Chapter 13

Future Challenges

Silicon photonics is now on the verge of entering the mass market from a niche one. Optimistic assessments [1] of the market forecast a large annual growth rate (more than 40%) up to a volume of around 0.5 billion US dollars at the chip level and almost 4 billion US dollars at the transceiver level in 2025. More than 80% of this volume is assigned to optical intra-data-center connects. Indeed, data centers could be the market drivers for silicon photonics, with their need for low cost per data lane, low power consumption per data lane, high reliability, and high fabrication yield. Other market segments with high commercialization potential are telecommunication (metropolitan areas) and medical equipment. Silicon photonics delivers key components to aeronautics/aerospace, sensors, autonomous traffic, and high-performance computing. The tipping point for silicon-based photonics was obtained by adding Ge-on-Si photodetectors to CMOS technology on SOI substrates. This allowed complete monolithic integration of the receiver part, but silicon photonics is at a lower level of maturity than the electronics industry, and there are still challenges to overcome. For these challenges, technical breakthroughs will be necessary in laser source performance, in small size and small power modulators, and in monolithic integration techniques.

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13.1 Group IV Laser Performance

The largest principal challenge concerns group IV lasers and efficient light sources (light-emitting diode [LED]), which are monolithically integrated on silicon. Basic research on this topic within the last decade has given two very remarkable results.

- Optical gain and electrically induced laser emission from band-to-band transitions are possible even with indirect semiconductors if the energetic distance between the indirect and direct bandgaps is small. Electrically stimulated laser emission from slightly strained and unstrained Ge on Si (120–136 meV energy difference between direct and indirect transitions) confirmed room temperature operation [2, 3], although with high threshold currents.
- Direct bandgaps with group IV semiconductors are possible with highly tensile strained Ge (biaxial tensile strain of about 2% and uniaxial strain of more than 4%) or GeSn alloys (Sn amount of more than 7%). Both structures are only metastable at the thicknesses needed for optical devices. Optically stimulated emission [4] is demonstrated at low temperatures. Both mentioned directions of material modification toward the direct optical character of group IV semiconductors shift the emission wavelengths more in the infrared (>1.6 μm) region compared to Ge.

The rather slow progress of group IV laser device realization is because of quality problems in layer preparation and device processing of metastable materials [5]. Narrow process windows are necessary to avoid strain relaxation of highly strained structures from misfit dislocations and to avoid phase separation from homogenous GeSn alloys containing more than 1% Sn. The main measure of the material quality of a laser structure is given by the nonradiative recombination rate. Nonradiative recombination via midgap defect levels (contaminants, dislocations, vacancies, and interstitials) competes with the radiative recombination of the laser. The group IV laser question motivated a broad, basic investigation of properties and stability of metastable materials, which is interesting in itself and for its high application potential. Sophisticated defect characterization methods [6], like deep-level transient spectroscopy, polarized Raman spectroscopy [7], and atom probe tomography [8]; surface studies of the phase separation [9] at the limit of metastability; and investigations of the strain relaxation mechanism and its effects on Sn incorporation [10], gave valuable insight into the complex interplay of different growth parameters. Insight into the growth process resulted in suggestions of virtual higher-quality substrates [11]. A high density of misfit dislocations (typical dislocation spacing of 10 nm) at the interface to the Si substrate is necessary for elastic strain relaxation. However, growth kinetics allow the densities of the undesired threading dislocations (TDs) to vary by several orders of magnitude. In Ref. [11], they modeled the reduction of TD density in heteroepitaxial coalesced layers in terms of the bending of TDs induced by image forces at nonplanar selective epitaxial growth surfaces before the coalescence. The reduction of TD density was quantitatively verified for Ge layers on (001) Si with line-and-space SiO_2 masks. GeSn layers (Sn contents from 5% to 15%) on virtual Ge substrates have a lattice mismatch of about 0.7% to 2.2%. The strain relaxation in such metastable GeSn is investigated under low-temperature growth conditions for different amounts of Sn (up to 5% [12], up to 13% [13], and up to 22% [14]). Alternative growth strategies use lateral growth of GeSn [15] directly on Si oriented in the (111) direction. GeSn layers show good thermal stabilities at annealing temperatures of up to 500°C [15]. A Fabry–Perot-type GeSn waveguide with 12.6% Sn demonstrated lasing with an optical pumping threshold density of 325 kW cm^{-2} at 20 K [4], and a couple of more successful demonstrations have since followed. However, the lasing threshold of those GeSn lasers was still too high to be practical, possibly owing to faster-than-desired nonradiative recombination processes. On the other hand, the application of large mechanical tensile strain [16] can also address the challenge of the indirect bandgap in Ge by fundamentally altering the band structure; the small energy difference between the Γ and L conduction valleys can be reduced even further with tensile strain, resulting in an increased material gain. With regard to practical realization, several innovative platforms for inducing large mechanical strain have been experimentally demonstrated [17]. The status of laser development is explained on the well-documented example of a uniaxially strained Ge microbridge [16] that is in stiction with the underlying oxide layer. The close contact improves the thermal resistance, which is the thermal bottleneck in suspended microbridges. Multimode lasing from pulsed optical pumping was observed up to a temperature of 83 K. A pair of distributed Bragg reflectors provided the light amplification in the gain medium (strained Ge bridge). The onset of lasing was determined by the visibility of narrow multimode peaks and by the superlinear increase of intensity. This usually chosen procedure in low-power emitters simplifies the role of bleaching before the onset of net gain. The losses caused mainly by free carrier absorption are partly overcome by the gain [18], leading to a net absorption bleaching below the laser onset. In strained Ge, the intervalence band absorption from free holes is assumed to be larger as the free electron contribution because of hole transitions between the valence sub-band's light/heavy hole and spin off hole.

