## **Contents**

## Preface xi

| 1       | Packaging and Test of Photonic Integrated Circuits (PICs) $1$         |
|---------|---|
|         | Stéphane Bernabé, Tolga Tekin, Bogdan Sirbu, Jean Charbonnier,        |
|         | Philippe Grosse, and Moritz Seyfried                                  |
| 1.1     | Introduction 1  |
| 1.2     | Challenges and Specificities of PIC Packaging and Test 2              |
| 1.2.1   | Optical Interconnects 3   |
| 1.2.2   | Coupling Structures 5   |
| 1.2.2.1 | Edge Coupler 5  |
| 1.2.2.2 | Vertical Grating Coupler (VGC) 6                                      |
| 1.2.2.3 | Evanescent Coupling 7   |
| 1.2.3   | Wafer-level Test 7  |
| 1.2.4   | Module Packaging 10   |
| 1.2.5   | Fiber Optic Assembly (Pigtailing) 12                                  |
| 1.2.5.1 | PIC Alignment to a Lensed Fiber 12                                    |
| 1.2.5.2 | PIC Butt Coupling to a Standard Cleaved Single-mode Fiber 12          |
| 1.2.5.3 | Lens Coupling Scheme 13   |
| 1.2.5.4 | Optical Waveguide Interposer Coupling 14                              |
| 1.2.6   | Emerging Trends for Module Mass Manufacturing 15                      |
| 1.3     | Advances in Optical Coupling Strategies 18                            |
| 1.3.1   | Toward Passive Alignment Strategies 19                                |
| 1.3.2   | Advanced Technologies for Vision-Assisted Technologies 20             |
| 1.3.2.1 | Open-Loop Alignment 20  |
| 1.3.2.2 | Closed-Loop Alignment 20  |
| 1.3.3   | Advanced Technologies for Self-alignment Strategies 21                |
| 1.3.3.1 | Self-alignment of Fiber to PIC Through an Silicon Optical Bench Using |
|         | Flip-Chip 22  |
| 1.3.3.2 | Self-alignment-assisted Microlenses Assembly 22                       |
| 1.3.3.3 | Self-alignment of Polymer Waveguides 22                               |
| 1.3.3.4 | Self-alignment of Optical Plug 23                                     |
| 1.3.4   | Laser/PIC Coupling 23   |
| 1.4     | Electronic/Photonic Convergence 25                                    |



