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, \( p \)-Type GaN and Highly Luminescent InGaN (Late 1980s) .............. 4
   1.4 Summary ........................................ 8
   References ........................................ 8

   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 Not a Factor of Production ........... 17
      2.3.2 Scenario 2: Light Is 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/AlGaN 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/AlGaN 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

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>84</td>
</tr>
<tr>
<td>5.2 Piezoelectric and Spontaneous Polarization in Group-III Nitrides</td>
<td>84</td>
</tr>
<tr>
<td>5.3 Growth of GaN and InGaN on Different Non- and Semipolar Surface Orientations</td>
<td>88</td>
</tr>
<tr>
<td>5.3.1 Heteroepitaxial Growth of Non- and Semipolar GaN on Sapphire, Silicon, Spinel, and LiAlO₂ Substrates</td>
<td>89</td>
</tr>
<tr>
<td>5.3.2 Surface Morphologies and Strutural Defects of Non- and Semipolar GaN Films</td>
<td>91</td>
</tr>
<tr>
<td>5.3.3 Indium Incorporation in InGaN Layers and Quantum Wells on Different Semipolar and Nonpolar Surfaces</td>
<td>94</td>
</tr>
<tr>
<td>5.4 Polarization of the Light Emission from Non- and Semipolar InGaN QWs</td>
<td>95</td>
</tr>
<tr>
<td>5.4.1 Light Emission from Nonpolar InGaN QWs</td>
<td>98</td>
</tr>
<tr>
<td>5.4.2 Light Emission from Semipolar InGaN QWs</td>
<td>99</td>
</tr>
<tr>
<td>5.5 Performance Characteristics of Non- and Semipolar InGaN QW Light Emitting Diodes</td>
<td>105</td>
</tr>
<tr>
<td>5.5.1 Wavelength Shift</td>
<td>105</td>
</tr>
<tr>
<td>5.5.2 Droop</td>
<td>107</td>
</tr>
<tr>
<td>5.5.3 Polarization and Light Extraction</td>
<td>108</td>
</tr>
<tr>
<td>5.5.4 3D-Semipolar LEDs on c-Plane Sapphire</td>
<td>109</td>
</tr>
<tr>
<td>5.5.5 State-of-the-Art of Non- and Semipolar Blue, Green, and White LEDs</td>
<td>109</td>
</tr>
<tr>
<td>5.5.6 Towards Yellow LEDs and Beyond</td>
<td>111</td>
</tr>
<tr>
<td>5.6 Summary and Outlook</td>
<td>112</td>
</tr>
</tbody>
</table>

