

Contents

1	Introduction Part A. Progress and Prospect of Growth of Wide-Band-Gap III-Nitrides	1
	Hiroshi Amano	
1.1	History of III–V Research (1950s to 1970s)	1
1.2	Dawn of GaN Research (1970s to Mid 1980s)	3
1.3	Low-Temperature-Deposited Buffer Layer, <i>p</i> -Type GaN and Highly Luminescent InGaN (Late 1980s)	4
1.4	Summary	8
	References	8
2	Introduction Part B. Ultra-efficient Solid-State Lighting: Likely Characteristics, Economic Benefits, Technological Approaches . . .	11
	Jeff Y. Tsao, Jonathan J. Wierer Jr., Lauren E.S. Rohwer, Michael E. Coltrin, Mary H. Crawford, Jerry A. Simmons, Po-Chieh Hung, Harry Saunders, Dmitry S. Sizov, Raj Bhat, and Chung-En Zah	
2.1	Some Likely Characteristics of Ultra (>70 %) Efficient SSL	12
2.2	The Ultimate SSL Source Is Spiky	14
2.2.1	Spiky Spectra Give Good CRI	14
2.2.2	Spiky Spectra Give the Highest MWLERs	15
2.3	Economic Benefits of Ultra-efficient SSL	17
2.3.1	Scenario 1: Light Is <i>Not</i> a Factor of Production	17
2.3.2	Scenario 2: Light <i>Is</i> a Factor of Production	18
2.3.3	A Qualified Nod to Scenario 2: More Light = More Productivity	19
2.4	Two Competing Approaches: Low and High Power Densities . . .	20
2.4.1	Low Power Density Approach (LEDs)	21
2.4.2	High Power-Density Approach	23
2.5	Summary	24
	References	25

3	Epitaxy Part A. LEDs Based on Heteroepitaxial GaN on Si Substrates	27
	Takashi Egawa and Osamu Oda	
3.1	Introduction	27
3.2	Epitaxial Growth and Characterization	30
3.2.1	GaN Growth on Sapphire	30
3.2.2	GaN Growth on SiC	36
3.2.3	GaN/Si Using Low Temperature (LT) Intermediate Layers .	36
3.2.4	GaN/Si Using High Temperature (HT) AlN/AlGaIn Intermediate Layers	37
3.2.5	GaN/Si Using HT Intermediate Layers (ILs) and Multilayers (MLs)	38
3.2.6	GaN/Si Using SLS Interlayers	39
3.3	Fabrication of LEDs and Their Performances	43
3.3.1	Device Characteristics of LED Structures with HT AlN/AlGaIn Intermediate Layers [62–66]	43
3.3.2	Effect of Thin AlN Intermediate Layers and AlN/GaN MLs [35, 71–78]	44
3.3.3	Wafer Bonding and Lift-Off [79]	47
3.3.4	Effect of the Insertion of SLS Layers [97–99]	50
3.3.5	Other Structures	51
3.4	Conclusion	54
	References	54
4	Epitaxy Part B. Epitaxial Growth of GaN on Patterned Sapphire Substrates	59
	Kazuyuki Tadatomo	
4.1	Introduction	59
4.2	Properties and Fabrication of PSSs	60
4.3	Growth of GaN on PSS, and Properties of GaN-LEDs on PSS . . .	62
4.3.1	SAG and ELO	62
4.3.2	GaN Growth on PSS and the Mechanism of Decreasing Dislocation Density by ELO	65
4.3.3	Characteristics of LEDs Grown on PSS	67
4.4	The Principle of Light Extraction Efficiency Improvement of GaN-Based LEDs by Patterned Sapphire Substrate	68
4.4.1	Impact of Surface Structure of LEDs on Light Extraction Efficiency Improvement	68
4.4.2	The Principle of Light Extraction Efficiency Improvement of GaN-Based LEDs by Patterned Sapphire Substrate . . .	69
4.4.3	Development of PSS with Micrometer-Sized Structures . .	70
4.4.4	Development of PSS with Sub-micrometer-Sized Structures	72
4.5	Novel Application of PSS to Growth of Nonpolar or Semipolar GaN	75
4.6	Summary	77
	References	78

