

# Contents

---

## Part I Background Information

---

<b>1. Introduction</b>	<b>1</b>
1.1 Thin Film Growth from Beams in a High Vacuum Environment	2
1.1.1 Vacuum Conditions for MBE	3
1.1.2 Basic Physical Processes in the MBE Vacuum Chamber	6
1.2 Evolution of the MBE Technique	13
1.2.1 The Early Stages of MBE	13
1.2.2 MBE in the 1980s	16
1.3 Modifications of the MBE Technique	16
1.3.1 Gas Source MBE	17
1.3.2 Phase-Locked Epitaxy	19
1.3.3 Atomic Layer Epitaxy	23
1.3.4 FIBI-MBE Processing Technology	25
1.3.5 A Classification Scheme for the MBE Techniques	27

---

## Part II Technological Equipment

---

<b>2. Sources of Atomic and Molecular Beams</b>	<b>29</b>
2.1 The Effusion Process and the Ideal Effusion Cell	30
2.1.1 Langmuir and Knudsen Modes of Evaporation	31
2.1.2 The Cosine Law of Effusion	32
2.2 Effusion from Real Effusion Cells	35
2.2.1 The Near-Ideal Cylindrical Effusion Cell	35
2.2.2 The Cylindrical Channel Effusion Cell	43
2.2.3 Hot-Wall Beam Cylindrical Source	44
2.2.4 The Conical Effusion Cell	48
2.3 Effusion Cells Used in CPS MBE Systems	53
2.3.1 Conventional Effusion Cells	53
2.3.2 Dissociation (Cracker) Effusion Cells	58
2.3.3 Electron Beam and Laser Radiation Heated Sources	62
2.4 Beam Sources Used in GS MBE Systems	69
2.4.1 Arsine and Phosphine Gas Source Crackers	69
2.4.2 Gas Sources Used in MO MBE	71

IX

<b>3. High Vacuum Growth and Processing Systems</b> .....	73
3.1 Building Blocks of Modular MBE Systems .....	74
3.1.1 The Cassette Entry Stage .....	76
3.1.2 The Interstage Substrate Transfer System .....	78
3.1.3 The Preparation and Analysis Stages .....	81
3.1.4 The MBE Deposition Chamber .....	85
3.1.5 Beam Sources .....	89
3.1.6 Monitoring and Analytical Facilities .....	99
3.2 Multiple-Growth and Multiple-Process Facilities in MBE Systems .....	107
3.2.1 The Hot-Wall Beam Epitaxy Growth System .....	108
3.2.2 Focused Ion Beam Technology .....	113

---

### Part III Characterization Methods

---

<b>4. In-Growth Characterization Techniques</b> .....	120
4.1 RHEED .....	121
4.1.1 Fundamentals of Electron Diffraction .....	122
4.1.2 Origin of RHEED Features .....	129
4.1.3 RHEED Data from Reconstructed Semiconductor Surfaces .....	134
4.1.4 RHEED Rocking Curves .....	138
4.1.5 RHEED Intensity Oscillations .....	141
4.2 Ellipsometry .....	147
4.2.1 Fundamentals of Ellipsometry .....	148
4.2.2 Ellipsometric Systems Used for In-Growth Analysis in MBE .....	153
<b>5. Postgrowth Characterization Methods</b> .....	159
5.1 Survey of Postgrowth Characterization Methods .....	161
5.2 Auger Electron Spectroscopy .....	162
5.2.1 Chemical Composition of Solid Surfaces .....	167
5.2.2 Sputter Depth Profiling .....	172
5.3 X-Ray Diffraction .....	175
5.3.1 Diffraction Under Nonideal Conditions .....	176
5.3.2 High Resolution X-Ray Diffraction .....	180
5.3.3 X-Ray Diffraction at Multilayers and Superlattices .....	182
5.4 Photoluminescence .....	184
5.4.1 Photoluminescence in Binary Compounds .....	185
5.4.2 Photoluminescence in Ternary and Quaternary Compounds .....	189
5.4.3 Photoluminescence of Quantum Well Structures and Superlattices .....	191

5.5	Electrical Characterization .....	195
5.5.1	Determination of Carrier Concentration and Mobility ...	195
5.5.2	Deep Level Transient Spectroscopy .....	200
5.6	Sophisticated Characterization Methods .....	205
5.6.1	Transmission Electron Microscopy .....	206
5.6.2	Rutherford Backscattering and Channeling .....	209

---

## Part IV MBE Growth Processes

---

6.	<b>Fundamentals of the MBE Growth Process .....</b>	<b>215</b>
6.1	General View of the MBE Growth Process .....	215
6.1.1	Equilibrium States in MBE .....	215
6.1.2	The Transition Layer Concept .....	217
6.2	Relations Between Substrate and Epilayer .....	218
6.2.1	Critical Thickness for the Formation of Misfit Dislocations .....	219
6.2.2	Role of the Crystallographic Orientation of the Substrate .....	225
6.2.3	Role of the Substrate Surface Reconstruction .....	230
6.3	The Near-Surface Transition Layer .....	235
6.3.1	Physical and Chemical Adsorption .....	235
6.3.2	Spatial Arrangement of the Near-Surface Transition Layer .....	241
6.4	Growth Interruption and Pulsed Beam Deposition .....	243
6.4.1	Recovery Effect During Growth Interruption .....	243
6.4.2	Growth of Superlattice Structures by Phase-Locked Epitaxy .....	245
6.4.3	UHV Atomic Layer Epitaxy .....	247
6.4.4	Migration Enhanced Epitaxy .....	250
6.4.5	Molecular Layer Epitaxy .....	254
6.5	Doping During MBE Processes .....	258
6.5.1	Unintentional Doping .....	258
6.5.2	Thermodynamics of Doping by Co-deposition .....	260
6.5.3	Delta-Function-Like Doping Profiles .....	265
6.5.4	In-Growth Doping with Ionized Beams .....	267
7.	<b>Material-Related Growth Characteristics in MBE .....</b>	<b>278</b>
7.1	Si and IV-IV Heterostructures .....	278
7.1.1	Si Substrate Preparation Procedures .....	279
7.1.2	Homoeptitaxy of Si Films .....	281
7.1.3	Heteroeptitaxy of Ge and Sn on Si Substrates .....	286
7.1.4	$\text{Ge}_x\text{Si}_{1-x}$ /Si Heterostructures and Superlattices .....	291
7.1.5	Devices Grown by Si MBE .....	295
7.2	GaAs- and As-Containing Compounds .....	301
7.2.1	Preparation of the GaAs(100) Substrate Surface .....	302
7.2.2	Growth of GaAs on GaAs(100) Substrates .....	305

7.2.3 Growth of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ Heterostructures .....	314
7.2.4 Growth of GaAs on Si Substrates .....	321
7.2.5 Device Structures Grown by GaAs MBE .....	327
7.3 Narrow-Gap II–VI Compounds Containing Hg .....	332
7.3.1 Substrates for MBE of Hg Compounds .....	333
7.3.2 Hg-Compound Heterostructures Grown by MBE .....	337
7.3.3 Device Structures .....	338

---

## Part V Conclusion

---

<b>8. Outlook</b> .....	341
8.1 Miscellaneous Material Systems Grown by MBE .....	341
8.2 MBE-Related Growth Techniques .....	346
8.3 Development Trends of the MBE Technique .....	349
<b>References</b> .....	351
<b>Subject Index</b> .....	379