

## Table of Contents

<b>Foreword</b> . . . . .	xi
<b>Introduction</b> . . . . .	xv
<b>Chapter 1. Light-Emitting Diodes: Principles and Challenges</b> . . . . .	1
Chapter written by Georges ZISSIS	
1.1. History of a revolution in the world of the light sources . . . . .	1
1.2. LEDs and lighting . . . . .	3
1.3. Principle of operation, color, efficiency, lifetime and quality of LEDs . . . . .	11
1.3.1. White light production from LEDs: principles and challenges . . . . .	15
1.3.2. Lifetime . . . . .	19
1.3.3. Quality of LEDs . . . . .	21
1.4. Challenges facing LEDs . . . . .	22
1.5. Bibliography . . . . .	26
<b>Chapter 2. Substrates for III-Nitride-based Electroluminescent Diodes</b> . . . . .	29
Chapter written by Philippe DE MIERRY	
2.1. Introduction . . . . .	29
2.2. Crystal structure and epitaxial relation with 6H-SiC and Al <sub>2</sub> O <sub>3</sub> . . . . .	33
2.3. Defects and constraints due to heteroepitaxy . . . . .	38
2.3.1. Dislocations . . . . .	38
2.3.2. Disorientation of the substrate . . . . .	41

2.3.3. Epitaxial stress . . . . .	43
2.3.4. Thermal stress . . . . .	43
2.4. MOVPE growth of GaN on sapphire . . . . .	45
2.4.1. GaN growth . . . . .	45
2.4.2. Standard 2D epitaxy . . . . .	48
2.4.3. 3D epitaxial growth . . . . .	49
2.4.4. Epitaxial lateral overgrowth (ELO 1S). . . . .	51
2.4.5. Anisotropic growth. . . . .	53
2.4.6. Two stage ELO GaN growth (ELO 2S). . . . .	55
2.4.7. GaN growth using pendeo-epitaxy . . . . .	57
2.4.8. Nano epitaxy. . . . .	59
2.5. Bulk nitride substrates . . . . .	61
2.5.1. HNPS (high nitrogen pressure solution method) for the fabrication of crystalline GaN . . . . .	62
2.5.2. Ammonothermal synthesis of GaN. . . . .	63
2.5.3. Halide vapor phase epitaxy (HVPE) of GaN. . . . .	64
2.6. Conclusion . . . . .	67
2.7. Bibliography . . . . .	68
<b>Chapter 3. III-Nitride High-Brightness Light-Emitting Diodes . . .</b>	<b>75</b>
Chapter written by Amélie DUSSAIGNE and Nicolas GRANDJEAN	
3.1. Introduction . . . . .	75
3.2. p-n junction in GaN. . . . .	77
3.3. Active region: InGaN/GaN quantum well . . . . .	80
3.3.1. Growth and structure . . . . .	81
3.3.2. Optical properties. . . . .	83
3.4. Radiative efficiency. . . . .	91
3.5. Conclusion and prospects . . . . .	95
3.6. Bibliography . . . . .	96
<b>Chapter 4. Diode Processing . . . . .</b>	<b>99</b>
Chapter written by Philippe GILET	
4.1. Introduction . . . . .	99
4.2. Orders of magnitude . . . . .	100
4.3. Diode configurations . . . . .	103
4.3.1. Conventional chip (CC). . . . .	105
4.3.2. Flip chip (FC) . . . . .	105
4.3.3. Vertical thin film (VTF) . . . . .	106

4.3.4. Thin film flip chip (TFFC) . . . . .	107
4.4. Light extraction at wafer level . . . . .	108
4.5. Diode processing, etching, contact deposition . . . . .	111
4.5.1. N-type contacts . . . . .	113
4.5.2. P-type contacts . . . . .	113
4.6. Etching . . . . .	116
4.7. Substrate removal . . . . .	117
4.8. Potential evolutions . . . . .	118
4.9. Bibliography . . . . .	119
<b>Chapter 5. Packaging . . . . .</b>	<b>123</b>
Chapter written by Adrien GASSE	
5.1. Introduction . . . . .	123
5.2. Different packaging processes . . . . .	124
5.2.1. Historical background . . . . .	124
5.2.2. From the wafer to the chip . . . . .	125
5.2.3. Components with connection pins . . . . .	128
5.2.4. SMT leadform components . . . . .	129
5.2.5. SMT “leadless” components . . . . .	133
5.2.6. Other technologies . . . . .	134
5.2.7. Conclusion . . . . .	136
5.3. Thermal management . . . . .	136
5.3.1. Motivations . . . . .	136
5.3.2. Heat dissipation modes . . . . .	137
5.3.3. Thermal dissipation in LEDs . . . . .	139
5.3.4. Comparison of different packaging processes . . . . .	141
5.3.5. Conclusion . . . . .	145
5.4. Light extraction in LEDs . . . . .	146
5.4.1. Lateral light extraction in LEDs . . . . .	146
5.4.2. Vertical light extraction through a lens . . . . .	147
5.4.3. Lens/encapsulant materials . . . . .	149
5.4.4. Lenses and encapsulant implementation . . . . .	153
5.5. LED component characteristics . . . . .	153
5.5.1. Thermal and electrical characteristics . . . . .	153
5.5.2. Optical characteristics . . . . .	154
5.5.3. Binning . . . . .	156
5.5.4. Reliability . . . . .	157
5.6. Conclusion and trends . . . . .	158