5	Growth and Optical Properties of GaN-Based Non- and Semipolar LEDs	83
	Michael Kneissl, Jens Rass, Lukas Schade, and Ulrich T. Schwarz	
5.1	Introduction	84
5.2	Piezoelectric and Spontaneous Polarization in Group-III Nitrides	84
5.3	Growth of GaN and InGaN on Different Non- and Semipolar Surface Orientations	88
5.3.1	Heteroepitaxial Growth of Non- and Semipolar GaN on Sapphire, Silicon, Spinel, and LiAlO ₂ Substrates	89
5.3.2	Surface Morphologies and Structural Defects of Non- and Semipolar GaN Films	91
5.3.3	Indium Incorporation in InGaN Layers and Quantum Wells on Different Semipolar and Nonpolar Surfaces	94
5.4	Polarization of the Light Emission from Non- and Semipolar InGaN QWs	95
5.4.1	Light Emission from Nonpolar InGaN QWs	98
5.4.2	Light Emission from Semipolar InGaN QWs	99
5.5	Performance Characteristics of Non- and Semipolar InGaN QW Light Emitting Diodes	105
5.5.1	Wavelength Shift	105
5.5.2	Droop	107
5.5.3	Polarization and Light Extraction	108
5.5.4	3D-Semipolar LEDs on <i>c</i> -Plane Sapphire	109
5.5.5	State-of-the-Art of Non- and Semipolar Blue, Green, and White LEDs	109
5.5.6	Towards Yellow LEDs and Beyond	111
5.6	Summary and Outlook	112
	References	113
6	Active Region Part A. Internal Quantum Efficiency in LEDs	121
	Elison Matioli and Claude Weisbuch	
6.1	Introduction	122
6.2	Assessment of IQE from Photoluminescence Measurements	123
6.3	Principle of IQE Assessment from Electroluminescence Measurements	125
6.3.1	Calculation of Light Extraction Efficiency in a Simple GaN-Based LED	128
6.3.2	Application to LEDs Grown on Bulk GaN Substrates, Complex LED Structures and Lasers	130
6.4	Experimental Assessment of IQE	131
6.4.1	IQE Measurement of a State-of-the-Art LED	132
6.4.2	EL-Based IQE Measurement of a Poor Performing LED: Effect of Surface Roughness	134
6.5	Model for Photon Recycling	136
6.6	Conclusions	137

Appendix A Theoretical Model of Light Emission in LEDs:

 QW Emission Described by Classical Dipoles 139

 A.1 Analytical Model for Light Extraction Efficiency 140

 A.2 Exact Calculation of the Electric Field in a Multilayer
 Structure 141

 A.3 Model for Light Extraction in a Simple LED Geometry . . 144

 A.4 Determination of the Extraction Efficiency:
 Evaluation of η_{extr} , η_{extr}^0 , $\mathcal{T}_m^\rho(\theta, \lambda)$ and $\langle \mathcal{T}_m(0^\circ) \rangle_\lambda$ 146

Appendix B Sensitivity of Model to LED Parameters 148

Appendix C Modelling the Angle-Resolved Emission from LEDs:

