# Contents

About the Authors .................................................. xi
Preface ................................................................. xiii

## 1 Introduction

1.1 Progress in Electronics ......................................... 1
1.2 Features and Brief History of Silicon Carbide ................. 3
  1.2.1 Early History ........................................... 3
  1.2.2 Innovations in SiC Crystal Growth ....................... 4
  1.2.3 Promise and Demonstration of SiC Power Devices ..... 5
1.3 Outline of This Book ........................................... 6
   References ...................................................... 6

## 2 Physical Properties of Silicon Carbide

2.1 Crystal Structure ................................................ 11
2.2 Electrical and Optical Properties ............................. 16
  2.2.1 Band Structure .......................................... 16
  2.2.2 Optical Absorption Coefficient and Refractive Index ... 18
  2.2.3 Impurity Doping and Carrier Density .................... 20
  2.2.4 Mobility .................................................. 23
  2.2.5 Drift Velocity ............................................ 27
  2.2.6 Breakdown Electric Field Strength ....................... 28
2.3 Thermal and Mechanical Properties ........................... 30
  2.3.1 Thermal Conductivity .................................... 30
  2.3.2 Phonons .................................................. 31
  2.3.3 Hardness and Mechanical Properties .................... 32
2.4 Summary ........................................................ 32
   References ...................................................... 33

## 3 Bulk Growth of Silicon Carbide

3.1 Sublimation Growth ............................................. 39
  3.1.1 Phase Diagram of Si-C .................................. 39
  3.1.2 Basic Phenomena Occurring during the Sublimation (Physical Vapor Transport) Method 39
  3.1.3 Modeling and Simulation ................................ 44
3.2 Polytype Control in Sublimation Growth ....................... 46
3.3 Defect Evolution and Reduction in Sublimation Growth
  3.3.1 Stacking Faults 50
  3.3.2 Micropipe Defects 51
  3.3.3 Threading Screw Dislocation 53
  3.3.4 Threading Edge Dislocation and Basal Plane Dislocation 54
  3.3.5 Defect Reduction 57
3.4 Doping Control in Sublimation Growth 59
  3.4.1 Impurity Incorporation 59
  3.4.2 n-Type Doping 61
  3.4.3 p-Type Doping 61
  3.4.4 Semi-Insulating 62
3.5 High-Temperature Chemical Vapor Deposition 64
3.6 Solution Growth 66
3.7 3C-SiC Wafers Grown by Chemical Vapor Deposition 67
3.8 Wafering and Polishing 67
3.9 Summary 69
References 69

4 Epitaxial Growth of Silicon Carbide 75
4.1 Fundamentals of SiC Homoepitaxy 75
  4.1.1 Polytpe Replication in SiC Epitaxy 75
  4.1.2 Theoretical Model of SiC Homoepitaxy 78
  4.1.3 Growth Rate and Modeling 83
  4.1.4 Surface Morphology and Step Dynamics 87
  4.1.5 Reactor Design for SiC Epitaxy 89
4.2 Doping Control in SiC CVD 90
  4.2.1 Background Doping 90
  4.2.2 n-Type Doping 91
  4.2.3 p-Type Doping 92
4.3 Defects in SiC Epitaxial Layers 93
  4.3.1 Extended Defects 93
  4.3.2 Deep Levels 102
4.4 Fast Homoepitaxy of SiC 105
4.5 SiC Homoepitaxy on Non-standard Planes 107
  4.5.1 SiC Homoepitaxy on Nearly On-Axis \{0001\} 107
  4.5.2 SiC Homoepitaxy on Non-basal Planes 108
  4.5.3 Embedded Homoepitaxy of SiC 110
4.6 SiC Homoepitaxy by Other Techniques 110
4.7 Heteroepitaxy of 3C-SiC 111
  4.7.1 Heteroepitaxial Growth of 3C-SiC on Si 111
  4.7.2 Heteroepitaxial Growth of 3C-SiC on Hexagonal SiC 114
4.8 Summary 114
References 115

5 Characterization Techniques and Defects in Silicon Carbide 125
5.1 Characterization Techniques 125
  5.1.1 Photoluminescence 126
  5.1.2 Raman Scattering 134
  5.1.3 Hall Effect and Capacitance–Voltage Measurements 136
  5.1.4 Carrier Lifetime Measurements 137
8 Unipolar Power Switching Devices 301
8.1 Junction Field-Effect Transistors (JFETs) 301
  8.1.1 Pinch-Off Voltage 302
  8.1.2 Current–Voltage Relationship 303
  8.1.3 Saturation Drain Voltage 304
  8.1.4 Specific On-Resistance 305
  8.1.5 Enhancement-Mode and Depletion-Mode Operation 308
  8.1.6 Power JFET Implementations 311
8.2 Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) 312
  8.2.1 Review of MOS Electrostatics 312
  8.2.2 MOS Electrostatics with Split Quasi-Fermi Levels 315
  8.2.3 MOSFET Current–Voltage Relationship 316
  8.2.4 Saturation Drain Voltage 319
  8.2.5 Specific On-Resistance 319
  8.2.6 Power MOSFET Implementations: DMOSFETs and UMOSFETs 320
  8.2.7 Advanced DMOSFET Designs 321
  8.2.8 Advanced UMOS Designs 324
  8.2.9 Threshold Voltage Control 326
  8.2.10 Inversion Layer Electron Mobility 329
  8.2.11 Oxide Reliability 339
  8.2.12 MOSFET Transient Response 342
References 350

