Silicon Photonics

Despite the fact that silicon photonics has its origins in the late 1980s and early 1990s (e.g., [1]–[3]), only in the last three years has the field developed significant momentum, so much so that we can expect an explosion of applications and technical developments in the next decade. Most promising are applications in the fields of optical interconnects, low-cost telecommunications, and optical sensors, perhaps including disposable biosensors. These applications have the common driving requirement of low cost. This requirement is likely to be satisfied in part by the leveraging of vast silicon microelectronics infrastructure, and hence, the involvement of semiconductor manufacturers is the key to advancement of low-cost silicon photonics. Furthermore, it underlines the likelihood that technolo-

***Bahram Jalali,
Mario Paniccia,
and Graham Reed***

gy success will be based on a silicon platform, since this is simply the most well-understood and most studied material in modern technological development. Consequently, prior to discussing the advances in generic silicon photonic devices in detail, it is instructive to consider these three potential application areas with the aim of putting the technological developments discussed later in this article into context.

In addition to cost, a major driver for optical interconnects is increased bandwidth in a variety of application areas, including rack-to-rack (1–100 m), board-to-board (~50–100 cm), chip-to-chip (~1–50 cm) and even intrachip applications. This is because, even at small transmission distances, copper interconnects become bandwidths limited above 10 GHz due to frequency-dependent losses, such as skin effect and dielectric losses from the printed circuit

Bahram Jalali (jalali@ucla.edu) is with UCLA, Los Angeles, CA, USA. Mario Paniccia is with Intel Corp., Santa Clara, CA, USA. Graham Reed is with University of Surrey, Surrey, U.K.

board (PCB) substrate material. Furthermore, the situation is expected to be exacerbated above 10 GHz by reflections and crosstalk effects [4, p. 115]. For intrachip applications, the limitations are also associated with the dimensional scaling of copper interconnects and the RC time constant associated with the shrinking dimensions. Hence, there is an industry-wide desire to reduce resistivity and the dielectric constant within the integrated circuit. These issues are compounded by the difficulty of realizing a suitable optical architecture for intrachip applications, although a range of architectures has been discussed (e.g., [5], [6]).

Consequently, while intrachip interconnects remain the biggest challenge, the other applications are currently regarded as more viable, with a view generally taken that copper interconnects will probably become viable for bandwidths up to 20 GHz [7] as designers find innovative ways to extend the serviceable life of such components. However, intrachip and other short-reach optical interconnects can be regarded somewhat differently.

Silicon photonics technology may first find applications in fiber-optic communication. Applications are likely to be focused in the low-cost, moderate performance parts of the network. These include areas in the data center and enterprise as well as emerging optical access networks. One notable emerging market is fiber to the premises (FTTP) in the United States or the equivalent fiber to the home (FTTH) in Europe. This emerging market is still subject to change in terms of accepted device and system protocols, although it is clear that the demand is set to be extremely high and the market is to be large. Since the nature of the market is high volume and low cost, it is likely that low-cost options will be essential, and hence, a mass-production technology such as silicon photonics, while immature, could have significant impact in this area.

Silicon photonics could also play a key role in sensing applications, notably biosensing. The mass production element of a silicon photonics sensor is clearly an attribute that would be attractive both to manufacturers and users of the technology. However, sensor applications are somewhat different from the areas discussed above, due to the plethora of very-low-cost passive optical technologies that compete in this space. One likely application area for silicon-based systems is the so-called lab-on-a-chip in which both reaction and analysis take place in a single device. In the future, this could be extended to include electronic intelligence, a natural benefit to the sensor application area from continuing advances in the telecom and optical interconnect areas. Jokerst et al. [9] have considered the integrated biosensor application areas in a host of material technologies. They see silicon as a key material in this field but note that the integration and miniaturization issues are the secrets to the success. This is not surprising and is an issue that is strategic to all application areas. Therefore, the realization of low-cost intelligent sensors in silicon

photonics technology is likely to follow the evolution of other application areas. Nevertheless, in the short term, components of such systems will continue to evolve, notably miniaturization of the sensing head itself.

