

CONTENTS

Preface		v
Chapter 1	An Overview of the Development of Major Light Sources: From Light Bulbs to Solid State Lighting	
	<i>Y. S. Liu</i>	
1.	Introduction	1
1.1	Major milestones in the development of light sources	2
2.	Incandescence light bulbs	4
3.	Fluorescence light	6
4.	Coherent light sources: semiconductor lasers	7
5.	GaN-based blue and white LED	8
6.	DOE ALITE 1995	10
7.	Japan MITI's "21st Century Solid State Lighting Project" 1998	12
8.	USA Next Generation Lighting Initiative Alliance (NGLIA)	14
9.	China's National SSL Program 2006	15
10.	Taiwan's solid state lighting program	16
10.1	GaN-based solid state lighting research	16
10.2	Next Generation Semiconductor Lighting Research and Development Consortium (2002-2005)	17
11.	Conclusion	18
Chapter 2	High Pressure Bulk Crystal Growth of (Ga,Al)N	
	<i>P. Geiser, J. Jun, B. Batlogg and J. Karpinski</i>	
1.	Introduction	21
2.	The group-III nitrides AlN, GaN and InN	23
2.1	Crystal structure	23
2.2	Material properties, defects and dopants	24
2.3	Direct synthesis of group-III nitrides	30
3.	Growth of group-III nitride bulk single crystals	33
3.1	High nitrogen pressure apparatus for crystal growth (HNPSG)	34
3.2	Cubic anvil cell for $Al_xGa_{1-x}N$ crystal growth (CAC)	37
4.	Results and discussion	39
4.1	$Al_xGa_{1-x}N$ bulk single crystals, growth results	39

4.2	Material characterization	41
4.3	Parameters influencing the Al content in $\text{Al}_x\text{Ga}_{1-x}\text{N}$	45
4.4	Suppression of crystal growth in $\text{Ga}_{1-y}\text{Al}_y$ alloys with $y > 0.01$	48
4.5	GaN bulk single crystals	50
5.	Conclusions and outlook	51
Chapter 3	Structural and Optical Investigation of InGaN/GaN Multiple Quantum Well Light Emitting Diodes Grown by Metalorganic Chemical Vapor Deposition	
	<i>Z. C. Feng, J. R. Yang, A. G. Li and I. T. Ferguson</i>	
1.	Introduction	58
2.	Experimental	59
3.	Structural properties of InGaN/GaN MQWs	60
3.1	High resolution X-ray diffraction (HRXRD)	60
3.2	High resolution transmission electron microscopy (HRTEM)	62
3.3	High-angle annular dark field (HAADF) images	63
4.	Optical properties of InGaN/GaN MQW LEDs	64
4.1	Temperature dependent photoluminescence	64
4.2	PL band shifts and quantum efficiency	65
4.3	Excitation-power-dependent photoluminescence of InGaN/GaN green LED wafer	66
4.4	Different T-behavior of photoluminescence from InGaN/GaN green and blue LED wafers	69
5.	Special electron microscopy of InGaN/GaN MQWs	72
5.1	V-shape defects	72
5.2	TEM digital analysis of lattice images (DALI)	73
5.3	Different TEM Studies on InGaN-based LEDs	74
6.	Special luminescence spectroscopy of InGaN/GaN MQWs	75
6.1	Photoluminescence excitation (PLE) spectroscopy	75
6.2	PLE fitting and quantum confined Stokes effect	77
6.3	Temperature dependent time resolved photo-luminescence	78
6.4	Decay time versus temperature	81
6.5	Detection energy dependent time resolved Photoluminescence	82
7.	Summary	83

Chapter 4 MOCVD Growth and Efficiency Improvement for Ultraviolet Light Emitting Diodes

S. J. Park and M. K. Kwon

1. Introduction	89
2. Issue of InGaN, AlInGaN, AlGaN material system	90
2.1 InGaN	90
2.2 AlInGaN	91
2.3 AlGaN layer	92
3. Substrate issue	93
3.1 Homoepitaxy on GaN substrate	93
3.2 AlN substrate	97
4. Defect control of epi-layer	98
4.1 Epitaxial lateral over-growth (ELOG)	98
4.2 Delta doping	99
4.3 Facet control technique	100
4.4 Superlattice buffer	103
5. Internal quantum efficiency	104
5.1 Band offset between well and barrier layer	105
5.2 Pulsed atomic layer epitaxy (PALE)	107
5.3 Ga droplet layer	109
5.4 Si delta doped barrier layer	111
6. External quantum efficiency	112
6.1 Patterned sapphire substrate (PSS)	113
6.2 Mesh electrode	114
6.3 DBR	114
6.4 Photonic crystal (PC)	115
6.5 PEC etching (photoelectrochemical etching)	118
7. Summary	121