The low-dimensional structure may be designed by means of lithography, as in the given example, which is a technologically advanced method. However, bottom-up nanowires, where the constituent atoms assemble to form a larger structure [19], will be under focus in future work. Low-dimensional core/shell nanowire structures demonstrated good optical emission and absorption properties [20]. Design works focus on GeSnSi/GeSn quantum wells [21] for proper carrier confinement in diode structures or transistor laser structures [22].

13.2 Monolithic Integration Issues

A less spectacular but essential challenge is given by the need for integration of different photonic devices and for the integration of photonic integrated circuits with conventional microelectronic circuits [23]. Simply speaking, the use of a common substrate material is only one important prerequisite of monolithic integration. Also, the different device structures and material properties have to be similar enough [24] that only a few additional fabrication steps have to be added. Let us give an example from microelectronics to outline the importance of these aspects. A combination of high-transconductance bipolar circuits with complementary metal-oxide-semiconductor (CMOS) logic—called BICMOS—offers advantages for highly desirable system integration of digital processing and input/output units. Both approved technologies utilize silicon substrates and silicon manufacturing. The market share of BICMOS is in the lower-percentage regime despite minimal technical problems because of necessary trade-offs in device optimization. Si-based photonics use diode-type devices for the detection, modulation, and emission of light [25]. Detection is optimized for low-power zero-bias operation with a low-doped absorption region; the corresponding absorption wavelength is in the energy level above the bandgap. Absorption modulators are working with the same diode structure [26], which is switched between two reverse-voltage values for signal modulation. However, the modulation wavelength corresponds to an energy slightly below the bandgap energy. LED and laser are operated under forward bias, and the emission energy is above the bandgap energy. In principle, the simple diode structure is again usable. However, optimization for good carrier confinement tends toward low-dimensional structures within the emission region [27]. Indeed, monolithic photonic integration addresses research topics [28] like system architecture, device physics, fabrication techniques, and material synthesis. The chosen wavelength regime influences essentially the system architecture. For the telecommunication wavelength regime from 1.3 μm to 1.7 μm, the principal scheme will be dominated by external light sources that couple in light via fiber connections into the on-chip photonic waveguide network. Actually, that is the existing procedure in laboratory work, which allows the use of the sophisticated discrete group III–V lasers and the highly developed telecommunication measurement equipment. Substantial improvements are needed for self-aligned mounting and housing techniques, which are the bottleneck for large-scale use. Ideally, different optical input/output configurations are available, similar to the situation with electrical power and signals. On a chip, the silicon waveguide network is supported by Ge-based detectors and modulators. Ge-based detectors are already accepted in manufacturing [23]. Ge-based absorption modulators are assumed to outperform the interference modulators with respect to low power consumption [24]. Integrated light sources will be in our opinion the exception in this wavelength regime, although excellent research results from monolithic and hybrid integrated group III–V compounds were reported and although room temperature operation of Si-based Ge lasers with electrical stimulation was demonstrated. Complex integration schemes for group III–V devices [29, 30] and high threshold currents for Ge-on-Si lasers are the reasons for this assessment. We predict a different situation for the wavelength region of 2–4 μm, with a high potential for the integration of light sources based on GeSn alloys or strained Ge [31]. At first glance, this assessment may astonish because neither room temperature operation nor electrical laser stimulation was demonstrated but both were expected due to the conversion of the indirect semiconductor Ge into a direct one by applying tensile elastic strain or alloying with Sn. In both cases the material is only metastable but strong progress is seen in the structural stability and preparation of such material classes [5]. In the future, the electrical properties [32] have to be given higher priority to understand the device behavior. A p-type background was detected by investigations of Zaima and group [33], which could be a hint for vacancy concentrations (more than $10^{16}/cm^2$) much higher than usual in Si. Differential reflectivity spectroscopy [34] emerged as a versatile method to judge the recombination properties of carriers in as-grown layers. Common structural, optical, and electrical investigations push the search for higher performance of laser devices from metastable materials.

Some research fields, now of high scientific interest, will rapidly gain more practical importance with device scaling in integrated Si-based photonic circuits. These fields include plasmonics [35, 36], photonic crystals [37], nonlinear effects [38, 39], and millimeter-wave generation [40, 41] from light mixing.

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