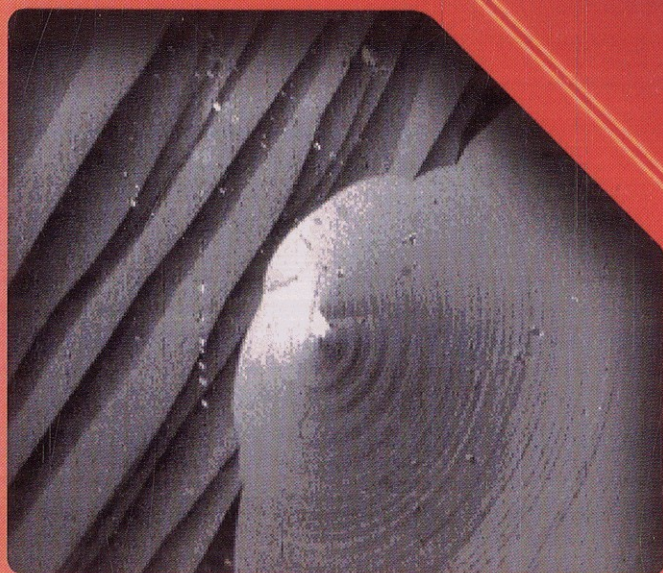


Edited by
**Peter Capper and
Michael Mauk**

Liquid Phase Epitaxy

of Electronic, Optical
and Optoelectronic
Materials



 **WILEY**

Wiley Series
in Materials for
Electronic
& Optoelectronic
Applications

Contents

Series Preface	xi
Preface	xiii
Acknowledgements	xix
List of Contributors	xxi
1 Introduction to Liquid Phase Epitaxy	1
<i>Hans J. Scheel</i>	
1.1 General aspects of liquid phase epitaxy	1
1.2 Epitaxial growth modes, growth mechanisms and layer thicknesses	3
1.3 The substrate problem	15
1.4 Conclusions	16
Acknowledgements	17
References	17
2 Liquid Phase Epitaxy in Russia Prior to 1990	21
<i>V.A. Mishurnyi</i>	
2.1 Introduction	21
2.2 Specific features of growth of quantum-well heterostructures by LPE	23
2.2.1 LPE growth from a capillary	23
2.2.2 Low-temperature LPE	25
2.2.3 LPE growth of InGaAsP quantum well heterostructures	29
2.3 Rare-earth elements in LPE technology of some III-V binary compounds and solid solutions	35
2.4 Conclusions	37
Acknowledgements	37
References	38
3 Phase Diagrams and Modeling in Liquid Phase Epitaxy	45
<i>Kazuo Nakajima</i>	
3.1 Introduction	45
3.2 Equilibrium phase diagrams	46
3.2.1 Binary, ternary and quaternary phase diagrams	46

3.2.2	Calculation of binary, ternary and quaternary phase diagrams	49
3.2.3	Calculation of phase diagrams considering the surface, interface and strain energies	54
3.2.4	Experimental determination of phase diagrams	59
3.2.5	Miscibility gap	64
3.3	Technologies of LPE growth	66
3.4	III-V materials for LPE growth	68
3.5	Lattice matching	69
3.6	Growth of misfit-dislocation-free wafers	71
3.7	Phase diagrams of growth mode	73
3.8	Growth kinetics	77
3.8.1	Calculation of III-V layer thickness	77
3.8.2	Compositional variation in III-V ternary layers	78
3.9	Summary	79
	References	79
	Appendix	82
4	Equipment and Instrumentation for Liquid Phase Epitaxy	85
	<i>Michael G. Mauk and James B. McNeely</i>	
4.1	Introduction	85
4.2	Overview, general description and operation of horizontal slideboat LPE system	89
4.3	Crucibles and slideboats	91
4.4	Alternative slideboat designs	92
4.5	Furnaces and heating	96
4.6	LPE ambient	98
4.7	Tubes, sealing and gas handling	99
4.8	Controllers and heating	99
4.9	Temperature measurements and other instrumentation	100
4.10	Safety	101
4.11	Production LPE systems	101
	References	105
5	Silicon, Germanium and Silicon-Germanium Liquid Phase Epitaxy	109
	<i>Michael G. Mauk</i>	
5.1	Introduction and scope of review	110
5.2	Historical perspective	111
5.3	Basis of silicon and germanium LPE	115
5.3.1	Nucleation of silicon from a molten metal solution	119
5.4	Silicon LPE methods	124
5.4.1	Steady-state methods of solution growth and LPE	125
5.5	Solvent selection	135
5.6	Low-temperature silicon LPE	137
5.7	Purification of silicon for solar cells in an LPE process	138
5.8	Electrical properties of LPE-grown silicon	140
5.9	LPE of Si- and Ge-based alloys	141