The cost reduction can also benefit analog optical links and other microwave photonics systems. One of the barriers against proliferation of microwave photonics has been the high cost of components that meet the demanding requirements of analog applications. Driven by the large dynamic range in microwave photonic systems, components must exhibit low noise, high linearity, and high saturation power. Although silicon photonics has enjoyed tremendous progress in the past five years, it is still a nascent technology. In some cases, such as silicon photodetectors (PDs), research has a longer history, and the performance of these devices is approaching their III-V counterparts. In other cases such as modulator technology, it is less mature, and in the case of the laser, an electrically pumped device is yet to be demonstrated. The benchmark for silicon photonic researchers has been III-V devices used in digital communication. Consequently, even in the case of PDs, issues unique to microwave photonics, such as linearity and saturation power, have not been properly investigated. To be sure, as device performance continues to improve, more attention to analog performance will undoubtedly be called for. In the meantime, passive silicon photonic devices may find applications in wide-band microwave signal processing. An example of the micro ring resonator (RR), or micro-RR, is shown in Figure 1. These structures have passbands separated by the free spectral range of the filter, the latter being dependent of the size of the ring. A microwave signal that has been modulated onto an optical carrier can be filtered with such devices. Current fabrication technology makes it possible to realize optical quality factors of 10^5 – 10^6 , a range that corresponds to passbands of 2–20 GHz at telecommunication wavelengths. Micro-RR can also form cavities for silicon Raman lasers, as discussed later in this article.

Light Emission

The creation of silicon light emitters and lasers has often been considered as the holy grail of silicon photonics because of its potential payoff as well as the significant challenge posed by nature. The challenge has to do with

Figure 1. A micro-RR.

bulk crystalline silicon being an indirect bandgap material, which means that the upper and the lower electronic states (conduction and valence bands) do not have the same value of momentum (see Figure 2). Because the photon of interest has negligible momentum compared to that of the electron, the electron-hole recombination needs to be mediated by emitting or absorbing a phonon to conserve momentum. In the terminology of quantum mechanics, this is a second-order process, which implies that, although not forbidden, the probability of occurrence is extremely low. Such radiative recombination events are rare, as characterized by a very long lifetime on the order of 1 s. On the other hand, experimentally

measured carrier lifetime in silicon is in the millisecond to microsecond range, depending on the impurity or defect concentration. This suggests that radiative processes in silicon are insignificant, and experimentally observed recombination occurs through impurities or defects. Such processes are nonradiative, where the energy is eventually dissipated as heat. A useful metric is the electron-to-photon conversion efficiency given by the ratio of nonradiative lifetime to total lifetime. This computes to an efficiency of 10^{-3} – 10^{-6} for bulk silicon. In contrast, in a direct bandgap III-V semiconductor, where momentum is readily conserved during recombination, the radiative lifetime rate is orders of magnitude higher than in silicon. The radiative process is so fast that, in a good-quality crystal, defect or impurity-assisted nonradiative processes cannot compete with it. This leads to a conversion efficiency that is close to unity for material such as gallium arsenide (GaAs).

While there have been numerous approaches aimed at overcoming or circumventing this limitation, most belong to one of three main categories:

- overcoming the indirect band structure by using spatial confinement of the electron
- introduction of rare earth impurities as optically active dopants
- the use of Raman scattering to achieve optical gain.

In the following, we briefly review the salient features of each approach, with the understanding that the length limitation

of this article prevents us from citing most contributions to the field. A more comprehensive review can be found in [10].

Quantum Confinement of Electrons

This concept exploits the fact that space and momentum variables comprise a Fourier transform pair, similar to the relationship between the frequency and time scale of microwave signals. When a conduction electron is free to roam the silicon crystal, its momentum is well defined. Spatial confinement of the electron within a silicon nanocrystal (NC) creates an ambiguity in the value of its momentum, a phenomenon that is referred to as the Heisenberg uncertainty principle. When the amount of this momentum ambiguity approaches the initial momentum mismatch, momentum conservation is relaxed, and the efficiency of light emission increases. A thin film of silica (SiO_2) impregnated silicon NCs is the most common approach for confinement of electrons. In these structures, the emission wavelength and efficiency depend on the size of silicon NCs, which in turn is highly dependent on the processing conditions. A typical spectrum is shown in Figure 3 (dotted curve) [11]. The emission wavelength is below the band edge of silicon, implying that the light

Figure 2. In a direct bandgap material, e.g. GaAs, electrons in the conduction band recombine with the holes in the valence band, transferring their energies to emitted photons. In an indirect bandgap material, e.g., silicon, the recombination is mediated by absorption or emission of a phonon.