 Accounting for Surface Roughness 150

References 151

7 Active Region Part B. Internal Quantum Efficiency 153

Jong-In Shim

7.1 LED Efficiency 153

7.2 Efficiency Droop Mechanisms 156

 7.2.1 Efficiency Droop Overview 156

 7.2.2 Auger Nonradiative Recombination 158

 7.2.3 Defect-Related Nonradiative Recombination 160

 7.2.4 Transport-Related Nonradiative Recombination 161

 7.2.5 Saturated Radiative Recombination 162

 7.2.6 Comprehensive Efficiency Droop Model 166

7.3 IQE Measurement Methods 170

 7.3.1 Constant ABC Model 173

 7.3.2 Temperature-Dependent Photoluminescence (TDPL)
 Method 177

 7.3.3 Intensity-Dependent Photoluminescence (IDPL) Method . . 180

 7.3.4 Temperature-Dependent Time-Resolved
 Photoluminescence (TD-TRPL) Method 182

 7.3.5 Room-Temperature Time-Resolved Photoluminescence
 (RT-TRPL) Method 184

7.4 Conclusion 191

References 192

**8 Electrical Properties, Reliability Issues, and ESD Robustness
of InGaN-Based LEDs 197**

M. Meneghini, G. Meneghesso, and E. Zanoni

8.1 Current-Voltage Characteristics 197

8.2 The Ideality Factor of GaN-Based LEDs 202

8.3 Current Conduction in Reverse-Bias 204

8.4 Degradation of LEDs 207

8.5 Degradation of the Blue Semiconductor Chip Activated
 by Current 208

8.6	Degradation of the Blue Semiconductor Chip Activated by Temperature	214
8.7	Degradation of the Package/Phosphor System	217
8.8	ESD-Failure of GaN-Based LEDs	220
8.9	Conclusions	225
	References	225
9	Light Extraction Efficiency Part A. Ray Tracing for Light Extraction Efficiency (LEE) Modeling in Nitride LEDs	231
	C. Lalau Keraly, L. Kuritzky, M. Cochet, and C. Weisbuch	
9.1	Introduction	231
9.2	Background on Ray Optics	232
9.2.1	Snell-Descartes Law	232
9.2.2	Fresnel Coefficients	233
9.2.3	Modeling with a Ray Optics Approach	234
9.3	The Issue of LEE in GaN-Based LEDs	235
9.4	Ray Propagation and Absorption in Layered Structures	236
9.4.1	Localized vs. Distributed Loss Sources	238
9.4.2	Material Absorption	238
9.4.3	Quantum Well Absorption and Photon Recycling	239
9.4.4	Metal Losses: Mirrors and Contacts	239
9.5	Extraction Strategies and Considerations	240
9.5.1	Index Matching and Guided Modes	240
9.5.2	The Effect of Surface or Interface Texturing	241
9.5.3	Limit to the Ray Tracing Method	242
9.5.4	Sidewall Extraction and Chip Shaping	243
9.6	Simulation of Real LEDs	244
9.6.1	GaN on GaN Chip Simulations	247
9.6.2	Patterned Sapphire Substrate (PSS)	251
9.6.3	Limitations in GaN Chip Dimensions	253
9.6.4	Flip Chip LEDs	254
9.6.5	Index Effects	255
9.7	Conclusions	256
	Appendix A Discussion of the Origins of the Effects of Surface Roughness and of Sapphire Patterning	257
	A.1 The Effect of GaN Surface Roughening: Randomization	257
	A.2 The Effect of Patterned Sapphire Substrate (PSS)	260
	Appendix B Comparison of Roughening and Angled Sidewalls for GaN Substrate LEDs	265
	Appendix C Simulations of Periodic “Rough” Surfaces vs. Random Rough Surfaces	266
	References	267