5.10 Selective LPE and liquid phase ELO	142
5.11 Solar cells	144
5.11.1 Epitaxial silicon solar cells by LPE	145
5.11.2 Si solution growth on nonsilicon substrates for solar cells	149
5.12 Other applications of silicon and germanium LPE	150
5.13 Conclusions and outlook	151
References	151
Appendix 1. Phase equilibria modeling: The silicon-metal liquidus	166
A1.1 The silicon-metal binary liquidus	168
A1.2 Alloy solvents	168
Appendix 2. Impurities and doping in silicon LPE	171
Appendix 3. Effects of oxygen and water vapor in Si LPE	175
A3.1 Thermodynamics of silicon oxidation	176
A3.2 Silicon passivity and melt reducing agents	178
6 Liquid Phase Epitaxy of Silicon Carbide	179
<i>R. Yakimova and M. Syväjärvi</i>	
6.1 Introduction	179
6.2 Fundamental aspects of LPE of SiC	180
6.3 Growth methods for SiC LPE	185
6.3.1 Modified travelling solvent method	186
6.3.2 Dipping method	191
6.3.3 Container free LPE	191
6.3.4 Vapour–liquid–solid mechanism	192
6.4 Characteristic features of SiC LPE	193
6.4.1 Step-bunching	193
6.4.2 Micropipe filling	195
6.5 LPE of SiC under reduced gravity	196
6.6 Applications	198
References	199
7 Liquid Phase Epitaxy of Gallium Nitride	203
<i>Hans J. Scheel and Dennis Elwell</i>	
7.1 Introduction	203
7.2 Control of epitaxial growth modes	207
7.3 Thermodynamics and phase diagrams	209
7.4 Requirements for LPE	211
7.4.1 Solvents	211
7.4.2 Crucibles	213
7.4.3 Growth atmosphere	214
7.4.4 Substrates	215
7.5 LPE results, characterization of LPE(solution)-grown GaN	218
7.6 Cubic GaN	221
7.7 Conclusions and outlook	221
References	222

8 Liquid Phase Epitaxy of Quantum Wells and Quantum Dots	227
<i>A. Krier, X.L. Huang and Z. Labadi</i>	
8.1 Introduction	227
8.2 LPE growth of quantum wells	228
8.3 Thickness of rapid slider LPE layers	231
8.4 Interface abruptness	235
8.5 Compositional homogeneity	236
8.6 Devices incorporating ultrathin LPE layers	237
8.7 LPE growth of InAs quantum wells	239
8.7.1 PL characterisation	241
8.8 LPE growth of quantum dots for mid-infrared optoelectronic devices	243
8.8.1 InSb QDs on GaAs (100) substrates	244
8.8.2 Investigation of InAsSb QDs	247
8.9 Mid-infrared luminescence of encapsulated InAsSb QDs	249
8.10 Electroluminescence of InAsSb QD LEDs	251
8.11 Summary	253
Acknowledgements	253
References	254
9 Liquid Phase Epitaxy of $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ (MCT)	259
<i>P. Capper</i>	
9.1 Introduction	259
9.2 Growth	261
9.2.1 Introduction	261
9.2.2 Phase diagram and defect chemistry	262
9.2.3 LPE growth techniques	264
9.3 Material characteristics	269
9.3.1 Composition and thickness	271
9.3.2 Crystal quality and surface morphology	272
9.3.3 Impurity doping and electrical properties	273
9.3.4 Multiple-layer heterojunction structures	278
9.4 Device status	278
9.4.1 LPE growth on Si-based substrates	283
9.5 Summary and future developments	283
References	284
10 Liquid Phase Epitaxy of Widegap II-VIs	289
<i>J. F. Wang and M. Isshiki</i>	
10.1 Introduction	289
10.2 Basic properties	289
10.3 LPE technique	291
10.4 Review of some experimental results	292
10.4.1 Growth from Zn, Zn-Ga and halide solvents	293
10.4.2 Growth from Te and Se solvents	296

