

Contents

Part 8 Crystal growth, wafer technology, and epitaxy

8.1	Crystal growth and wafer technology	
	M. WALTHER	3
8.1.1	Introduction	3
8.1.2	Bulk crystal growth and wafer technology	3
8.1.2.1	Substrates for compound semiconductor lasers	3
8.1.2.2	Bulk crystal growth of GaAs, InP, and GaSb	4
8.1.2.2.1	Melt growth: Liquid-encapsulated Czochralski (LEC), vapor-controlled Czochralski (VCZ)	5
8.1.2.2.2	Directional solidification techniques: Bridgman variants, gradient freeze method .	6
8.1.2.2.3	Dislocations and thermal stress	6
8.1.2.2.4	Doping of substrates for laser applications	7
8.1.2.3	Wafering	8
	References for 8.1	9
8.2	Epitaxy	
	M. WALTHER	11
8.2.1	Introduction	11
8.2.2	Growth modes and requirements	11
8.2.3	Molecular beam epitaxy (MBE) and related growth techniques	12
8.2.3.1	MBE systems	12
8.2.3.2	MBE growth model, surface diffusion, and desorption	13
8.2.4	Metal-organic chemical vapor phase epitaxy (MOVPE)	14
8.2.4.1	MOVPE systems	14
8.2.4.2	Growth kinetics	15
8.2.5	Heteroepitaxy for laser structures	15
8.2.5.1	Material consideration: Dislocations and impurities	16
8.2.5.2	Strain effects	16
8.2.5.3	Growth of III-V alloys for laser systems	17
	References for 8.2	20

Part 9 Edge-emitting laser diodes

9.1	Laser diodes in the visible spectral range: GaN-based blue and green laser diodes	
	M. KNEISSL, J. RASS	27
9.1.1	Introduction	27
9.1.1.1	History	27
9.1.1.2	Applications	27
9.1.1.3	State of the art	28
9.1.2	Materials properties of group-III nitrides	29
9.1.2.1	The AlGaInN material system	29
9.1.2.2	Substrates and crystal orientations	30
9.1.2.3	Doping	31
9.1.3	InGaN laser diode heterostructures	32
9.1.3.1	InGaN quantum wells	32
9.1.3.2	Polarization fields	33
9.1.3.3	Waveguide and cladding layers	34
9.1.3.4	Carrier confinement	36
9.1.3.5	Laser diode designs	37
9.1.4	Performance characteristics of laser diodes	38
9.1.4.1	Blue laser diodes on (0001) GaN	38
9.1.4.2	Green laser diodes on (0001) GaN	39
9.1.4.3	Green laser diodes on non- and semipolar GaN	39
	References for 9.1	40
9.2	Laser diodes in the visible spectral range: red-emitting laser diodes	
	W. SCHMID, U. STRAUSS	43
9.2.1	Introduction	43
9.2.2	InAlGaP-material system and comparison with AlGaAs	44
9.2.2.1	Ordering	46
9.2.2.2	Dopants	46
9.2.2.3	Refractive index and absorption coefficient of InAlGaP	47
9.2.3	Epi structures for red laserdiodes	48
9.2.4	Laser chip structures	49
9.2.5	Facet stability	50
	References for 9.2	52
9.3	Diode lasers in the near infra-red spectral range	
	P. CRUMP	59
9.3.1	Introduction	59
9.3.2	Diode lasers based on GaAs substrate	60
9.3.2.1	Material properties	60
9.3.2.2	Substrate	61
9.3.2.3	Doping	62
9.3.2.4	Active region	62
9.3.2.5	Waveguide and cladding layers	64
9.3.2.6	Contact layer	65

9.3.2.7	Vertical and lateral structure design	65
9.3.2.8	Results.....	67
9.3.3	Diode lasers based on InP substrates.....	68
9.3.3.1	Material properties	68
9.3.3.2	Substrate.....	69
9.3.3.3	Doping.....	69
9.3.3.4	Active region	69
9.3.3.5	Waveguide and cladding layers	71
9.3.3.6	Contact layer	71
9.3.3.7	Vertical and lateral structure design	71
9.3.3.8	Results.....	72
	References for 9.3	74
9.4	Quantum cascade lasers	
	Q.K. YANG, O. AMBACHER.....	79
9.4.1	Introduction	79
9.4.2	Fabrication procedure	80
9.4.3	Mid-to-far infrared (3-30 μm) quantum cascade lasers	82
9.4.4	Terahertz (30-300 μm) quantum cascade lasers	83
9.4.5	Valence-band quantum cascade structure	85
9.4.6	Applications of quantum cascade lasers.....	85
	References for 9.4	87

Part 10 Vertical-cavity surface-emitting lasers

10.1	Vertical-cavity surface-emitting lasers	
	P. UNGER.....	95
10.1.1	Introduction	95
10.1.2	Basic concept of a VCSEL.....	95
10.1.3	Properties and applications of VCSELs.....	97
10.1.4	Wavelengths and material systems	98
	References for 10.1	100

Part 11 Quantum dot lasers

11.1	Quantum dot diode lasers	
	A.E. ZHUKOV	105
11.1.1	Introduction	105
11.1.2	Synthesis and basic properties of self-organized QDs	106
11.1.2.1	Formation of quantum dots and their basic structural properties	106
11.1.2.2	Optical properties, inhomogeneous line broadening	108
11.1.2.3	Control of emission wavelength.....	109
11.1.3	Optical gain in quantum dot lasers	111
11.1.3.1	Effect of inhomogeneous broadening and upper states	111
11.1.3.2	Excited-state lasing.....	113

