Contents

1 Heteroepitaxy of Nonpolar and Semipolar GaN 1
Qian Sun and Jung Han
1.1 Introduction 1
1.2 Kinetic Wulff Plot (V-Plot) of GaN 3
1.3 Heteroepitaxy of Nonpolar GaN on Planar Substrates 6
1.4 Heteroepitaxy of Semipolar GaN on Planar Substrates 15
1.5 OCE of Semipolar GaN on Nonplanar Substrates 22
1.6 Summary and Outlook 23
References 25

2 High-Quality Al-Rich AlGaN Alloys 29
B.N. Pantha, J.Y. Lin, and H.X. Jiang
2.1 Introduction 29
2.2 Growth of AlGaN 31
2.2.1 Typical Growth Condition of AlGaN 31
2.2.2 Effect of In as Surfactant in Al-Rich AlGaN Alloys 32
2.2.3 AlN/$Al_xGa_{1-x}N$ Quantum Well Structures Grown on Substrates with Different Orientations 35
2.3 Fundamental Properties of $Al_xGa_{1-X}N$ Alloys 43
2.3.1 Band Structures of Al_xGa_{1-x} N Alloys 43
2.3.2 Bandgap Bowing in Al_xGa_{1-x} N Alloys 44
2.3.3 Unique Optical Properties of AlGaN Alloys 46
2.3.4 Exciton Localization in AlGaN Alloys 49
2.4 Optical Properties of Al_xGa_{1-x} N 57
2.4.1 Impurity Transitions in Al_xGa_{1-x} N Alloys 57
2.4.2 Impurity Transition in Mg-Doped AlGaN Alloys 62
2.4.3 Energy Level of Various Acceptors in AlN 64
2.5 Electrical Properties of AlGaN 66
2.5.1 n-Type $Al_xGa_{1-x}N$ Alloys 66
2.5.2 p-Type $Al_xGa_{1-x}N$ 71

2.6 Concluding Remarks 76
References 77

3 Deep Ultraviolet Light-Emitting Diodes 83
Michael Shur, Max Shatalov, Alex Dobrinsky, and Remis Gaska
3.1 Introduction 83
3.2 Materials Properties 91
3.3 Materials Growth 92
3.4 Design of Deep UV LEDs 96
3.4.1 DUV LED Fabrication 102
3.4.2 DUV LED Performance 103
3.4.3 Conclusion 112
A.1 Band Structure Parameters for AlN, InN, and GaN (STR 2011) 114
A.2 Mechanical and Polarization Properties of AlN, InN, and GaN (STR 2011) 114
A.3 Ionization Energies and Nonradiative Recombination Constants for AlN, InN, and GaN (STR 2011) 115
A.4 Optical Constants for Materials Used for LED Design 115
A.5 Definition of Efficiencies of Ultra-Violet Light Emitting Diode (UV LED) 115
References 116

4 Green Nitride LEDs 121
Xian-An Cao
4.1 The "Green Gap" 121
4.2 Advances in Growth of c-Plane Green LEDs 123
4.2.1 Green LEDs on (0001) sapphire 123
4.2.2 Green LEDs on Free-Standing (0001) GaN 128
4.3 Piezoelectric Polarization in c-Plane Green LEDs 133
4.4 Green LEDs on Nonpolar and Semipolar Substrates 136
4.5 Carrier Localization in Green LEDs 139
4.6 Efficiency Droop in Green LEDs 144
4.7 Conclusions 148
References 149

5 Improved Light Extraction Efficiency in GaN-Based Light Emitting Diodes 153
Jihyun Kim
5.1 PEC Etch: c-Plane vs. a-Plane 154
5.2 Natural Lithography 156
5.3 Photonic Crystal 161
5.4 Plasmonics 161
5.5 Chip Shaping 162
5.6 Patterned Sapphire Substrate 163
References 163

