Type GaN Films	120
7.3.1 Introduction	120
7.3.2 Experimental Details	120
7.3.3 Results and Discussion: Explanation of the Hole Compensation Mechanism of p-Type GaN .	121
7.3.4 Summary: Hydrogen Passivation and Annealing of p-Type GaN	135
7.4 Properties and Effects of Hydrogen in GaN	136
7.4.1 Present State of Knowledge	137
7.4.2 Passivation	140
7.4.3 Hydrogen in As-Grown GaN	141
7.4.4 Diffusion of H in Implanted or Plasma-Treated GaN .	145
7.4.5 Summary	147
8. InGaN	149
8.1 Introductory Remarks: The Role of Lattice Mismatch	149
8.2 High-Quality InGaN Films Grown on GaN Films	150
8.2.1 Introduction: InGaN on GaN	150
8.2.2 Experimental Details: InGaN on GaN	151
8.2.3 Results and Discussion: InGaN on GaN	151
8.2.4 Summary: InGaN on GaN	154
8.3 Si-Doped InGaN Films Grown on GaN Films	155
8.3.1 Introduction: Si-Doped InGaN on GaN	155
8.3.2 Experimental Details: Si-Doped InGaN on GaN	155
8.3.3 Results and Discussion: Si-Doped InGaN on GaN	155
8.3.4 Summary: Si-Doped InGaN on GaN	159
8.4 Cd-Doped InGaN Films Grown on GaN Films	160
8.4.1 Introduction: Cd-doped InGaN on GaN	160
8.4.2 Experimental Details	161
8.4.3 Results and Discussion	161
8.4.4 Summary: Cd-Doped InGaN	166

XIV Contents

8.5	In _x Ga _{1-x} N/In _y Ga _{1-y} N Superlattices Grown on GaN Films	166
8.5.1	Introduction: In _x Ga _{1-x} N/In _y Ga _{1-y} N Superlattices	166
8.5.2	Experiments: In _x Ga _{1-x} N/In _y Ga _{1-y} N Superlattices	167
8.5.3	Results and Discussion: In _x Ga _{1-x} N/In _y Ga _{1-y} N Superlattices	167
8.5.4	Summary: In _x Ga _{1-x} N/In _y Ga _{1-y} N Superlattices	174
8.6	Growth of In _x Ga _{1-x} N Compound Semiconductors and High-Power InGaN/AlGaN Double Heterostructure Violet Light Emitting Diodes	174
8.6.1	Introduction	174
8.6.2	Experimental Details	174
8.6.3	Growth and Properties of In _x Ga _{1-x} N Compound Semiconductors	177
8.6.4	High Power InGaN/AlGaN Double Heterostructure Violet Light Emitting Diodes	181
8.6.5	Summary	183
8.7	p-GaN/n-InGaN/n-GaN Double-Heterostructure Blue Light Emitting Diodes	184
8.7.1	Experimental Details	184
8.7.2	Results and Discussion	184
8.7.3	Summary	188
8.8	High-Power InGaN/GaN Double-Heterostructure Violet Light Emitting Diodes	188
9.	Zn and Si Co-Doped InGaN/AlGaN Double-Heterostructure Blue and Blue-Green LEDs	193
9.1	Zn-Doped InGaN Growth and InGaN/AlGaN Double-Heterostructure Blue Light Emitting Diodes	193
9.1.1	Introduction	193
9.1.2	Experimental Details	194
9.1.3	Zn-Doped InGaN	194
9.1.4	InGaN/AlGaN DH Blue LEDs	198
9.2	Candela-Class High-Brightness InGaN/AlGaN Double-Heterostructure Blue Light Emitting Diodes	201
9.3	High-Brightness InGaN/AlGaN Double-Heterostructure Blue-Green Light Emitting Diodes	203
9.4	A Bright Future for Blue-Green LEDs	207
9.4.1	Introduction	207
9.4.2	GaN Growth	209
9.4.3	InGaN	209
9.4.4	InGaN/AlGaN DH LED	209
9.4.5	Summary	214

10. InGaN Single-Quantum-Well LEDs	215
10.1 High-Brightness InGaN Blue, Green, and Yellow LEDs with Quantum-Well Structures	215
10.1.1 Introduction	215
10.1.2 Experimental Details	216
10.1.3 Results and Discussion	217
10.1.4 Summary.....	220
10.2 High-Power InGaN Single-Quantum-Well Blue and Violet Light Emitting Diodes	220
10.3 Super-Bright Green InGaN Single-Quantum-Well Light Emitting Diodes.....	223
10.3.1 Introduction	223
10.3.2 Experimental Details	224
10.3.3 Results and Discussion	225
10.3.4 Summary.....	229
10.4 White LEDs	230
11. Room-Temperature Pulsed Operation of Laser Diodes	237
11.1 InGaN-Based Multi-Quantum-Well Laser Diodes	237
11.1.1 Introduction	237
11.1.2 Experimental Deatils	237
11.1.3 Results and Discussion	239
11.1.4 Summary.....	242
11.2 InGaN Multi-Quantum-Well Laser Diodes with Cleaved Mirror Cavity Facets.....	242
11.2.1 Introduction	242
11.2.2 Experimental Details	242
11.2.3 Results and Discussion	244
11.2.4 Summary.....	247
11.3 InGaN Multi-Quantum-Well Laser Diodes Grown on MgAl ₂ O ₄ Substrates	247
11.3.1 Characteristics of InGaN Multi-Quantum-Well Laser Diodes.....	252
11.4 The First III-V-Nitride-Based Violet Laser Diodes	256
11.4.1 Introduction	256
11.4.2 Experimental Details	256
11.4.3 Results and Discussion	258
11.4.4 Summary.....	262
11.5 Optical Gain and Carrier Lifetime of InGaN Multi-Quantum-Well Laser Diodes	262
11.6 Ridge-Geometry InGaN Multi-Quantum-Well Laser Diodes ..	268
11.7 Longitudinal Mode Spectra and Ultrashort Pulse Generation of InGaN Multi-Quantum-Well Laser Diodes	273

XVI Contents

12. Emission Mechanisms of LEDs and LDs	279
12.1 InGaN Single-Quantum-Well (SQW)-Structure LEDs	279
12.2 Emission Mechanism of SQW LEDs	281
12.3 InGaN Multi-Quantum-Well (MQW)-Structure LDs	284
12.4 Summary	289
13. Room Temperature CW Operation of InGaN MQW LDs ..	291
13.1 First Continuous-Wave Operation of InGaN Multi-Quantum-Well-Structure Laser Diodes at 233 K	291
13.2 First Room-Temperature Continuous-Wave Operation of InGaN Multi-Quantum-Well-Structure Laser Diodes	296
13.5 RT CW Operation of InGaN MQW LDs with a Long Lifetime	301
13.6 Blue/Green Semiconductor Laser	305
13.6.1 Blue/Green LEDs	305
13.6.2 Bluish-Purple LDs	307
13.6.3 Summary	313
13.7 RT CW InGaN MQW LDs with improved Lifetime	314
14. Latest Results: Lasers with Self-Organized InGaN Quantum Dots	319
14.1 Introduction	319
14.2 Fabrication	319
14.3 Emission Spectra	320
14.4 Self-Organized InGaN Quantum Dots	325
14.5 Advances in LEDs	326
14.6 Advances in Laser Diodes	328
15. Conclusions	335
15.1 Summary	335
15.2 Outlook	336
Appendix	339
Biographies	343
Shuji Nakamura	343
Gerhard Fasol	344
Stephen Pearton	345
References	347
Index	361