



Materials Aspects of GaAs and InP Based Structures

V. Swaminathan

*AT&T Bell Laboratories
Breinigsville, Pennsylvania*

A. T. Macrander

*Argonne National Laboratory
Argonne, Illinois*



Prentice Hall, Englewood Cliffs, New Jersey 07632

CONTENTS

PREFACE	XV
CHAPTER 1 INTRODUCTION	1
1.1 Emergence of GaAs and InP	1
1.2 Bonding and Crystal Structure	2
<i>1.2.1 Fractional Ionic Character in Bonding in III-V Semiconductors,</i>	<i>3</i>
<i>1.2.2 Brillouin Zones,</i>	<i>4</i>
1.3 Energy Band Structure	5
<i>1.3.1 The k-p Method,</i>	<i>6</i>
1.4 Energy Band Structure of Alloys	9
<i>1.4.1 Material Parameters of Alloy Semiconductors,</i>	<i>10</i>

1.5 Tables of Material Properties 14

1.5.1 Binary Compounds, 14

1.5.2 Alloy Semiconductors, 25

References 40

CHAPTER 2 CRYSTAL GROWTH

43

2.1 Growth of Bulk Crystals 43

2.1.1 Phase Equilibria, 44

2.1.2 Crystal Growth Techniques, 47

2.1.3 Crystalline Imperfections, 56

2.2 Liquid Phase Epitaxy 78

2.2.1 Crystal Growth Apparatus, 79

2.2.2 Thermodynamic Principles of LPE Growth, 83

2.2.3 Crystal Growth Kinetics, 100

2.2.4 Crystal Growth of Ternary and Quaternary Alloys, 103

2.2.5 Surface Morphology, 111

2.2.6 Crystal Growth of High Purity Epitaxial Layers, 114

2.3 Trichloride Vapor Phase Epitaxy 116

2.3.1 Introduction, 116

2.3.2 Crystal Growth of GaAs and InP, 117

2.3.3 Crystal Growth of GaInAs and GaInAsP, 120

2.4 Hydride Vapor Phase Epitaxy 122

2.4.1 Introduction, 122

2.4.2	<i>Basic Chemistry and Crystal Growth</i>	122
2.4.3	<i>Surface Preservation and Reactor Design for Abrupt Interfaces</i>	128
2.5	Metal-Organic Chemical Vapor Deposition (MOCVD)	131
2.5.1	<i>Introduction</i>	131
2.5.2	<i>Reactor Design</i>	133
2.5.3	<i>Models for Crystal Growth</i>	134
2.5.4	<i>Indium Depletion, Parasitic Reactions, Low-Pressure MOCVD, and Crystal Growth in InP, GaInAs, and GaInAsP</i>	136
2.5.5	<i>Crystal Growth of Semi-Insulating Fe-Doped InP</i>	137
2.5.6	<i>MOCVD Summary</i>	138
2.6	Molecular Beam Epitaxy	138
2.6.1	<i>Effusion Cells</i>	139
2.6.2	<i>Ultra-High-Vacuum Crystal Growth Conditions</i>	140
2.6.3	<i>Surface Analysis</i>	141
2.6.4	<i>Substrate Preparation</i>	142
2.6.5	<i>Crystal Growth Process</i>	142
2.6.6	<i>Reflection High-Energy Electron Diffraction</i>	149
2.7	Gas Source MBE and Metal-Organic MBE	156
2.7.1	<i>Introduction</i>	156
2.7.2	<i>Gas Source MBE</i>	156
2.7.3	<i>Metal-Organic MBE</i>	160
	References	165

CHAPTER 3	X-RAY STRUCTURAL CHARACTERIZATION	181
3.1	X-Ray Double Crystal Diffractometry 181	
3.1.1	<i>Introduction, 181</i>	
3.1.2	<i>Indium Phosphide Substrates, 185</i>	
3.1.3	<i>Single Epitaxial Layer Measurements and Comparisons to Dynamical Diffraction Theory, 185</i>	
3.1.4	<i>Double Heterostructures, 201</i>	
3.1.5	<i>Superlattices, 204</i>	
3.1.6	<i>Heteroepitaxial Structures with Large Mismatches, 212</i>	
3.2	Other X-Ray Characterization Methods 216	
3.2.1	<i>The Back Reflection Laue Method, 216</i>	
3.2.2	<i>The Bond Method, 217</i>	
3.2.3	<i>Point Defect Influences on Lattice Parameters and X-Ray Measurements, 219</i>	
3.2.4	<i>X-Ray Topography, 226</i>	
	References 229	
CHAPTER 4	ELECTRICAL CHARACTERIZATION	233
4.1	Intrinsic Semiconductors 233	
4.2	Extrinsic Semiconductors 235	
4.3	Mobility and the Hall Effect 237	
4.4	Carrier Emission and Capture 239	
4.5	Depletion Capacitance 242	

- 4.6 Deep Level Influences on Diode Capacitance 245
- 4.7 Deep Level Characterization Techniques--
TSCAP and DLTS 249
- 4.8 Other Deep Level Characterization Techniques--
Admittance Spectroscopy, Constant Capacitance Bias
Transients, and Current Transients 254
- 4.9 Semi-Insulating Material 255
- References 262

