Contents

Preface to the First Edition xv
Preface to the Second Edition xvii
Glossary of Acronyms Used in Text xix
Notation for Organometallic Precursor Molecules xxiii

1 Overview of the OMVPE Process 1
  1.1 Introduction 1
  1.2 Comparison of Epitaxial Techniques 3
    1.2.1 Liquid-Phase Epitaxy (LPE) 3
    1.2.2 Vapor-Phase Epitaxy (VPE) 5
    1.2.3 Molecular-Beam Epitaxy (MBE) 5
    1.2.4 Organometallic Vapor-Phase Epitaxy (OMVPE) 6
    1.2.5 Chemical-Beam Epitaxy (CBE) 8
  1.3 Overview of the OMVPE Growth Process 8
References 16
2 Thermodynamics

2.1 Basic Thermodynamics of Phase Equilibrium
2.1.1 Equilibrium Conditions
2.1.2 Solution Thermodynamics
2.2 Phase Diagrams
2.2.1 Binary Systems
2.2.2 Ternary Systems
2.2.3 Quaternary Systems
2.3 Thermodynamic Driving Force for Epitaxial Growth
2.3.1 Equilibrium Conditions
2.3.2 Equilibrium at the Solid/Vapor Interface
2.3.3 Growth Rate
2.3.4 Solid Nonstoichiometry
2.4 Solid Composition
2.4.1 Mixing on the Cation Sublattice
2.4.2 Mixing on the Anion Sublattice
2.4.3 Dopant Incorporation
2.5 Quaternary Systems
2.6 Thermodynamics of the Surface
2.6.1 Surface Reconstruction
2.6.2 Effect of the Surface on Ordering
2.6.3 Stoichiometry and Doping
2.6.4 Solid Composition

References

3 Physical Processes Occurring on the Surface

3.1 Introduction
3.2 Surface Measurement Techniques
3.3 Direct Observation of Surface Features
3.4 Atomic-Level Growth Processes
3.4.1 Adsorption and Desorption
3.4.2 Adatom Motion

References
3.4.3 Step Motion 132
3.4.4 Surfactant Effects 141

3.5 Effects of Surface Processes on OMVPE Growth
3.5.1 Dopant Incorporation 142
3.5.2 Selective Growth 144
3.5.3 Atomic-Scale Ordering 144

References 146

4 Source Molecules 151

4.1 Introduction 151
4.2 Group II Molecules 161
4.3 Group III Molecules 163
4.4 Group V Sources 170
  4.4.1 As and P Sources 170
  4.4.2 Sb Precursors 190
  4.4.3 N Precursors 191
4.5 Group VI Precursor Molecules 195
  4.5.1 Te Precursors 195
  4.5.2 S and Se Precursors 199
4.6 Organometallic Dopant Precursors 201

References 203

5 Kinetics 211

5.1 Background 211
  5.1.1 Theory of Absolute Reaction Rates 212
  5.1.2 Homogeneous Reactions 214
  5.1.3 Heterogeneous Reactions 220
  5.1.4 Multistep Reactions 220
5.2 OMVPE Growth Process 221
5.3 Homogeneous Pyrolysis Reactions 225
  5.3.1 Pyrolysis Reactions for Cation Source Molecules 225
5.3.2 Pyrolysis Reactions for Anion Source Molecules 241
5.3.3 Kinetics of Simultaneous Pyrolysis of Anion and Cation Precursors 262
5.4 Heterogeneous Pyrolysis Reactions 274
5.4.1 Heterogeneous Pyrolysis of TMGa 274
5.4.2 Heterogeneous Pyrolysis of TEGa 275
5.4.3 Other Group III Precursors 276
5.4.4 Heterogeneous Pyrolysis of Group V Precursors 277
5.4.5 Heterogeneous Pyrolysis of Combined Cation and Anion Precursors 279
5.5 Ordering 281
References 289

6 Hydrodynamics and Mass Transport 297
6.1 Introduction 297
6.2 Complete Hydrodynamic Treatment of OMVPE 298
6.3 Boundary-Layer Model 308
6.4 Approximate Analytical Approach for Horizontal OMVPE Reactors 309
6.5 Application to Reactor Design 313
References 316

