Chapter 1

Introduction

Who are the technical parents of silicon photonics? Undoubtedly, the long-lasting technological success of silicon microelectronics, with their high integration levels on one side and the complete replacement of long-distance wire communication by optical fiber glass transmission on the other side, nurtured the demand to join optical waveguide transmission and reliable system integration on a silicon wafer scale. The pioneers (e.g., Soref and Lorenzo [1], Petermann [2], and Abstreiter [3]) proposed in the 1980s and the early 1990s waveguide and optoelectronic device integration on silicon although the indirect semiconductor silicon was considered as less favorable for optical functions. Indeed, the device and circuit development in microelectronics and optoelectronics started in different directions. Focus [4] on a basically simple device type (metal oxide semiconductor transistor) and on a few materials for the technology (semiconductor Si, dielectrics SiO_2, metal Al) made circuit design and integration in microelectronics easy. Progress in device and circuit performance was achieved by shrinkage of the device dimensions. This period of microelectronics, named "dimension scaling," lasted from the beginning of integrated circuit manufacturing (around the year 1975) to about the years 2000–2005. In optoelectronics, the performance was driven by sophisticated heterostructures based on III/V semiconductors that had excellent absorption, emission, and modulation properties for

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optical signals. At this time (around the year 2000) it was clear that telecommunication was governed at far distances (more than 10 km) by optical signal transmission and at near distances by electrical signals. Near distances meant distances within an enterprise (0.1–10 km), between racks (1–100 m), between boards (10–100 cm), between chips (1–10 cm), and on a chip (<1 cm). With increasing speed (3–10 GHz), the optical communication was predicted to be competitive also at near distances because electrical connections suffer from the resistance-capacitance (RC) limitation of the speed of interconnects. Irrespective of the speed of devices, the speed of electronic circuits is ultimately limited by the interconnect time delay that is inversely proportional to the RC product.

1.1 Si Photonics

Silicon (Si) photonics is the prime candidate to cover the application range at the border region between pure electrical and pure optical solutions. The essential property of planar Si waveguides is due to their high refractive index contrast when fabricated on silicon-on-insulator (SOI) substrates (Fig. 1.1). These commercially available SOI substrates are composed of a Si wafer with a thin (typically 1 μm) SiO_2 (insulator) layer and an even thinner (typically 0.2–0.4 μm) Si layer on top.

The waveguide formation along a lithographically defined pattern uses etching (mainly dry etching by a reactive gas). Ridge waveguides show in cross section a ridge (Fig. 1.1, left side) on a partially etched Si top layer surrounding. The waveguide of small dimensions is called a nanowire if the complete Si layer outside the waveguide is etched (Fig. 1.1, right side). The waveguide core from a semiconductor like Si has a high refractive index n (about 3.5). The cladding from glass has a much lower refractive index, of about 1.5. Figure 1.1 does not show the top cover from glass that is used for circuit protection. Table 1.1 compares the index contrast $\Delta n/n$ for different waveguide materials.

The refractive index contrast of 60% from SOI waveguides is much higher than in fiberglass (typically 1%) but also substantially higher than in insulator (SiO_2/SiN) or semiconductor heterostructure (e.g., SiGe/Si) waveguides (typically 10%). This high index contrast allows single-mode waveguides of small dimensions, high curvature of waveguides lines, and high packing density. The SOI waveguide preparation with standard technologies of Si microelectronics guarantees high yield and reproducibility, favors cost-effective fabrication, and offers monolithic integration with electronic supply and readout circuits. The availability of the silicon foundry service [5] gives manifold options for fables activities in design, characterization, and system applications. The silicon waveguide is absorbing in the visible spectral range but gets transparent in the infrared (wavelengths $\lambda > 1.2$ µm). Especially, the telecommunication wavelength regimes around 1.3 µm and 1.55 µm are compatible with Si photonics [6, 7]. However, the available wavelength regime in low-doped Si is much broader, at least up to 8 µm. Impurities like oxygen or carbon may disturb the transparency in wavelength bands above 8 µm [8].

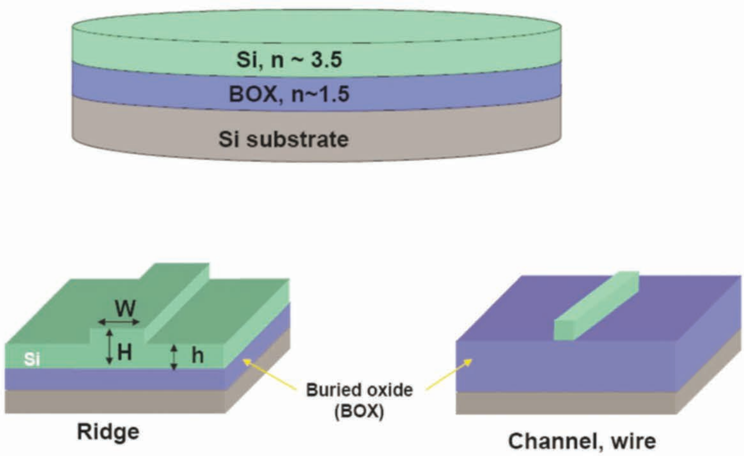

Figure 1.1 Silicon-on-insulator (SOI) waveguide structure. Upper part: Starting substrate consisting of a Si substrate covered with an oxide layer (buried oxide [BOX]) and a single crystalline Si top layer. After selective etching, a waveguide with a width *W* and a height *H* is formed (lower part). Partial etching of the top Si layer down to a thickness *h* creates a ridge waveguide (left side), and complete etching forms a wire structure. A protective oxide layer (not shown here) covers the waveguide structure.