10.4.3 Growth from Sn solvent	299
10.4.4 Growth from Bi solvent	301
10.5 Conclusion	302
References	302
11 Liquid Phase Epitaxy of Garnets	305
<i>Taketoshi Hibiya and Peter Görnert</i>	
11.1 Introduction	305
11.2 LPE growth	309
11.3 <i>Phase diagram and chemistry</i>	311
11.3.1 Phase diagram	311
11.3.2 Chemical thermodynamics of LPE	314
11.3.3 Effect of oxygen partial pressure on magnetic properties	317
11.4 Growth mechanism and morphology	317
11.4.1 Mass transport and growth rate	317
11.4.2 Control of morphology	321
11.5 Bi-substituted garnet films	323
11.6 Properties of magnetic garnet films	325
11.6.1 Misfit strain	325
11.6.2 Faraday rotation	328
11.6.3 Optical absorption	328
11.6.4 Magnetic anisotropy	333
11.7 Applications of garnet films	334
11.8 Conclusions	337
Acknowledgements	337
References	337
12 Liquid Phase Epitaxy: A Survey of Capabilities, Recent Developments and Specialized Applications	341
<i>Michael G. Mauk</i>	
12.1 Introduction	342
12.2 Comparison of epitaxy techniques and some advantages of LPE	343
12.3 Previous reviews of LPE	355
12.4 Modeling of LPE processes	355
12.5 Survey of new developments and specialized applications of LPE	356
12.5.1 Five- and six-component III-V semiconductor alloys by LPE	357
12.5.2 LPE layers with atomically smooth surfaces	358
12.5.3 Quantum wells, superlattices and nanostructures by LPE	358
12.5.4 Growth of thick ternary and quaternary alloy layers for 'virtual' substrates with adjustable lattice parameters	360
12.5.5 Selective epitaxy and ELO	363
12.5.6 Melt epitaxy	366
12.5.7 Rare earth doping and other doping effects in LPE	366
12.5.8 Fundamental studies of crystal growth, melt convection and liquid-metal transport properties	367
12.5.9 Novel melt compositions for LPE	369
12.5.10 Liquid phase electroepitaxy	370

12.5.11 LPE of thallium-, manganese-, and bismuth-containing III-V alloys	373
12.5.12 Control of segregation in LPE-grown alloys	374
12.5.13 LPE heteroepitaxy	376
12.5.14 SiC and III-V nitride LPE	381
12.5.15 Some other materials grown by LPE or solution growth	383
12.5.16 LPE for shaped crystal growth	389
12.6 Conclusions and outlook	391
References	392
13 Liquid Phase Epitaxy for Light Emitting Diodes	415
<i>Michael G. Mauk</i>	
13.1 Introduction	415
13.2 Commercial LEDs	419
13.3 LPE for wide-bandgap (blue and UV) LEDs	420
13.3.1 Silicon carbide LEDs	420
13.3.2 Wide-bandgap II-VI compound LEDs	421
13.3.3 III-V nitride LEDs	422
13.4 LPE for mid-infrared LEDs	422
13.5 LPE for new LED design concepts	424
13.6 Outlook	426
References	430
Index	435