6 GaN-Based Sensors 165
F. Ren, B.H. Chu, K.H. Chen, C.Y. Chang, Victor Chen, and S.J. Pearton
6.1 Introduction 165
6.2 Gas Sensing 167
6.2.1 H_2 Sensing 167
6.2.2 O_2 Sensing 169
6.2.3 CO_2 Sensing 171
6.2.4 CH_4 Sensing 173
6.3 Sensor Functionalization 174
6.4 pH Measurement 175
6.5 Exhaled Breath Condensate 177
6.6 Heavy Metal Detection 179
6.7 Biotoxin Sensors 182
6.7.1 Botulinum 182
6.8 Biomedical Applications 184
6.8.1 Prostate Cancer Detection 186
6.8.2 Kidney Injury Molecule Detection 187
6.8.3 Breast Cancer 189
6.8.4 Lactic Acid 191
6.8.5 Chloride Ion Detection 193
6.8.6 Pressure Sensing 194
6.8.7 Traumatic Brain Injury 196
6.9 Nerve Cell Monitoring 197
6.10 InN Sensors 199
6.11 Summary and Conclusions 202
References 203

7 GaN HEMT Technology 209
Wayne Johnson and Edwin L. Piner
7.1 Introduction 209
7.2 Substrate Considerations 210
7.2.1 Silicon 211
7.2.2 SiC 212
7.2.3 Sapphire 212
7.2.4 GaN 213
7.3 Epitaxy and Device Structures 213
7.3.1 GaN Epitaxy 213
7.3.2 Nucleation 214
7.3.3 Buffer Layer Structure 216
7.4 Device Layer Structure 218
7.4.1 GaN Cap 219
7.4.2 AlN Interlayer 220
7.4.3 Back Barrier Structures 220

7.5 HEMT Device Processing 221
7.5.1 Metalization 222
7.5.2 Isolation 223
7.5.3 Passivation and Field Plating 224
7.6 HEMT Packaging and Products 226
7.6.1 Air Cavity Packaging 226
7.6.2 Plastic Overmold 227
7.6.3 GaN HEMT Products 228
7.7 Future Directions for GaN HEMTs 229
7.7.1 GaN-on-Diamond 229
7.7.2 Heterointegration 230
7.7.3 InAlN HEMTs 231
References 234

8 Recent Advances in High-Voltage GaN MOS-Gated Transistors for Power Electronics Applications 239
T. Paul Chow and Z. Li
8.1 Introduction 239
8.2 Device Structures and Design 240
8.3 Device Design 241
8.4 Experimental Results 244
8.5 Technical Challenges and Reliability 248
8.6 Summary 249
References 249

9 Radiation Effects in GaN 251
Alexander Y. Polyakov
9.1 Introduction 251
9.2 Fundamental Studies of Radiation Defects in GaN and Related Materials 252
9.2.1 Threshold Displacement Energy: Theory and Experiment 252
9.2.2 Radiation Defects in GaN: Defects Levels, Effects on Charge Carriers Concentration, Mobility, Lifetime of Charge Carriers, Thermal Stability of Defects 253
9.3 Radiation Effects in Other III-Nitrides 274
9.4 Radiation Effects in GaN Schottky Diodes, in AlGaN/GaN and GaN/InGaN Heterojunctions and Quantum Wells 276
9.5 Radiation Effects in GaN-Based Devices 282
9.6 Prospects of Radiation Technology for GaN 285
9.7 Summary and Conclusions 287
References 289

10 Recent Advances in GaN Nanowires: Surface-Controlled Conduction and Sensing Applications 295
Ruei-San Chen, Abhijit Ganguly, Li-Chyong Chen, and Kuei-Hsien Chen
10.1 Introduction 295
10.2 Surface-Controlled Transport 296
10.2.1 Surface Photoconduction 296
10.2.2 Size-Dependent Transport Properties 300
10.2.3 Persistent Photoconductivity 303
10.3 Molecular Sensing 305
10.3.1 Gain Amplified and Selective Gas Sensing 305
10.3.2 Biomolecular Sensing 306
10.4 Summary 312
References 312