Table 1.1 Refractive index contrast of typical waveguide structures

Material	n	$\Delta n/n$
Glass fiber	1.5	1%
SiO_2/SiN	1.5	10%
Semiconductor heterostructure	3.5	10%
SOI	3.5	60%

Note: Given is the refractive index n of the core material and the relative change $\Delta n/n$ between the core and the cladding. The high index contrast of SOI waveguides allows dense packing of photonic structures.

1.2 Si-Based Photonics

Active devices in photonics for emission, detection, and absorption modulation need strong light-matter interaction in the selected infrared transmission regime. This needs a different material for the active devices that should provide a strong light-matter interaction at the selected wavelength regime but with a good transparency of the Si waveguides.

As favorite solutions for these contrary requests for waveguide and active device emerged heterostructure semiconductor waveguide/device combinations. The semiconductor for the device needs to be chosen with a bandgap E_g lower than that of Si (E_{gSi} = 1.12 eV at room temperature). This provides a wavelength regime

$$1.24\ \mu\text{m}/E_g\ (\text{eV}) < \lambda > 1.1\ \mu\text{m} \tag{1.1}$$

that fulfils both high transparency of the Si waveguide and strong light-matter interaction for small active devices.

Silicon-Based Photonics as the title of this book refers to the fact that a silicon-based heterostructure is essential to fulfilling all the basic photonic system functions. The heterostructures are chosen either from a group III/V semiconductor on Si or preferably from a group IV semiconductor on Si. In the latter case, "group IV photonics" is an alternative term for this flourishing research topic.

The envisaged application spectrum of Si photonics started with telecommunication [9] networks in metro areas and then expanded to data center and cloud service [10], to on-chip clock distribution, and to links between cores of multicore processors and links between core and memories. The last-mentioned application spectra address the bottleneck in on-chip communication in ultra-large-scale integrated circuits. Figure 1.2 shows the principally simple arrangement of the optical path on the example of the clock distribution. The laser light couples with the chip from an external laser via a fixed monomode fiberglass mounting. The use of an external laser has the advantages that available high-performance lasers may be used, that power for the laser operation is distributed outside the thermally stressed electronic chip, and that this external clock laser may be used for several chips. The light is modulated either externally or internally, and then it is distributed via waveguides into different subchip areas. In Fig. 1.2, an internal modulator varies the laser light intensity that is distributed to different chip regions by the waveguide lines split up from the input line. Similar schemes provide fast access to memory contents for processor operation. Germanium photodetectors (d) convert the optical signal into an electrical signal at the waveguide line ends. The electrical signal is then distributed around within the small chip regions without the power and speed problems of the electrical clock distribution on large chip areas. Although the scheme is rather simple, the realization on an already complex electronic chip needs to overcome integration process and packaging issues. The majority of system investigations [11] use the common telecom wavelength of 1.3–1.6 μm, but years ago Soref [12] had already backed the use of the broad available wavelength spectrum from near infrared to mid-infrared. This broad spectrum not only delivers an incredible number of frequency slots for communication but also offers new possibilities for imaging and sensing in biology and chemistry [9, 11, 13]. The wavelength regime between 1.5 μm and 3 μm spans a frequency regime from 200 THz to 100 THz, a difference that is a thousand times the frequency span now used or planned for mobile communication or automotive radar. Interference of two lasers with slightly different wavelengths provides a signal the frequency of which may be chosen from the millimeter wavelength to the terahertz range, depending on the frequency difference [14]. Compact chip-sized solutions based on silicon photonics will certainly push the applications in this area between microwave and optics.

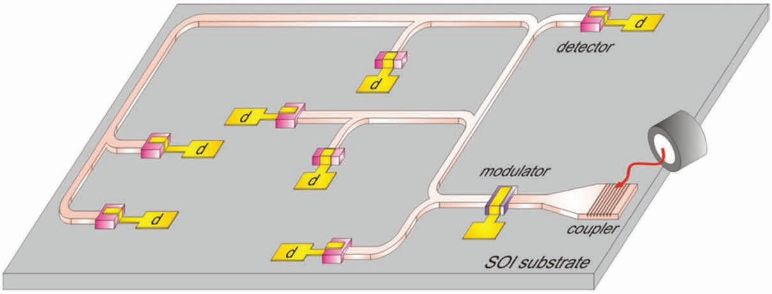

Figure 1.2 Scheme of an optical clock frequency distribution. Laser light from an external source is coupled in the chip waveguide via a grating coupler structure (from the right side).

1.3 Book Content

The book focuses on the integration of heterostructure devices with Si photonics, which has resulted in the recent advances of a photonics branch that is named "Si-based photonics." Some material and device phenomena appear in heterostructures not present in Si stand-alone technology. The most prominent of these phenomena are lattice mismatch, dislocation generation, high elastic strain, and metastable alloys. Strong progress in material science now allows the utilization of the effects from strain and metastability. These effects are also interesting in microelectronics for performance improvements, but in Si-based photonics, they are necessary for full functionality.

The reader will find basics about band structure and optical properties in Chapter 2. A concise treatment of classical Si-photonics topics is given in Chapters 3–7, with explanations of waveguides, resonators, couplers, photonic crystal, and slow light. These chapters are mainly for readers who are interested in the topic because of its increasing importance in different fields. Chapters 8–12 cover different device structures for light emission, detection, modulation, extension of the wavelength beyond 1.6 μm, and lasing. An outlook for the next challenges is given in Chapter 13.

With the given mix of basics and front-end research, the authors hope to meet the demands of a broad audience, from students and researchers to engineers who are already working in this field or who intend to start studies because of the widespread potential in technology and application.

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