

Contents

Preface *XI*

List of Contributors *XIII*

1	Defects in Germanium	<i>1</i>
	<i>Justin R. Weber, Anderson Janotti, and Chris G. Van de Walle</i>	
1.1	Introduction	<i>1</i>
1.2	Methods for Studying Defects and Impurities	<i>2</i>
1.2.1	Experimental Techniques	<i>2</i>
1.2.2	First-Principles Calculations	<i>3</i>
1.3	Impurities	<i>5</i>
1.3.1	Shallow Dopants	<i>5</i>
1.3.2	Hydrogen	<i>8</i>
1.4	Intrinsic Defects	<i>8</i>
1.4.1	Vacancies	<i>8</i>
1.4.1.1	Electronic Structure	<i>8</i>
1.4.1.2	Formation Energy	<i>9</i>
1.4.1.3	Defect Levels	<i>10</i>
1.4.1.4	Comparison with Silicon	<i>13</i>
1.4.1.5	Diffusion	<i>13</i>
1.4.2	Self-Interstitials	<i>14</i>
1.4.3	Dangling Bonds	<i>16</i>
1.4.3.1	Electronic Levels	<i>16</i>
1.4.4	Impact on Devices	<i>18</i>
1.5	Summary	<i>19</i>
	References	<i>19</i>
 2	 Hydrogen in Ge	 <i>25</i>
	<i>Jörg Weber</i>	
2.1	Introduction	<i>25</i>
2.2	Properties of Hydrogen in Ge	<i>26</i>
2.2.1	Incorporation of Hydrogen	<i>26</i>
2.2.2	Isolated Hydrogen	<i>27</i>
2.2.3	Hydrogen Dimers	<i>30</i>

2.2.3.1	Interstitial H ₂	30
2.2.3.2	The H ₂ * Defect	31
2.2.3.3	H ₂ Molecules in Hydrogen-Induced Platelets	32
2.2.3.4	Complexes of Hydrogen with Other Defects	34
2.3	Hydrogen Passivation of Shallow Donors and Acceptors in Ge	36
2.3.1	Donor Passivation	37
2.3.2	Hydrogen in p-type Ge	40
2.3.3	Schottky Contacts on p-type Ge	43
2.4	Summary	45
	Acknowledgments	45
	References	45
3	Epitaxy of Ge Layers on Blanket and Patterned Si(001) for Nanoelectronics and Optoelectronics	49
	<i>Jean-Michel Hartmann</i>	
3.1	General Introduction	49
3.2	Epitaxial Growth of Ge Thick Layers on Si(001)	50
3.2.1	Growth Protocol and Kinetics	50
3.2.2	Surface Morphology	51
3.2.3	Strain State	52
3.2.4	Defects Density and Distribution in the Ge Layers	54
3.3	Ge Surface Passivation with Si	55
3.3.1	Passivation Protocol	55
3.3.2	Surface and Film Morphology	57
3.4	SEG of Ge in Cavities at the End of Optical Waveguides	59
3.5	Fabrication, Structural, and Electrical Properties of Compressively Strained Ge-on-Insulator Substrates	61
3.5.1	The c-Ge on Si _{0.15} Ge _{0.85} Process Flow	62
3.5.2	Structural Properties of the c-Ge on Si _{0.15} Ge _{0.85} Stacks as a Function of the Ge Layer Thickness	64
3.5.2.1	Surface Morphology	64
3.5.2.2	Macroscopic Strain State	65
3.5.2.3	Defect Density	66
3.5.3	Properties of the c-GeOI Substrates	68
3.5.3.1	Structural Properties	68
3.5.3.2	Electrical Properties	69
3.5.3.3	Benchmark	71
3.6	Conclusion and Perspectives	72
	References	73
4	Heavy Doping in Si_{1-x}Ge_x Epitaxial Growth by Chemical Vapor Deposition	77
	<i>Junichi Murota</i>	
4.1	Introduction	77
4.2	<i>In situ</i> Doping of B, P, and C in Si _{1-x} Ge _x Epitaxial Growth	78