5.7. Appendix . . . . .	160
5.7.1. Physical properties of materials . . . . .	160
5.8. Bibliography . . . . .	163
<b>Chapter 6. Photoelectric Characterization of Electroluminescent Photodiodes . . . . .</b>	<b>165</b>
Chapter written by Christian EUGÈNE and Jean-Michel DESWERT	
6.1. Photometry of LEDs . . . . .	165
6.1.1. Recap of fundamental knowledge . . . . .	166
6.1.2. Parameters of interest . . . . .	171
6.1.3. Required properties of photometers/radiometers . . . . .	171
6.1.4. Measurement of luminous intensity . . . . .	176
6.1.5. Measurement of luminous flux . . . . .	179
6.1.6. Spectral measurements . . . . .	188
6.2. Electrical characteristics of LEDs . . . . .	191
6.2.1. Forward voltage. . . . .	191
6.2.2. Temperature effect . . . . .	192
6.2.3. Operating conditions of LEDs for photometric measurements. . . . .	194
6.2.4. Stand of the normalization . . . . .	195
6.3. Bibliography . . . . .	196
<b>Chapter 7. Quality of White Light from LEDs . . . . .</b>	<b>197</b>
Chapter written by Françoise VIÉNOT	
7.1. Introduction: white light and visual quality . . . . .	197
7.1.1. White light . . . . .	197
7.1.2. A few ideas on the quality of light . . . . .	198
7.1.3. The human visual function: receptors, retina, brain . . . . .	199
7.1.4. Chapter presentation . . . . .	200
7.2. Notions of colorimetry and photometry . . . . .	201
7.2.1. Colorimetry . . . . .	201
7.2.2. Photometric quantities. . . . .	206
7.3. Obtaining white light with LEDs . . . . .	211
7.3.1. White light diodes based on short wavelength emission . . . . .	211
7.3.2. White light diodes based on the UV diode . . . . .	212
7.3.3. Combining red, green and blue . . . . .	212
7.3.4. Examples of combining many LEDs, spectrum optimization . . . . .	213
7.3.5. Normalization of the color of white diodes. . . . .	214
7.4. Color rendering of sources . . . . .	215

7.4.1. The CRI of the CIE . . . . .	216
7.4.2. Calculation details . . . . .	219
7.4.3. Update of the CIE position to take the observer's judgment into account . . . . .	220
7.5. Works on quality of light from LEDs. . . . .	220
7.5.1. Models . . . . .	220
7.5.2. Color simulations. . . . .	224
7.5.3. Experimental validations . . . . .	224
7.5.4. Conclusion on the complexity of visual judgment . . . . .	228
7.6. Applications of LEDs to lighting . . . . .	228
7.7. Conclusion: advantages, precautions and perspectives . . . . .	229
7.8. Acknowledgements . . . . .	230
7.9. Bibliography . . . . .	230
<b>Chapter 8. OLED Technology . . . . .</b>	<b>233</b>
Chapter written by Tony MAINDRON and David VAUFREY	
8.1. Introduction . . . . .	233
8.1.1. Organic materials: a history . . . . .	233
8.1.2. Birth of the first OLED device . . . . .	234
8.2. Electroluminescent diodes. . . . .	234
8.2.1. Organic semiconductor categories . . . . .	236
8.2.2. Deposition technique description . . . . .	238
8.3. Organic semiconductors: theory . . . . .	239
8.3.1. Introduction to semiconductivity in organic chemistry . . . . .	239
8.3.2. Electronic transport model in amorphous organic solids . . . . .	242
8.4. OLED electrical characteristics . . . . .	245
8.4.1. Charge carriers injection models . . . . .	245
8.4.2. Charge carriers transport models . . . . .	246
8.5. Different structure types of OLEDs . . . . .	249
8.5.1. Direct and inverted diodes . . . . .	249
8.5.2. Using the substrate emitting diode and the top surface emitting diode . . . . .	250
8.5.3. Heterojunction diode and band engineering . . . . .	250
8.5.4. Light extraction . . . . .	252
8.5.5. Fluorescence versus phosphorescence. . . . .	253
8.6. OLED lighting dedicated architectures. . . . .	255
8.6.1. Single emitting layer structure. . . . .	255
8.6.2. Double emitting layer structures . . . . .	257
8.6.3. n-emitting layer structures ( $n \geq 3$ ) . . . . .	258

8.6.4. Stacked OLEDs and tandem structures . . . . .	258
8.6.5. Converters (down conversion). . . . .	259
8.7. OLED stability and lifetime: encapsulation issue . . . . .	259
8.8. OLEDs for lighting . . . . .	262
8.9. Bibliography . . . . .	264
<b>List of Authors</b> . . . . .	<b>267</b>
<b>Index</b> . . . . .	<b>269</b>