Preface

Optoelectronics and photonics are playing an essential role in many aspects of daily life, including information and communication technologies, environmental and green technologies, mechanical and chemical sensing, consumer electronics, and biomedicine. So far, the use of optical components in communication systems has been mainly limited to direct replacement of electrical cables by optical cables. With the continual increase in link bit rates, optical cables are now replacing electrical cables for shorter and shorter interconnect lengths. Optoelectronic and photonic technologies are becoming less costly and more integrated, and there is currently an opportunity for optics to move "inside the box" and change the interconnect topology at all levels.

Currently, most optoelectronic devices are fabricated as discrete components. This approach is based on serial (e.g., step-by-step) fabrication and packaging, and it makes optoelectronic technology drastically different compared to microelectronics, where the domination of parallel fabrication made possible ultra-large-scale integration with the price of individual devices below $\$10^{-8}$. Also, discrete assembly reduces the optoelectronic system reliability and decreases the manufacturing yield. Additional complications arise due to materials issues: in microelectronics the major material is elemental Si, while traditional semiconductor materials for optoelectronics are III–V alloys with much more complex technological requirements. Finally, optical waveguides and waveguide based devices are very bulky compared to electron devices; thus, the densities of electron devices in integrated circuits are many orders of magnitude greater compared to that in integrated optoelectronic systems.

Silicon photonics, where photonics devices are fabricated by using silicon or silicon compatible materials and where the manufacturing is based on the available microelectronics infrastructure, is emerging as the technology that can face all these challenges. The first volume of this series of books on silicon photonics appeared in 2004. We stated then that "This book is aimed at presenting the fascinating picture of the state of-the-art in silicon photonics and providing perspectives on what can be expected in the near future." Many of the visionary concepts reported there have been surpassed by reality. Silicon photonics is booming and growing at an incredible pace with many breakthroughs appearing day by day. Speed, integration density, active components, logic, nonlinear optics, etc., are all surpassed frontiers, which silicon photonics has continuously moved apart. At the beginning of the second decade of the new millennium, several devices enabled by silicon photonics are already on the market and new ones are emerging day by day.

Due to the broad nature and importance of the topic, as well as the rapid progress in this field, it is quite appropriate to publish this sequel to our first book on *Silicon Photonics* in the Springer Topics in Applied Physics Series. We envisaged this book as the second of a series of books on silicon photonics, i.e., we are willing to produce further books on this topic as the field develops.

The present book is focused on components and integration and opens with a Chapter by Yamada, which reviews the fundamental characteristics and basic applications of such waveguides. Some passive devices, such as branches and wavelength filters, and dynamic devices based on the thermo-optic effect or carrier plasma effect have been developed by using silicon photonic wire waveguides. These waveguides also offer an efficient media for nonlinear optical functions, such as wavelength conversion. Their optical polarization characteristics can be a serious obstacle to some practical applications, but such difficulties can be eliminated by using a monolithically integrated polarization diversity system. Chapter 2 by Xu explores further the problems associated with mode polarization in waveguides. This chapter reviews the characteristics of silicon-on-insulator ridge waveguide birefringence, as governed by the waveguide cross-section geometry, the cladding stress level, and cladding thickness. Typical stress levels in dielectric cladding films such as silicon dioxide and silicon nitride are such that the stress-induced birefringence is of comparable magnitude to the waveguide geometrical birefringence. Hence the total waveguide birefringence can be precisely controlled by counter balancing these two factors. The application of this technique for achieving polarization independence and polarization splitting in photonic components is described using passive and active tuning of the stress-induced birefringence. In Chapter 3 Roelkens and Van Thourhout elaborate on the use of diffraction gratings to achieve an efficient, compact, alignment-tolerant, polarization-independent, and broadband optical coupling between an optical fiber and optoelectronic components. An optical probe based on a diffraction grating integrated on the facet of a single-mode fiber is described that enables testing individual components in a silicon-on-insulator nanophotonic integrated circuit. Chapter 4 by Chang et al. tackles the difficult technical problem of providing on-chip light sources, which are a critical component for integrated silicon photonics but lag other photonic components in their level of development. Erbium is an optical dopant that can be employed as a viable means for on-chip light generation, which also has the advantage of being compatible with long-distance telecommunications transmission wavelengths. In this chapter, Er-doped silicon-rich silicon nitride and Er silicates are introduced as promising host materials for compact on-chip light sources. Germanium on silicon is an enabler of silicon photonics as well as high-speed CMOS electronics and recently germanium has played a significant role in integrating materials such as III–Vs on silicon. In Chapter 5 Ichikawa et al. describe an ultra-thin germanium buffer layer technology that has created entirely new fields for applications such as high-efficiency cost-effective tandem solar cells using silicon as the cell as well as the mechanical substrate. Such solar cells have successfully reproduced their ideal external quantum efficiency and prove that it is possible to successfully integrate silicon and GaAs.

The remaining four chapters focus on system integration. First, Scandurra in Chapter 6 describes possible applications of silicon photonics to the system-on-chip (SoC) domain. The higher and higher integration density is becoming such that many issues arise when a SoC has to be integrated, and electrical limits of interconnect wires are a limiting factor for performance that could be overcome through the use of the optical interconnect. Today, many semiconductor industries are investigating such a novel field and a number of projects are currently in progress to demonstrate the feasibility of such a revolutionary on-chip communication system relying on both CMOS technology and photonics. Chapter 7 develops this concept further. Liao et al. highlight a recent demonstration of a silicon photonic integrated chip that is capable of transmitting data at an aggregate rate of 200 Gb/s. It is based on wavelength division multiplexing where an array of eight high-speed silicon optical modulators is monolithically integrated with a demultiplexer and a multiplexer. This demonstration represents a key milestone on the way to fabricating terabit per second transceiver chips to meet future demands. In Chapter 8 Pinguet et al. describe the intimate relationship between process, devices, and system design by examining the development of Luxtera's CMOS Photonics technology. They address the challenges of integrating optoeletronic elements, including germanium photodiodes, in a commercial CMOS process without significantly affecting the electronics performance and the manufacturability of the process. A complete monolithically integrated wavelength division multiplexed 40-Gbps transceiver chip is fabricated as an example of the application of their complete technology platform and to demonstrate its capabilities for optoelectronic integration. Lastly, Fedeli et al. in Chapter 9 address different ways to merge photonics devices on an electronic circuit with microelectronics tools on large size wafers. The preferred route is above-integrated-circuit fabrication, with two options ruled by thermal constraints. The high-temperature option is based on wafer bonding on an optical silicon-on-insulator module, and the low-temperature option relies on the heterogeneous integration of III–V devices.

Finally, we dedicate this book to the memory of Ulrich Gösele (1949–2009), our colleague who recently and prematurely passed away. He was among the first who initiated the field by discovering the quantum nature of porous silicon and the possibility of its use in optoelectronics. Moreover, he pioneered the technique of wafer bonding, which is nowadays a common practice to realize hybrid devices.

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