Chapter 5 Fabrication of GaN Light Emitting Diodes by Laser-off Technique

C. F. Chu, J. T. Chu, H. C. Kuo and S. C. Wang

1. Introduction	127
2. Current issues of conventional LED	129
2.1 Thermal stable metallization of P-type ohmic contact	129
2.2 Growth substrate	130
2.3 Light output power	131
2.3.1 Emitting area of GaN LEDs	131
2.3.2 The reflectivity of GaN/material interface	134

2.4	Laser lift-off setup and process conditions	134
2.4.1	Laser system	134
2.4.2	Laser interaction on GaN material	136
2.4.3	Thermal model of laser interactions	139
2.4.4	LLO process	141
3.	Major considerations and approaches for LLO of GaN LEDs	144
3.1	Laser energy requirements and modification	144
3.2	Selection of substrate and bonding metal	145
3.3	Two types of LLO-LEDs configurations	148
3.3.1	P-side up GaN LLO-LEDs	148
3.3.2	P-side down GaN LLO-LEDs	148
4.	Fabrication of LLO-LEDs	149
4.1	Fabrication of freestanding P-side up GaN LLO-LEDs on conductive substrate	149
4.2	Fabrication steps of P-side down LLO-LEDs on Cu	151
4.3	Performance of P-side down LLO-LEDs on Cu	152
Chapter 6 High-Resolution Electron Microscopy Observations of GaN-Based Laser Diodes		
<i>M. Shiojiri</i>		
1.	Introduction	159
2.	HAADF-STEM imaging	161
3.	Structural and compositional analysis of MQW InGaN/GaN layers and strained AlGaIn/GaN superlattices	168
3.1	MQW InGaIn/GaN layers	170
3.2	Strained AlGaIn/GaN superlattices	178
Chapter 7 Growth and Development of III-Nitride Photodetectors		
<i>U. Chowdhury, C. J. Collins and P. Li</i>		
1.	Introduction	190
1.1	Applications	190
1.2	Suitability	191
1.3	Types of photodetectors	192
1.4	Performance criteria	195
2.	Visible-blind photodetectors	197
2.1	Early work	197
2.2	AlGaIn based devices – towards solar-blindness	202
2.3	Devices grown on Si substrates	203
2.4	Avalanche detectors and phototransistors	204

2.5	Vacuum UV performance	206
2.6	Other miscellaneous works	207
3.	Solar-blind photodetectors	209
3.1	Schottky devices and top-illuminated p-i-n devices	209
3.2	Back-illuminated p-i-n devices and focal-plane array	211
4.	Conclusion	215
Chapter 8	Laser Diodes Grown on Bulk GaN Substrate	
	<i>P. Perlin, M. Leszczynski, P. Prystawko, M. Boćkowski, I. Grzegory, C. Skierbiszewski and T. Suski</i>	
1.	Introduction	223
2.	GaN substrates for laser diodes applications	226
2.1	High nitrogen pressure solution growth method and its experimental set up	228
2.2	Habit and morphology of HNP-GaN crystals grown without seeding	230
2.3	Seeded growth by HNPS method	231
2.4	HVPE growth on HNP-GaN crystals	232
3.	Homoepitaxial MOVPE growth of laser structures on bulk GaN substrates	232
4.	Laser diodes grown on bulk GaN by molecular beam epitaxy	235
5.	Performance of nitride laser diodes grown on bulk gallium nitride substrates	239
5.1	Overview	239
5.2	High-pressure grown GaN substrates for the future generation of high power laser diodes	240
6.	Crystallographic defects in laser diode structures	243
6.1	Mismatch problem of AlGaIn layers	243
6.2	Mg-related defects	245
6.3	In-related defects	246
7.	Reliability of nitride laser diodes	246
Chapter 9	III-Nitride Lighting Emitting Diodes on Si	
	<i>N. C. Chen and C. F. Shih</i>	
1.	Introduction	253
2.	Growth	254
2.1	Challenge of growing GaN on Si	254
2.2	Nucleation layers	256
2.3	Control of stress and reduction of dislocations	259