### References

91

## 6 Active Region Part A. Internal Quantum Efficiency in LEDs

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Introduction</td>
<td>122</td>
</tr>
<tr>
<td>6.2 Assessment of IQE from Photoluminescence Measurements</td>
<td>123</td>
</tr>
<tr>
<td>6.3 Principle of IQE Assessment from Electroluminescence Measurements</td>
<td>125</td>
</tr>
<tr>
<td>6.3.1 Calculation of Light Extraction Efficiency in a Simple GaN-Based LED</td>
<td>128</td>
</tr>
<tr>
<td>6.3.2 Application to LEDs Grown on Bulk GaN Substrates, Complex LED Structures and Lasers</td>
<td>130</td>
</tr>
<tr>
<td>6.4 Experimental Assessment of IQE</td>
<td>131</td>
</tr>
<tr>
<td>6.4.1 IQE Measurement of a State-of-the-Art LED</td>
<td>132</td>
</tr>
<tr>
<td>6.4.2 EL-Based IQE Measurement of a Poor Performing LED: Effect of Surface Roughness</td>
<td>134</td>
</tr>
<tr>
<td>6.5 Model for Photon Recycling</td>
<td>136</td>
</tr>
<tr>
<td>6.6 Conclusions</td>
<td>137</td>
</tr>
</tbody>
</table>
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 $\eta_{\text{extr}}$, $\eta_{\text{extr}}^0$, $T_m^0(\theta,\lambda)$ and $\langle T_m(0^\circ)\rangle_\lambda$ ........... 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
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.6 Degradation of the Blue Semiconductor Chip Activated by Temperature</td>
<td>214</td>
</tr>
<tr>
<td>8.7 Degradation of the Package/Phosphor System</td>
<td>217</td>
</tr>
<tr>
<td>8.8 ESD-Failure of GaN-Based LEDs</td>
<td>220</td>
</tr>
<tr>
<td>8.9 Conclusions</td>
<td>225</td>
</tr>
<tr>
<td>References</td>
<td>225</td>
</tr>
<tr>
<td>9 Light Extraction Efficiency Part A. Ray Tracing for Light Extraction Efficiency (LEE) Modeling in Nitride LEDs</td>
<td>231</td>
</tr>
<tr>
<td>C. Lalau Keraly, L. Kuritzky, M. Cochet, and C. Weisbuch</td>
<td></td>
</tr>
<tr>
<td>9.1 Introduction</td>
<td>231</td>
</tr>
<tr>
<td>9.2 Background on Ray Optics</td>
<td>232</td>
</tr>
<tr>
<td>9.2.1 Snell-Descartes Law</td>
<td>232</td>
</tr>
<tr>
<td>9.2.2 Fresnel Coefficients</td>
<td>233</td>
</tr>
<tr>
<td>9.2.3 Modeling with a Ray Optics Approach</td>
<td>234</td>
</tr>
<tr>
<td>9.3 The Issue of LEE in GaN-Based LEDs</td>
<td>235</td>
</tr>
<tr>
<td>9.4 Ray Propagation and Absorption in Layered Structures</td>
<td>236</td>
</tr>
<tr>
<td>9.4.1 Localized vs. Distributed Loss Sources</td>
<td>238</td>
</tr>
<tr>
<td>9.4.2 Material Absorption</td>
<td>238</td>
</tr>
<tr>
<td>9.4.3 Quantum Well Absorption and Photon Recycling</td>
<td>239</td>
</tr>
<tr>
<td>9.4.4 Metal Losses: Mirrors and Contacts</td>
<td>239</td>
</tr>
<tr>
<td>9.5 Extraction Strategies and Considerations</td>
<td>240</td>
</tr>
<tr>
<td>9.5.1 Index Matching and Guided Modes</td>
<td>240</td>
</tr>
<tr>
<td>9.5.2 The Effect of Surface or Interface Texturing</td>
<td>241</td>
</tr>
<tr>
<td>9.5.3 Limit to the Ray Tracing Method</td>
<td>242</td>
</tr>
<tr>
<td>9.5.4 Sidewall Extraction and Chip Shaping</td>
<td>243</td>
</tr>
<tr>
<td>9.6 Simulation of Real LEDs</td>
<td>244</td>
</tr>
<tr>
<td>9.6.1 GaN on GaN Chip Simulations</td>
<td>247</td>
</tr>
<tr>
<td>9.6.2 Patterned Sapphire Substrate (PSS)</td>
<td>251</td>
</tr>
<tr>
<td>9.6.3 Limitations in GaN Chip Dimensions</td>
<td>253</td>
</tr>
<tr>
<td>9.6.4 Flip Chip LEDs</td>
<td>254</td>
</tr>
<tr>
<td>9.6.5 Index Effects</td>
<td>255</td>
</tr>
<tr>
<td>9.7 Conclusions</td>
<td>256</td>
</tr>
<tr>
<td>Appendix A Discussion of the Origins of the Effects of Surface Roughness and of Sapphire Patterning</td>
<td>257</td>
</tr>
<tr>
<td>9.1.1 The Effect of GaN Surface Roughening: Randomization</td>
<td>257</td>
</tr>
<tr>
<td>9.2.2 The Effect of Patterned Sapphire Substrate (PSS)</td>
<td>260</td>
</tr>
<tr>
<td>Appendix B Comparison of Roughening and Angled Sidewalls for GaN Substrate LEDs</td>
<td>265</td>
</tr>
<tr>
<td>Appendix C Simulations of Periodic “Rough” Surfaces vs. Random Rough Surfaces</td>
<td>266</td>
</tr>
<tr>
<td>References</td>
<td>267</td>
</tr>
</tbody>
</table>
10 Light Extraction Efficiency Part B. Light Extraction of High Efficient LEDs
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 n-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
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
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 $\lambda_d$ ..................................................................................... 366
13.5.2 Centroid Wavelength $\lambda_c$ ........................................................................................ 367
13.5.3 Peak Wavelength $\lambda_p$ ............................................................................................... 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