4.2.1	<i>In situ</i> Doping Characteristics in $\text{Si}_{1-x}\text{Ge}_x$ Epitaxial Growth	78
4.2.2	Relationship between Carrier and Impurity (B or P) Concentrations in $\text{Si}_{1-x-y}\text{Ge}_x\text{C}_y$ Epitaxial Film	82
4.3	Atomic-Layer Doping in $\text{Si}_{1-x}\text{Ge}_x$ Epitaxial Growth	84
4.3.1	Boron Atomic-Layer Doping in $\text{Si}_{1-x}\text{Ge}_x$ Epitaxial Growth	85
4.3.1.1	Surface Reaction of B_2H_6 on $\text{Si}_{1-x}\text{Ge}_x(100)$	85
4.3.1.2	$\text{Si}_{1-x}\text{Ge}_x$ Epitaxial Growth over B Atomic Layer Already Formed on the (100) Surface	87
4.3.2	Phosphorus Atomic-Layer Doping in $\text{Si}_{1-x}\text{Ge}_x$ Epitaxial Growth	88
4.3.2.1	Surface Reaction of PH_3 on $\text{Si}_{1-x}\text{Ge}_x(100)$	88
4.3.2.2	$\text{Si}_{1-x}\text{Ge}_x$ Epitaxial Growth over P Atomic Layer Already-Formed on the (100) Surface	89
4.3.3	Carbon Atomic-Layer Doping in $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}(100)$ Structure	94
4.3.3.1	Surface Reaction of SiH_3CH_3 on $\text{Si}_{1-x}\text{Ge}_x(100)$	94
4.3.3.2	$\text{Si}_{1-x}\text{Ge}_x$ Epitaxial Growth over C Atomic Layer Already Formed on the (100) Surface	94
4.4	Conclusion and Future Trends	96
	Acknowledgments	97
	References	97
5	FEOL Integration of Silicon- and Germanium-Based Photonics in Bulk-Silicon, High-Performance SiGe: C-BiCMOS Processes	101
	<i>Lars Zimmermann, Dieter Knoll, and Bernd Tillack</i>	
5.1	Introduction	101
5.2	Local SOI Technology	103
5.3	Passive Silicon Waveguide Technology	105
5.4	Modulator Technology	108
5.5	Photonics Integration in BiCMOS Flow	111
5.6	Germanium Photo Detector – Process Integration Challenges	114
5.7	Example Circuit – 10 Gbit s^{-1} Modulator with Driver	118
5.8	Outlook	120
	Acknowledgments	120
	References	121
6	Ge Condensation and Its Device Application	123
	<i>Shinichi Takagi</i>	
6.1	Principle of Ge Condensation and Fabrication Process	123
6.1.1	Basic Concept of Ge Condensation Process	123
6.1.2	Critical Process Parameters	125
6.2	GOI Film Characterization	127
6.2.1	Thickness Control	127
6.2.2	Residual Impurity	129
6.2.3	Strain Behavior	129
6.2.4	Defects and Dislocations	131
6.2.5	Electrical Properties	132

6.3	Device Application	132
6.3.1	Planar GOI MOSFET	133
6.3.2	MOSFETs Using Local Ge Condensation	135
6.3.2.1	Planar MOSFETs	135
6.3.2.2	Multi-gate and Nanowire MOSFETs	138
6.3.3	Stressor	139
6.3.4	Photonic Devices	139
6.4	Summary	140
	References	140
7	Waveguide Design, Fabrication, and Active Device Integration	147
	<i>Koji Yamada</i>	
7.1	Introduction	147
7.2	Design of Silicon Photonic Wire Waveguiding System	148
7.2.1	Guided Modes of Si Photonic Wire Waveguide	148
7.2.2	External Coupling of Silicon Photonic Wire Waveguide	152
7.2.3	Coupling to Ge Photonic Devices	153
7.3	Fabrication	155
7.3.1	Si Waveguide Core	155
7.3.2	Dynamic and Active Layers	155
7.3.3	SSCs and Overcladding	156
7.4	Propagation Performance of Waveguides	158
7.5	Integration of Si/Silica and Ge Photonic Devices	160
7.5.1	Integration of Si-Based Modulation Device and Ge-Based Photodetectors	160
7.5.2	Integration of Si/Silica-Based Wavelength Filter and Ge-Based Photodetectors	160
7.6	Summary	161
	References	162
8	Detectors	165
	<i>Subal Sahni and Gianlorenzo Masini</i>	
8.1	Introduction	165
8.2	Historical Background	165
8.3	Fiber-Optics Revolution	167
8.4	Avalanche Devices	167
8.5	Si-Photonics	168
8.6	High-Performance Ge Detectors	169
8.7	Process Options and Challenges	170
8.7.1	Physical Vapor Deposition (PVD)	170
8.7.2	Chemical Vapor Deposition	172
8.7.3	Rapid Melt Growth	174
8.7.4	Other Techniques	175
8.8	Device Architectures	177
8.9	Ge on Si Detectors in Highly Integrated Systems	180