11.1.3.3	Stacked quantum dot arrays	115
11.1.4	Peculiarities of quantum dot lasers	117
11.1.4.1	Quantum dot lasers emitting in the 1.2-1.3 μm range	117
11.1.4.2	Low-threshold QD lasers	119
11.1.4.3	Temperature stability of laser characteristics	121
11.1.4.4	Direct modulation	122
11.1.4.5	Mode-locked lasers	124
11.1.4.6	Reliability of QD lasers	126
11.1.4.7	Quantum dot lasers emitting beyond 1.3 μm , metamorphic growth	127
11.1.5	Quantum dot lasers with broad gain and emission spectra	128
11.1.5.1	Spectral broadening in QD lasers	128
11.1.5.2	QD lasers with chirped active region	129
11.1.5.3	Broadband QD lasers for multi-channel optical transmission	131
11.1.6	Conclusion	133
	References for 11.1	135

Part 12 Laser diode characterization and testing

12.1	Standard characterization methods	
	B. EPPICH	145
12.1.1	Introduction	145
12.1.2	Electro-optical characteristics	145
12.1.3	Beam characterization	147
12.1.3.1	Goniometric measurement of far-field distributions	147
12.1.3.2	Measurement of near-field distributions	149
12.1.3.3	Measurement of the beam-waist profile	150
12.1.3.4	Combined measurement of beam-waist diameter, near field, and far field	151
12.1.3.5	Beam propagation ratio M^2	151
12.1.3.6	Relevant ISO standards	153
	References for 12.1	154
12.2	Reliability and life time	
	B. SUMPF, K. HÄUSLER	155
12.2.1	Degradation measurements: tasks and objectives	155
12.2.2	Statistical basics	155
12.2.3	Distribution functions	156
12.2.3.1	Exponential distribution	156
12.2.3.2	Weibull distribution	157
12.2.3.3	Logarithmic normal distribution	158
12.2.4	Scale-accelerated failure time	159
12.2.5	Planning of life tests	161
12.2.6	Experimental set-up	162
12.2.7	Aging test – selection of samples, accompanying measurements	164
12.2.8	Statistical analysis of results	166
12.2.8.1	Analysis of wear-out	166
12.2.8.2	Analysis of random failures	168

12.2.9	Conclusion	170
	References for 12.2	171
12.3	Defect analysis	
	B. SUMPFF, U. ZEIMER	175
12.3.1	Cathodoluminescence	175
12.3.2	Photoluminescence	178
12.3.3	Transmission electron microscopy	179
12.3.4	Conclusion	180
	References for 12.3	181

Part 13 Micro-optics and beam shaping

13.1	Microoptics and freeform optical beam shaping	
	S. SINZINGER, R. KLEINDIENST	185
13.1.1	Introduction	185
13.1.2	Diffractive optics	186
13.1.3	Refractive and reflective microoptics	189
13.1.4	Microoptical systems integration	191
13.1.5	Active microoptics	193
13.1.6	Optical beam shaping	195
13.1.6.1	Beam transformation	195
13.1.6.2	Beam splitting	198
13.1.6.3	Beam shaping for diode laser arrays	201
	References for 13.1	205

Part 14 High-power diode lasers

14.1	Packaging of laser bars	
	K. BOUCKE	213
14.1.1	Overview	213
14.1.1.1	Mechanical requirements	213
14.1.1.2	Electrical requirements	214
14.1.2	Packaging process	214
14.1.2.1	p-side bonding of laser bars	214
14.1.2.1.1	Indium solder	215
14.1.2.1.2	Gold-tin solder	216
14.1.2.2	n-side contacting of laser bars	216
14.1.2.2.1	Wire bonding	216
14.1.2.2.2	Contact foils	217
14.1.2.3	Non-soldered packages	218
14.1.3	Heat sinks and heat sink assemblies for laser diode bars	218
14.1.3.1	General design and material considerations	218
14.1.3.2	Conductively cooled heat sinks	219
14.1.3.3	Convection-cooled heat sinks	220

14.1.3.4	Expansion-matched heat sinks and packages	221
14.1.4	Back-side cooled packages and multi-bar packages	223
	References for 14.1	225
14.2	High-power diode laser systems	
	H.-D. HOFFMANN	229
14.2.1	Introduction	229
14.2.2	Beam combination for power scaling	230
14.2.3	Beam transformation	234
14.2.4	Beam shaping	234
14.2.5	Fiber coupling	236
14.2.6	Vertical emitting arrays	237
14.2.7	Application of high-power diode lasers	238
14.2.7.1	Pumping of solid-state lasers	238
14.2.7.2	Direct materials processing	238
14.2.7.3	Medical applications	240
	References for 14.2	241
Part 15 External cavities and optically pumped disk lasers		
15.1	Edge emitters with external cavities	
	M. CHI, P.M. PETERSEN	245
15.1.1	Introduction	245
15.1.2	External cavity feedback technique for BALs	246
15.1.2.1	External cavity technique for a narrow-linewidth BAL system	246
15.1.2.2	External cavity technique for a high spatial beam quality BAL system	247
15.1.2.3	External cavity technique for a BAL system with both high spatial and temporal coherence	249
15.1.3	External cavity feedback technique for TDLs	251
15.1.4	Conclusion	253
	References for 15.1	256
15.2	Optically pumped semiconductor disk lasers	
	P. UNGER	259
15.2.1	Introduction	259
15.2.2	Basic concept of a semiconductor disk laser	259
15.2.3	Optimization of the disk laser structure	261
15.2.4	Intracavity frequency doubling	263
15.2.5	Summary of significant results	264
	References for 15.2	266
Index		269