7 Design of the OMVPE Process 319
7.1 Consolidated OMVPE Growth Model 319
7.1.1 Postulated Reaction Mechanisms 321
7.2 Kinetically Limited Growth 324
7.2.1 Low Temperature, Atmospheric Pressure 325
7.2.2 Low Temperature, Low Pressure 332
7.2.3 Low Temperature, Very Low Pressure 334
7.2.4 High Vacuum 339
7.2.5 Summary of Kinetically Limited OMVPE Growth 346
7.3 Midtemperature, All Pressures 348
7.4 High-Temperature Regime 353
7.5 OMVPE Growth of II/VI Compounds 354
7.6 Design of the Overall Process 364
  7.6.1 Reactor Geometry 364
  7.6.2 In Situ Controls 370
  7.6.3 Total Reactor Pressure 378
  7.6.4 Precursor Molecules 380
  7.6.5 Optimum Growth Conditions 381
  7.6.6 Reactor Configuration and Safety 382
References 384

8 Specific Materials 391
8.1 GaAs 392
  8.1.1 Growth Temperature 392
  8.1.2 Input V/III Ratio 394
  8.1.3 Substrate Orientation 396
  8.1.4 Source Materials 398
  8.1.5 Total Reactor Pressure 399
  8.1.6 Intentional Doping 401
  8.1.7 Uniformity and Reproducibility 404
8.2 AlGaAs 406
  8.2.1 Growth Temperature 407
  8.2.2 V/III Ratio 412
  8.2.3 Substrate Orientation 414
  8.2.4 Precursor Molecules 414
8.3 GaInAs, AlInAs, and AlGaInAs 415
8.4 InP 421
  8.4.1 Triethylindium at Low Pressures 421
  8.4.2 Trimethylindium 421
  8.4.3 Very Low Pressures (CBE) 426
  8.4.4 Other Sources 426
8.5 GaP, GaInP, and AlGaInP 427
  8.5.1 GaP 427
8.5.2 $Ga_xIn_{1-x}P$ 428
8.5.3 $AlGaInP$ 430

8.6 As/P Alloys 433
8.6.1 InAsP/GaAsP/AlAsP 434
8.6.2 GaInAsP 436

8.7 Antimony Compounds and Alloys 439
8.7.1 GaSb and AlGaSb 440
8.7.2 InSb 442
8.7.3 InAsSb 445
8.7.4 Other As/Sb Alloys 447
8.7.5 P/Sb Alloys 451

8.8 III/V Nitrides, AlGaInN 452
8.8.1 Group III–AsPN Metastable Alloys 459

8.9 Selective Growth of III/V Semiconductors 460

8.10 II/VI Semiconductors 462
8.10.1 HgCdTe 462
8.10.2 ZnS and ZnSe 466

8.11 Group IV Semiconductors 469

8.12 Nonsemiconductor Materials 470
8.12.1 Oxides 470
8.12.2 Nitrides 472
8.12.3 Metals 472

References 474

9 Superlattice Structures 485
9.1 AlGaAs/GaAs 489
9.2 GaInAs/InP 495
9.3 AlGaInP/GaInP 500
9.4 GaInAs/GaAs 502
9.5 AlGaInN 505
9.6 Strain-Layer Superlattices 506
9.6.1 Natural Strain-Layer Superlattices 508
9.7 GaAs on Si Substrates 508
9.8 SiGe Alloys 510
9.9 II/VI Compounds  511
9.10 Doping Superlattices  513
9.11 Atomic-Layer Epitaxy (ALE)  514
   9.11.1 Practical Implementation  515
References  519

10 Devices  525
10.1 Injection Lasers and LEDs  527
   10.1.1 AlGaAs/GaAs Lasers and LEDs  528
   10.1.2 GaInAsP/InP Lasers  533
   10.1.3 AlGaInAs and GaInAs LEDs and Lasers  536
   10.1.4 Antimonides for LEDs and Lasers  537
   10.1.5 AlGaInP/GaAs LEDs and Lasers  538
   10.1.6 AlGaInN LEDs and Lasers  543
   10.1.7 II/VI LEDs and Lasers  546
10.2 Photodiodes  546
   10.2.1 p-i-n Photodetectors  547
   10.2.2 APD Photodetectors  548
   10.2.3 Long-Wavelength Photodiodes  548
10.3 Electronic Switching Devices  549
   10.3.1 High Electron Mobility Transistors
       (GaAs/AlGaAs)  551
   10.3.2 High-Speed Electronic Devices
       in GaInAs  553
10.4 Solar Cells  555
10.5 Summary  557
References  557

Index  563