3. Recent development of the LEDs on Si	264
4. Conclusion	276
Chapter 10 Nitride Microdisplay and Micro-Scale Light Emitting Diode Arrays	
<i>H. W. Choi</i>	
1. Introduction	280
2. Light extraction in nitride materials	281
3. Micron-scale light emitting diodes	282
4. Micro-LED processing	285
5. Micro-displays	287
6. Interconnected micro-LEDs	288
7. Micro-optics and its integration to micro-LEDs	293
8. Novel geometry and configuration of micro-LEDs	295
9. Applications of micro-LED arrays	298
10. The future of micro-LEDs	300
Chapter 11 III-Nitride Films and Devices on Lithium Metal Oxides by Molecular Beam Epitaxy	
<i>G. Namkoong, S. Huang and A. Doolittle</i>	
1. Introduction	305
2. III-Nitride optoelectronic devices on LiGaO ₂	306
2.1 Lithium gallate (LiGaO ₂) substrates	306
2.2 Polarity	308
2.3 Strain in III-nitrides on LiGaO ₂	309
2.4 III-nitrides on LiGaO ₂	315
2.5 State of art MSM devices on LiGaO ₂	316
3. III-Nitride power transistor integration onto ferroelectric materials	320
3.1 Integration of III-nitride based amplifiers/drivers on optical modulators	320
3.2 Crystalline relationship between III-nitrides and LiNbO ₃ /LiTaO ₃	321
3.3 Surface preparation	325
3.4 Surface stability of LiNbO ₃ and LiTaO ₃	327
3.5 Polarity	328
3.6 AlGaN/GaN power transistor integration on LiNbO ₃	331
4. Conclusions and outlook	333

Chapter 12	III-Nitride Light-Emitting Devices on Patterned Sapphire Substrates	
	<i>D. S. Wu, W. K. Wang and R. H. Horng</i>	
1.	Introduction	337
2.	Experimental details	339
2.1	Fabrication of dry-etched patterned sapphire substrates	339
2.2	Fabrication of wet-etched patterned sapphire substrates	340
3.	Results and discussion	343
3.1	Characterization of nitride-based LEDs grown on dry-etched patterned sapphire substrates	343
3.2	Characterization of nitride-based LEDs grown on wet-etched patterned sapphire substrates	349
3.3	Characteristics of flip-chip InGaN-based LEDs on patterned sapphire substrates	353
3.4	Defect reduction and efficiency improvement of near-UV emitters via laterally overgrowth on GaN/patterned sapphire templates	357
4.	Conclusions and outlook	362
Chapter 13	Bandgap Engineering of III-Nitride Devices on Low-Defect Substrates	
	<i>S. Yu. Karpov</i>	
1.	Introduction	367
2.	Low-defect GaN and AlN substrates	371
3.	Light-emitting diodes and laser diodes	374
3.1	Factors controlling non-radiative carrier recombination in III-nitride heterostructures	374
3.2	Indium-free light-emitting diodes with a thick active region	375
3.3	Effect of crystal polarity on light-emitting diode operation	378
3.4	Carrier confinement in the laser diodes	381
4.	Field-effect transistors	385
4.1	Threading dislocation effect on two-dimensional electron mobility	385
4.2	Polarization dipoles in transistor heterostructures	386
4.3	Transistors on AlN substrate and double-heterostructures	388
4.4	A prototype of an N-polar transistor on AlN	389
5.	Summary	391

Chapter 14 III-Nitride Nano-Materials: Growth and Properties

A. B. Djurišić, X. M. Cai and M. H. Xie

1. Introduction	399
2. Boron nitride nanostructures	401
3. Gallium nitride nanostructures	404
4. Aluminum nitride nanostructures	412
5. Indium nitride nanostructures	414
6. Ternary nitride alloy nanostructures and III-nitride nano-heterostructures	417
7. Conclusions and outlook	418

Chapter 15 Recent Trends in Indium Nitride Nanomaterials

A. Ganguly, K. H. Chen, L. C. Chen and S. Chattopadhyay

1. Introduction	431
2. Synthesis of Indium Nitride nanomaterials	432
2.1 Thermal chemical vapour deposition (CVD)	433
2.1.1 Catalyst-assisted growth	434
2.1.2 Catalyst-free growth	438
2.2 Molecular beam epitaxy (MBE) and plasma-assisted MBE	441
2.3 Hydride vapour phase epitaxy (HVPE)	443
2.4 Metalorganic vapour phase epitaxy (MOVPE)	444
2.5 Chemical beam epitaxy (CBE)	445
2.6 Metalorganic chemical vapour deposition (MOCVD)	445
2.7 Solvothermal methods	448
3. Optical properties	449
3.1 Photoluminescence	449
3.2 Raman spectroscopy	451
4. Electrical properties	453
5. Applications	455
5.1 Sensors	455
6. Concluding remarks	457