| vi   C | ontents |
|--------|---------|
|--------|---------|

| 1.4.1   | Flip-chip Interconnects 26   |
|---------|--|
| 1.4.1.1 | Standard Die-to-die interconnects 26   |
| 1.4.1.2 | Advanced Interconnects for Future Needs 27   |
| 1.4.2   | Intra-connections (Through Silicon Vias and Through Glass Vias) 29   |
| 1.4.2.1 | TSV Last Process 29  |
| 1.4.2.2 | TSV Middle Process 30  |
| 1.4.2.3 | Through Glass Via (TGV) 31   |
| 1.4.3   | Fan-out Wafer-level Packaging (FOWLP) 31   |
| 1.4.4   | Interposers Integration Approach 32  |
| 1.4.4.1 | Interposers for Electronic Integrated Circuits (CMOS) 33   |
| 1.4.4.2 | Photonic Interposer and Photonic Systems on Chip 34  |
| 1.5     | Toward an Ecosystem in Test and Assembly of PICs 36  |
| 1.5.1   | Design Rules for Packaging and Test 36   |
| 1.5.1.1 | 3D Packaging 38  |
| 1.5.1.2 | Design Rules for Testing 39  |
| 1.5.2   | Advanced Techniques for Wafer-level Test 39  |
| 1.5.3   | Recent Achievements and Future Aspects in Assembly Machines 40   |
| 1.6     | Conclusion 45  |
|         | Acknowledgments 46   |
|         | References 46  |
| 2       | The Last Mile Technology of Silicon Photonics Toward   |
|         | Productions and Emerging Applications 53   |
|         | Bo Li, Shawn Yohanes Siew, Feng Gao, Shawn Wu Xie, Qiang Li, Chao Li,  |
|         | Xianshu Luo, Guo-Qiang Lo, and Junfeng Song  |
| 2.1     | Introduction 53  |
| 2.2     | Fiber-to-Chip Assembly 55  |
| 2.3     | Hybrid Integration of Light Source 59  |
| 2.4     | Electronic and Photonic Co-Packaging 63  |
| 2.5     | Outlook 65   |
| 2.5.1   | Silicon Photonics Emerging Applications 65   |
| 2.5.2   | Opportunities and Challenges 68  |
|         | References 70  |
| 3       | Integrated Nonlinear Photonics and Emerging  |
|         | Applications 75  |
|         | Yang Yue, Wenpu Geng, Yuxi Fang, and Yingning Wang   |
| 3.1     | Introduction 75  |
|         | Supercontinuum 77  |
|         | Applications 77  |
| 3.2.2   | History of SCG in Integrated Waveguides 79   |
| 3.2.3   | Representative Works 83  |
|         | Optical Frequency Comb 90  |
| 3.3.1   | Microresonator-Based OFC 91  |
| 3.3.2   | SC-Based OFC 99  |
|         | 1.4.1.1 1.4.1.2 1.4.2 1.4.2.1 1.4.2.2 1.4.2.3 1.4.3 1.4.4 1.4.4.1 1.4.4.2 1.5 1.5.1 1.5.1.1 1.5.1.2 1.5.2 1.5.3 1.6  2  2.1 2.2 2.3 2.4 2.5 2.5.1 2.5.2  3 3.1 3.2 3.2.1 3.2.2 3.2.1 3.2.2 3.2.3 3.3 3.3 3.3.1 |

| 3.3.3   | EO-Based OFC 99  |
|---------|--|
| 3.3.4   | MLL-Based OFC 99   |
| 3.3.5   | Applications 101   |
| 3.4     | Nonlinear Wave Mixing 102  |
| 3.4.1   | Introduction 102   |
| 3.4.2   | Nonlinear Optical Signal Processing in Integrated Waveguides 105 |
| 3.4.3   | Representative Works 108   |
| 3.5     | Conclusion and Perspectives 116                                  |
|         | References 117   |
| 4       | Excitation, Generation, Positioning, and Modulation for          |
| •       | Quantum Light Sources Integrated on Chip 135                     |
|         | Cuo Wu, Cuiping Ma, and Zhiming Wang                             |
| 4.1     | Introduction 135   |
| 4.2     | Excitation and Orientation of Quantum Emitters 136               |
| 4.3     | Chip-Scale Integration Based on Quantum Emitters 141             |
| 4.3.1   | Solution-Based Colloidal and Self-Assembled Quantum Dots 141     |
| 4.3.2   | Strain-Induced Emitter Sites of Two-Dimensional Materials 144    |
| 4.3.3   | Color Centers in Nanodiamond 148                                 |
| 4.4     | Deterministically Positioning of Quantum Emitter 154             |
| 4.5     | Quantum Light Interaction with Metasurface for Modulation 156    |
| 4.6     | Conclusion 159   |
|         | References 160   |
|         |  |
| 5       | Quantum Light Sources in Two-Dimensional Materials 167           |
|         | Yanan Wang and Philip XL. Feng                                   |
| 5.1     | Introduction 167   |
| 5.2     | Theory of Quantum Light Sources 168                              |
| 5.2.1   | Photon Statistics 168  |
| 5.2.1.1 | Thermal Light 169  |
| 5.2.1.2 | Coherent Light 170   |
| 5.2.1.3 | Squeezed Light 170   |
| 5.2.2   | Characteristics of Quantum Light Sources 172                     |
| 5.2.2.1 | Wavelength 172   |
| 5.2.2.2 | Lifetime, Emission Rate, and Brightness 172                      |
| 5.2.2.3 | Emission Linewidth 173   |
| 5.2.2.4 | Zero-Phonon Line (ZPL) and Debye-Waller Factor 173               |
| 5.2.2.5 | Photon Polarization and Dipole Orientation 173                   |
| 5.2.2.6 | Optically Addressable Spin State 174                             |
| 5.2.2.7 | Indistinguishability 174   |
| 5.3     | Quantum Light Sources in 2D Materials 175                        |
| 5.3.1   | Localized Excitons in Transition Metal Dichalcogenides 176       |
| 5.3.2   | Defect Centers in Hexagonal Boron Nitride 179                    |
| 5.3.3   | Graphene Quantum Dots 183  |