9 Bipolar Power Switching Devices 353
9.1 Bipolar Junction Transistors (BJTs) 353
  9.1.1 Internal Currents 353
  9.1.2 Gain Parameters 355
  9.1.3 Terminal Currents 357
  9.1.4 Current–Voltage Relationship 359
  9.1.5 High-Current Effects in the Collector: Saturation and Quasi-Saturation 360
  9.1.6 High-Current Effects in the Base: the Rittner Effect 366
  9.1.7 High-Current Effects in the Collector: Second Breakdown and the Kirk Effect 368
  9.1.8 Common Emitter Current Gain: Temperature Dependence 370
  9.1.9 Common Emitter Current Gain: the Effect of Recombination 371
  9.1.10 Blocking Voltage 373
9.2 Insulated-Gate Bipolar Transistors (IGBTs) 373
  9.2.1 Current–Voltage Relationship 374
  9.2.2 Blocking Voltage 384
  9.2.3 Switching Characteristics 385
  9.2.4 Temperature Dependence of Parameters 391
9.3 Thyristors 392
  9.3.1 Forward Conducting Regime 393
  9.3.2 Forward Blocking Regime and Triggering 398
  9.3.3 The Turn-On Process 404
  9.3.4 dV/dt Triggering 406
  9.3.5 The dl/dt Limitation 407
  9.3.6 The Turn-Off Process 407
  9.3.7 Reverse-Blocking Mode 415
References 415
Contents

10 Optimization and Comparison of Power Devices 417
10.1 Blocking Voltage and Edge Terminations for SiC Power Devices 417
  10.1.1 Impact Ionization and Avalanche Breakdown 418
  10.1.2 Two-Dimensional Field Crowding and Junction Curvature 423
  10.1.3 Trench Edge Terminations 424
  10.1.4 Beveled Edge Terminations 425
  10.1.5 Junction Termination Extensions (JTEs) 427
  10.1.6 Floating Field-Ring (FFR) Terminations 429
  10.1.7 Multiple-Floating-Zone (MFZ) JTE and Space-Modulated (SM) JTE 432
10.2 Optimum Design of Unipolar Drift Regions 435
  10.2.1 Vertical Drift Regions 435
  10.2.2 Lateral Drift Regions 438
10.3 Comparison of Device Performance 440
   References 443

11 Applications of Silicon Carbide Devices in Power Systems 445
11.1 Introduction to Power Electronic Systems 445
11.2 Basic Power Converter Circuits 446
  11.2.1 Line-Frequency Phase-Controlled Rectifiers and Inverters 446
  11.2.2 Switch-Mode DC–DC Converters 450
  11.2.3 Switch-Mode Inverters 453
11.3 Power Electronics for Motor Drives 458
  11.3.1 Introduction to Electric Motors and Motor Drives 458
  11.3.2 DC Motor Drives 459
  11.3.3 Induction Motor Drives 460
  11.3.4 Synchronous Motor Drives 465
  11.3.5 Motor Drives for Hybrid and Electric Vehicles 468
11.4 Power Electronics for Renewable Energy 471
  11.4.1 Inverters for Photovoltaic Power Sources 471
  11.4.2 Converters for Wind Turbine Power Sources 472
11.5 Power Electronics for Switch-Mode Power Supplies 476
11.6 Performance Comparison of SiC and Silicon Power Devices 481
   References 486

12 Specialized Silicon Carbide Devices and Applications 487
12.1 Microwave Devices 487
  12.1.1 Metal-Semiconductor Field-Effect Transistors (MESFETs) 487
  12.1.2 Static Induction Transistors (SITs) 489
  12.1.3 Impact Ionization Avalanche Transit-Time (IMPATT) Diodes 496
12.2 High-Temperature Integrated Circuits 497
12.3 Sensors 499
  12.3.1 Micro-Electro-Mechanical Sensors (MEMS) 499
  12.3.2 Gas Sensors 500
  12.3.3 Optical Detectors 504
   References 509

Appendix A Incomplete Dopant Ionization in 4H-SiC 511
   References 515

Appendix B Properties of the Hyperbolic Functions 517
<table>
<thead>
<tr>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix C  Major Physical Properties of Common SiC Polytypes</td>
</tr>
<tr>
<td>C.1 Properties</td>
</tr>
<tr>
<td>C.2 Temperature and/or Doping Dependence of Major Physical Properties</td>
</tr>
<tr>
<td>References</td>
</tr>
<tr>
<td>Index</td>
</tr>
</tbody>
</table>