CHAPTER 5 OPTICAL CHARACTERIZATION 264

- 5.1 Absorption 264
 - 5.1.1 *Fundamental Absorption, 265*
 - 5.1.2 *Measurement Techniques, 269*
 - 5.1.3 *Exciton Absorption, 272*
 - 5.1.4 *Intervalence Absorption, 276*
 - 5.1.5 *Impurity Absorption, 276*
 - 5.1.6 *Free Carrier Absorption, 278*
 - 5.1.7 *Optical Absorption in Heavily Doped Material, 279*
- 5.2 Photoluminescence 281
 - 5.2.1 *Radiative Recombination in Semiconductors, 281*
 - 5.2.2 *Minority Carrier Lifetime and Radiative Efficiency, 286*
 - 5.2.3 *Experimental Techniques, 287*
 - 5.2.4 *Carrier Generation and Diffusion, 289*
 - 5.2.5 *Exciton Recombination, 297*

	5.2.6 <i>Band-to-Band Recombination</i> , 304
	5.2.7 <i>Free-to-Bound Transitions</i> , 308
	5.2.8 <i>Donor-to-Acceptor Pair Recombination</i> , 311
	5.2.9 <i>Deep Level Transitions</i> , 318
	5.2.10 <i>Nonradiative Recombination Processes</i> , 319
5.3	Raman Spectroscopy 321
	5.3.1 <i>Principle of Raman Scattering</i> , 321
	5.3.2 <i>Experimental Aspects</i> , 322
	5.3.3 <i>First- and Second-Order Raman Scattering</i> , 323
	5.3.4 <i>Superlattices and Quantum Well Structures</i> , 329
	5.3.5 <i>Applications of RS</i> , 334
5.4	Other Optical Techniques 342
	5.4.1 <i>Infrared Localized Vibrational Mode Absorption</i> , 342
	5.4.2 <i>Photocurrent Measurements</i> , 345
	5.4.3 <i>Reflectance Modulation</i> , 353
	5.4.4 <i>Optical Detection of Magnetic Resonance (ODMR)</i> , 361
	References 366

CHAPTER 6 IMPURITIES AND NATIVE DEFECTS

376

6.1	Introduction 376
6.2	Classification and Notation 377
	6.2.1 <i>Native Point Defects</i> , 378

- 6.3 Shallow Level Impurities 379
 - 6.3.1 *Effective Mass Theory*, 380
 - 6.3.2 *Effective Mass Approximation for Acceptor State*, 381
 - 6.3.3 *Chemical Shifts and Central-Cell Corrections*, 382
 - 6.3.4 *Donor Levels Associated with Subsidiary Minima*, 385
 - 6.3.5 *Experimental Methods to Determine Impurity Energy Levels*, 385
- 6.4 Deep Impurities and Native Defects 386
 - 6.4.1 *Overview of Theory*, 386
 - 6.4.2 *sp³ Bonded Impurities*, 389
 - 6.4.3 *3d Transition Metal Impurities*, 397
- 6.5 Chemistry of Imperfections 401
 - 6.5.1 *Mass Action Relations*, 402
 - 6.5.2 *Equilibrium of Imperfections: Brouwer's Approximation*, 403
 - 6.5.3 *Reaction Constants*, 405
 - 6.5.4 *Interstitial and Antistructure Disorder*, 410
 - 6.5.5 *Partial Equilibrium: the Situation After Cooling*, 411
 - 6.5.6 *Alloy Semiconductors*, 411
 - 6.5.7 *Experimental Observation of Point Defects*, 413
- 6.6 Incorporation of Impurities 414
 - 6.6.1 *Introduction*, 414
 - 6.6.2 *Amphoteric Dopants*, 420

6.6.3	<i>Incorporation of Impurities During VPE Growth,</i>	420
6.6.4	<i>Incorporation of Impurities During MBE Growth,</i>	424
6.6.5	<i>Unintentional Impurities,</i>	426
6.7	Dislocations	427
6.7.1	<i>Types and Structures-Perfect Dislocations,</i>	427
6.7.2	<i>Electrical Properties of Dislocations,</i>	434
6.7.3	<i>Mechanical Properties and Impurity Hardening,</i>	437
6.7.4	<i>Dislocation Generation During Growth of Bulk Crystals and Its Reduction,</i>	450
	References	456

CHAPTER 7	DEFECTS AND DEVICE PROPERTIES	470
7.1	Introduction	470
7.2	Interface Effects	471
7.2.1	<i>Metal-Semiconductor Interface,</i>	472
7.2.2	<i>Insulator-Semiconductor Interface,</i>	488
7.3	Out-Diffusion of Impurities and Thermal Conversion	496
7.4	Defect Gettering	517
7.4.1	<i>Gettering at Implantation Damage,</i>	517
7.4.2	<i>Strain Induced Gettering,</i>	519
7.4.3	<i>Heterostructure Gettering at Heterostructures Interfaces,</i>	520
7.4.4	<i>Gettering at Dislocations,</i>	521
7.4.5	<i>Gettering at Back Surface Damage,</i>	523

7.5	Photonic Devices	524
7.5.1	<i>Recombination Enhanced Defect Motion,</i>	524
7.5.2	<i>Degradation in Lasers and Light Emitting Diodes,</i>	527
7.5.3	<i>Process Related Effects,</i>	540
7.5.4	<i>Degradation Modes in Photodetectors,</i>	549
7.6	Material Aspects of Field Effect Transistors,	549
7.6.1	<i>Introduction,</i>	555
7.6.2	<i>Heterostructure Field Effect Transistors,</i>	555
7.6.3	<i>DX Centers,</i>	561
7.6.4	<i>GaAs FETs,</i>	565
	References	575