| viii | Contents |   |
|------|----------|---|
|      | 5.3.4    | Quantum Light-Emitting Diodes 186   |
|      | 5.4      | Integration with On-Chip Components 189   |
|      | 5.4.1    | Theory of SPE-Cavity Coupling 190   |
|      | 5.4.1.1  | Strong Coupling Regime 190  |
|      | 5.4.1.2  | Weak Coupling Regime 191  |
|      | 5.4.2    | Integration with Dielectric Waveguides and Cavities 191                         |
|      | 5.4.2.1  | Transferring 2D SPEs onto Predefined Structures 192                             |
|      | 5.4.2.2  | Transferring or Fabricating Photonic Structures on 2D Materials 194             |
|      | 5.4.2.3  | Monolithic Integration 195  |
|      | 5.4.3    | Integration with Plasmonic Waveguides and Cavities 197                          |
|      | 5.5      | Integration with Off-Chip Components 199  |
|      | 5.5.1    | Flip-chip Integration 199   |
|      | 5.5.2    | Integration with Optic Fibers 200   |
|      | 5.6      | Summary and Outlook 202   |
|      |          | Acknowledgments 203   |
|      |          | References 204  |
|      | 6        | Inverse Design for Integrated Photonics Using Deep Neural<br>Network 209        |
|      |          | Keisuke Kojima, Toshiaki Koike-Akino, Yingheng Tang, and Ye Wang                |
|      | 6.1      | Introduction 209  |
|      | 6.2      | Deep Neural Network (DNN) Models 210  |
|      | 6.2.1    | Forward Modeling 211  |
|      | 6.2.2    | Inverse Modeling 212  |
|      | 6.2.3    | Generative Modeling 212   |
|      | 6.3      | Deep Learning for Forward Modeling to Predict Optical Response 212              |
|      | 6.4      | Deep Learning for Inverse Modeling to Construct Device Topology 217             |
|      | 6.5      | Deep Learning for Generative Modeling to Produce Device Topology Candidates 220 |
|      | 6.6      | Physics-informed Neural Networks 225  |
|      | 6.7      | Nanophotonic Power Splitter Design Using Generative Modeling 227                |
|      | 6.7.1    | Device Structure 228  |
|      | 6.7.2    | Device Simulation Procedure 229   |
|      | 6.7.3    | Network Architecture 230  |
|      | 6.7.4    | Network Training Procedure 231  |
|      | 6.7.5    | Device Generation Performance 232   |
|      | 6.7.6    | Hyperparameters 234   |
|      | 6.7.7    | Adjoint Method vs. Deep Learning 234  |
|      | 6.8      | Deep Learning Techniques 235  |
|      | 6.8.1    | Convolutional Neural Networks 235   |
|      | 6.8.2    | Transfer Learning and Fine Tuning 235   |
|      | 6.8.3    | AutoML: Meta Learning, Learning to Learn, Network Architecture<br>Search 236    |
|      | 6.9      | Conclusion 237  |
|      | ***      | References 237  |
|      |          | · · · · · · · · · · · · · · · · · · ·   |