10	Light Extraction Efficiency Part B. Light Extraction of High Efficient LEDs	271
	Ja-Yeon Kim, Tak Jeong, Sang Hern Lee, Hwa Sub Oh, Hyung Jo Park, Sang-Mook Kim, and Jong Hyeob Baek	
10.1	Enhanced Light Extraction for GaN LEDs Using Surface Shaping	271
10.2	Textured Surfaces for High Extraction	274
10.3	Patterned Sapphire Substrate	275
10.4	High-Power Vertical-Type LEDs	276
10.5	Wafer Bonding and Electroplating Techniques	278
10.6	Chemical Lift-Off	279
10.7	<i>n</i> -Type Contacts	279
10.8	Randomly Roughened Structure for VLEDs	281
10.9	Photonic Crystal Structure	281
10.10	High Power Flip-Chip LEDs	283
	References	288
11	Packaging, Phosphors and White LED Packaging	291
	Rong-Jun Xie and Naoto Hirosaki	
11.1	Introduction	291
11.2	Phosphor Materials for White LEDs	293
11.2.1	Selection Criteria of Phosphors	293
11.2.2	Selection of Host Crystals and Activators	294
11.2.3	Type of Phosphors	295
11.3	Color Issues and Luminous Efficacy of White LEDs	306
11.3.1	Color Rendering	306
11.3.2	Luminous Efficacy	307
11.3.3	Chromaticity Coordinates and Color Temperature	308
11.4	White LED Packaging	310
11.4.1	Phosphor-in-Cup White LEDs	310
11.4.2	Remote-Phosphor White LEDs	314
11.4.3	Quantum Dots White LEDs	317
11.5	Summary and Perspective	319
	References	320
12	High Voltage LEDs	327
	Wen-Yung Yeh, Hsi-Hsuan Yen, Kuang-Yu Tai, and Pei-Ting Chou	
12.1	Introduction of Assembled HVLED Modules and Single-Chip HVLEDs	327
12.2	Fabrication, Development, and Characteristics of HVLEDs	329
12.2.1	Structure and Fabrication of HVLED Micro-Chip	329
12.2.2	Basic Characteristics and Methods of Measurement for HVLEDs Under AC Operation	332
12.2.3	Light Emission Characteristics of HVLEDs Under AC Operation	333
12.2.4	Design and Characteristics of HVLED Devices	334

12.2.5	Characteristics of Various HVLEDs and Traditional DCLED	338
12.3	Important Issues on the Applications of HVLEDs	340
12.3.1	Characteristics of and Possible Solutions for Light Flickering	341
12.3.2	Total Harmonic Distortion Limits	342
12.3.3	The Effect of Floating Driving Voltage	343
12.3.4	Safety Considerations of HVLED Encapsulation Structural Design	343
12.3.5	Measurement Techniques for the Optical, Electrical, and Thermal Properties of HVLED Modules	345
12.3.6	Operating Lifetime	346
12.4	Summary	347
	References	348
13	Color Quality of White LEDs	349
	Yoshi Ohno	
13.1	Introduction	349
13.2	Chromaticity	351
13.2.1	Chromaticity Coordinates and Diagrams	351
13.2.2	CCT and Duv	354
13.2.3	Color Differences for Light Source	356
13.3	Color Rendering Characteristics	357
13.3.1	Object Color Evaluation	357
13.3.2	Color Rendering Index	359
13.3.3	Shortcomings of CRI	360
13.3.4	Color Quality Beyond CRI	363
13.4	Luminous Efficacy of Radiation	365
13.5	Color Characteristics for Single Color LEDs	366
13.5.1	Dominant Wavelength λ_d	366
13.5.2	Centroid Wavelength λ_c	367
13.5.3	Peak Wavelength λ_p	368
13.6	Future Considerations on Color Quality for White LED Developments	368
	References	370
14	Emerging System Level Applications for LED Technology	373
	Robert F. Karlicek Jr.	
14.1	Introduction	373
14.2	Advanced Lighting Systems	374
14.2.1	New Applications in the Field of Human Health and Wellbeing	376
14.2.2	Illumination with Communication	378
14.2.3	Illumination with Display Capability	380
14.3	Summary	381
	References	382
	Index	385

III-Nitride Based Light Emitting Diodes and Applications

Seong, T.-Y.; Han, J.; Amano, H.; Morkoç, H. (Eds.)

2013, XIII, 390 p., Hardcover

ISBN: 978-94-007-5862-9