8.10	Reliability	182
8.11	Conclusions	183
	References	183
9	Ge and GeSi Electroabsorption Modulators	191
	<i>Jifeng Liu</i>	
9.1	Introduction	191
9.2	EAE in Ge and GeSi: Theoretical and Experimental	192
9.2.1	Franz–Keldysh Effect	192
9.2.2	Quantum-Confined Stark Effect	197
9.2.3	Comparison of Ge FKE with QCSE Modulators	202
9.3	Waveguide Coupling	203
9.4	Current Progress in Ge and GeSi EAMs	207
9.5	Conclusions	213
	References	214
10	Strained Ge for Si-Based Integrated Photonics	219
	<i>Kazumi Wada, Kohei Yoshimoto, Yu Horie, Jingnan Cai, Peng Huei Lim, Hiroshi Fukuda, Ryota Suzuki, and Yasuhiko Ishikawa</i>	
10.1	Introduction	219
10.2	Bandgap and Strain: Theory	220
10.3	Bandgap and Strain: Experiment	224
10.3.1	Si	224
10.3.2	Ge on Si	226
10.3.3	GaAs on Ge on Si	228
10.4	Strain-Engineered Tunability of Lasers	230
10.5	Conclusions	231
	Acknowledgment	232
	References	232
11	Ge Quantum Dots-Based Light Emitting Devices	233
	<i>Xuejun Xu, Takuya Maruizumi, and Yasuhiro Shiraki</i>	
11.1	Introduction	233
11.2	Formation of Ge Dots on Si Substrates and Their Luminescent Properties	234
11.3	Enhanced Light Emission from Ge QDs Embedded in Optical Cavities	239
11.4	Optically Excited Light Emission from Ge QDs	240
11.4.1	Photonic Crystal Cavity	240
11.4.1.1	General Device Description	240
11.4.1.2	PL from PhC Microcavities	241
11.4.1.3	PL from L3-Type PhC Nanocavities	242
11.4.1.4	PL from Double-Heterostructure PhC Nanocavities	247
11.4.2	Microdisk/Ring	248
11.4.2.1	General Device Description	248

11.4.2.2	PL from Microdisks and Rings	249
11.5	Electrically Excited Light Emission from Ge ODs	251
11.5.1	Photonic Crystal Cavity	251
11.5.1.1	Vertical PIN Structure	252
11.5.1.2	Lateral PIN Structure	255
11.5.1.3	Optimized Lateral PIN Structure	258
11.5.2	Microdisk	261
11.6	Conclusion	263
	References	264
12	Ge-on-Si Lasers	267
	<i>Jifeng Liu</i>	
12.1	Introduction	267
12.2	Modeling and Analyses of Band-Engineered Ge Optical Gain Media	268
12.2.1	Optical Gain from the Direct Gap Transition of Ge	268
12.2.1.1	Unstrained Ge	268
12.2.1.2	Tensile Strained Ge	269
12.2.2	Band-Engineering by Combining Tensile Strain with N-type Doping	270
12.2.3	FCA Losses	271
12.2.4	Band Gap Narrowing in n^+ Ge	274
12.2.5	Net Optical Gain Analyses for Tensile-Strained N^+ Ge	275
12.2.6	Cocktail Band-Engineering Approach Involving Sn Alloying	277
12.2.7	Toward High Performance Ge QW Structures	279
12.3	Fabrication of Band-Engineered Ge-on-Si	280
12.3.1	Tensile Strained Ge-on-Si	281
12.3.2	N-Type Doping	282
12.3.2.1	Regular <i>In situ</i> Doping	284
12.3.2.2	Delta Doping Followed by Thermally Activated Drive-in Diffusion	285
12.3.2.3	Diffusion Doping from SOD Sources	286
12.3.3	Sn Alloying	287
12.4	Band-Engineered Ge-on-Si Light Emitters	288
12.4.1	Spontaneous Emission	289
12.4.1.1	Features of Direct Gap Emission from Ge	289
12.4.1.2	Spontaneous Emission from Ge and GeSn Microcavities	293
12.4.2	Optical Gain	294
12.4.3	Optically-Pumped Ge-on-Si Lasers	297
12.4.4	Electrically-Pumped Ge-on-Si Lasers	298
12.5	Conclusions	303
	Acknowledgments	303
	References	303