| 7            | Deep Learning Driven Data Processing, Modeling, and Inverse Design for Nanophotonics 245 Peter R. Wiecha, Nicholas J. Dinsdale, and Otto L. Muskens  |
|--------------|--|
| 7.1          | Introduction 245   |
| 7.1<br>7.2   | Artificial Neural Networks and Deep Learning 245   |
| 7.2<br>7.2.1 | Artificial Neurons and Neural Networks 246   |
|              |  |
| 7.2.2        | Training of Artificial Neural Networks 247   |
| 7.3          | Ultrafast Physics Predictions 248  |
| 7.3.1        | Specialized Physics Predictors: Fully Connected vs. Convolutional ANNs 249   |
| 7.3.2        | Generalized Nanophotonics Predictor Network 252  |
| 7.4          | Photonics Inverse Design 255   |
| 7.4.1        | Predictor Network as a Surrogate Model for Optimization 256  |
| 7.4.1.1      | Example: Polarization Conversion Maximization 257  |
| 7.4.1.2      | Example: Maximize Magnetic Near-Field 258  |
| 7.4.2        | Direct Inverse Design Networks 259   |
| 7.4.3        | Optimizing Inverse Design Performance 260  |
| 7.4.3.1      | Optimizing the Network Layout 262  |
| 7.4.3.2      | Quality of the Initial Dataset 262   |
| 7.4.3.3      | Iterative Training 264   |
| 7.4.3.4      | Postprocessing 265   |
| 7.5          | Advanced Data Processing for Photonics Applications 265  |
| 7.5.1        | Optical Data Storage below the Diffraction Limit 265   |
| 7.5.2        | Speckle Reconstruction for Real-time Hyperspectral Imaging 267   |
| 7.6          | Conclusion and Outlook 269   |
|              | References 270   |
| 8            | Optical Waveguide of Lithium Niobate Nanophotonics 277 Yarub Al-Douri  |
| 8.1          | Introduction 277   |
| 8.2          | Photonics Lithium Niobate 278  |
| 8.3          | Nanophotonic Lithium Niobate-Based Optical Waveguide 286   |
| 8.4          | Optical Studies of Nanophotonic Lithium Niobate-Based Optical Waveguide 287  |
| 8.5          | Nanophotonic LiNbO <sub>3</sub> Under Stirrer Time Effect 295  |
| 8.6          | Nanophotonic Studies of LiNbO <sub>3</sub> Under Stirrer Time Effect 297   |
| 8.7          | Conclusions 304  |
|              | References 305   |
| 9            | Active, Tunable, and Reconfigurable Nanophotonics 313 Trevon Badloe, Jaehyuck Jang, Heonyeong Jeong, Minsu Jeong, Inki Kim, Byoungsu Ko, Jihae Lee, Taejun Lee, Seong-Won Moon, Dong Kyo Oh, Younghwan Yang, Gwanho Yoon, and Junsuk Rho |
| 9.1          | Introduction 313   |
| 9.2          | Liquid Crystal-Integrated Tunable Devices 314  |

| x | Contents |
|---|----------|
|---|----------|

| 9.2.1 | Devices that Modulate Polarization 314                            |
|-------|---|
| 9.2.2 | Devices that Modulate Effective Refractive Index 316              |
| 9.3   | Optically Tunable Devices 318                                     |
| 9.3.1 | Devices that Are Dependent on the Direction of Incident Light 318 |
| 9.3.2 | Devices that Depend on Wavelength 319                             |
| 9.3.3 | Devices that Depend on Polarization (Spin) 321                    |
| 9.3.4 | Orbital Angular Momentum-dependent Devices 323                    |
| 9.4   | Phase Change Materials-Based Reconfigurable Devices 324           |
| 9.4.1 | Switchable Absorbers 324  |
| 9.4.2 | Thermochromic Smart Windows 327                                   |
| 9.5   | Mechanically Tunable Photonic Devices 329                         |
| 9.5.1 | Tunable Devices that Use Micro-electro-mechanical Systems 329     |
| 9.5.2 | Photonic Devices that Are Tuned Using Strain 331                  |
| 9.6   | Tunable Photonic Devices with Material Engineering 335            |
| 9.6.1 | Bandgap Engineering for Tunable Solid-state Devices 335           |
| 9.6.2 | Biomaterials for Tunable Biophotonic Devices 339                  |
| 9.7   | Electrically Tunable Photonic Devices 341                         |
|       | Acknowledgments 346   |
|       | References 346  |

Index 359