11 Minority Carrier Transport in ZnO and Related Materials 317
Elena Flitsyian, Zinovy Dashevsky, and Leonid Chernyak
11.1 Introduction 317
11.2 Role of Minority Carrier Diffusion Length in Bipolar Device Performance 319
11.3 Methods for Determination of Minority Carrier Lifetime and Diffusion Length 320
11.3.1 EBIC Technique 321
11.3.2 SPV Technique 322
11.3.3 TRPL Technique 322
11.4 Temperature Dependence of Minority Carrier Diffusion Length and Lifetime 323
11.4.1 Studies in n-Type ZnO 323
11.4.2 Studies in p-Type ZnO Doped with Antimony 326
11.5 Studies of Minority Carrier Recombination 331
11.5.1 Influence of Electron Trapping on Minority Carrier Diffusion Length 332
11.5.2 Optical Studies of the Effects of Electron Trapping on Minority Carrier Lifetime 335
11.5.3 Mechanism of Electron Injection Effect 341
11.5.4 Device Applications 342
11.6 Summary 345
References 345

12 Conduction in Degenerately Doped $Zn_{1-x}Al_xO$ Thin Films 349
Michael Snure, David Toledo, Paul Slusser and Ashutosh Tiwari
12.1 Introduction 349
12.2 Experimental Procedure 350
12.3 Results 351

12.4 Discussion 356
12.5 Summary 358
References 359

13 Multifunctional ZnO Nanostructure-Based Devices 361
Yicheng Lu, Pavel I. Reyes, Jian Zhong, and Hannhong Chen
13.1 Introduction 361
13.2 Multifunctional ZnO Nanostructures for Biosensing 362
13.2.1 Wettability Control on ZnO Nanostructures 363
13.2.2 Biofunctionalization of ZnO Nanostructures 367
13.2.3 Morphology Effects of ZnO Nanostructures on Adhesion of Biospecies 369
13.2.4 ZnO Nanostructure-Based Acoustic Biosensors 371
13.3 The 3D Electrodes Consisting of ZnO TCO Films and Nanostructures for Optoelectronic Devices 381
13.3.1 Integration of ZnO TCO Films and ZnO Nanotip Arrays 381
13.3.2 ZnO 3D Photoelectrodes for Dye-Sensitized Solar Cells 387
13.3.3 ZnO 3D Electrodes for Enhanced Emission Efficiency in GaN LED 398
13.4 Conclusion 407
References 408

14 ZnO/MgZnO Quantum Wells 413
Jeffrey Davis and Chennupati Jagadish
14.1 Properties of Conventional ZnO/ZnMgO Quantum Wells 414
14.2 Unconventional QW Structures 423
14.2.1 Non-Polar ZnO 423
14.2.2 Effects of Varying the Potential Profile 424
14.2.3 Coupled Quantum Wells 429
14.3 Progress Towards ZnO/ZnMgO QW Devices 430
14.4 Summary 432
References 432

15 N-Type Oxide Semiconductor Thin-Film Transistors 435
Pedro Barquinha, Rodrigo Martins, and Elvira Fortunato
15.1 Device Structure and Operation 435
15.2 Semiconductor Materials for TFTs 440
15.2.1 The Era of Oxide Semiconductors 440
15.2.2 Comparison of n-Type Oxide TFTs with Existing TFT Semiconductor Material Technologies 443
15.3 Multicomponent Oxide TFTs @ CENIMAT 446
15.3.1 Role of Oxygen During GIZO Sputtering 446
15.3.2 Role of Deposition Pressure and rf Power Density During GIZO Sputtering 449

15.3.3 Role of GIZO Target Composition 451
15.3.4 Role of GIZO Thickness 453
15.3.5 Role of TFT's Annealing Temperature 459
15.3.6 Role of Passivation Layer 462
15.3.7 Constant Drain Current and Constant Gate Bias Stress Measurements..... 466
15.4 Conclusions and Outlook 471
References..... 473

Index..... 477