Figure 3. Emission spectrum of silicon NCs embedded in a silica film (dotted); of Er in a silica film (dashed); and of Er in presence of NCs, both embedded in a silica film (solid) [11].

produced cannot propagate in a silicon waveguide since bulk silicon is opaque at these wavelengths. Another limitation is that when the NC-embedded SiO₂ is used as an optical waveguide, the propagation losses will be high due to light scattering from the NCs, which have a much higher refractive index (3.5) compared to the SiO₂ host (1.5). This complicates the use of this technology in planar lightwave circuits. Furthermore, questions linger regarding the reproducibility of material in which optical gain has been observed.

Erbium Doping

Erbium (Er)-doped fiber amplifiers and lasers have become successful commercial technologies to the extent that such amplifiers are standard building blocks of fiber-optic networks. Rendering silicon optically active by doping it with Er proved to be unsuccessful due to the limited solid solubility and the competition from nonradiative processes, including back transfer of energy from Er to silicon. Simply stated, it was found that silicon is not a good host for Er ions. Since an optical fiber is made from silica, a common material in silicon microelectronics, Er-doped silica waveguides have been the subject of extensive research. A typical luminescence spectrum is shown in Figure 3 (dashed line), exhibiting emission centered in the 1.55- μ m wavelength band (C-band) [11]. Corresponding to the low attenuation window of optical fibers, this is one of the most important wavelength bands for optical communication. In addition, silicon is transparent in this wavelength range; hence, such sources can be used along with silicon waveguide modulators if the efficient coupling of light from silica into silicon can be achieved.

Interestingly, if Er is introduced in a silica waveguide that also contains NCs of silicon, then the emission of Er is enhanced. This is shown by the solid line in Figure 3 and is attributed to the sensitizing action of silicon NCs [11]. Absorbing the incident photon and thus becoming excited, an NC that is in proximity of an Er ion transfers its energy to the ion, which will then return to its ground state by emitting a photon. This fortuitous phenomenon holds promise for creating silicon-based light emitters and amplifiers that operate in the 1.55- μ m wavelength band. In Figure 3, the satellite peak at 1.1 μ m is due to other transitions in the Er atom.

An apparent disadvantage of silica as a host for Er is that, being an insulator, it cannot be electrically pumped using an integrated diode. An innovative method being used to address this is by embedding the Er and NC containing silica within a metal oxide semiconductor (MOS) junction, where silica comprises the oxide region [11]. At sufficiently large voltage, electrons tunnel through the oxide and excite the NC. Silicon light-emitting diodes (LEDs) have been demonstrated with this technique; however, lasing has not been achieved. The device reliability issue, caused by the presence of hot electrons, has been a concern, although improvements

are expected with further design refinement. Two important barriers exist on the path toward an injection-type laser. The first is the free carrier losses in silicon NCs, a phenomenon that needs to be studied further. Second, it is not clear if high enough current densities, sufficient for lasing, can be achieved in a MOS diode.

Raman Scattering

The use of Raman scattering to overcome the indirect band structure of silicon was proposed in 2002 as an alternative to the approaches described above [12]. The advantage of this technique is the ability to use pure silicon without the need for NCs or Er doping; therefore, it is fully compatible with silicon microelectronics manufacturing. The traditional limitation of the Raman approach is that it cannot be electrically excited and requires an off-chip pump. On the other hand, given the fact that the foremost problem facing the very-large-scale integration (VLSI) chips is power dissipation, having the laser off-chip may be an advantage, since diode lasers and their driving circuitry are the main sources of power dissipation in an optical transmitter. Another advantage of Raman devices is that although they are optically pumped, they can be modulated directly using an integrated diode. The mechanism of modulation here is similar to those of silicon optical modulators wherein injected carriers modulate the optical absorption of the silicon. Raman scattering in semiconductors is a purely quantum mechanical effect, and its explanation is beyond the scope of this article. Fortunately, there exists a much simpler macroscopic model that provides an intuitive picture of Raman scattering. In the spontaneous scattering, thermal vibrations of lattice at frequency ω_v (15.6 THz in silicon) produce a sinusoidal modulation of the optical susceptibility. The incident pump field induces an electric polarization that is given by the product of the susceptibility and the incident field. The beating of the incident field oscillation (ω_p) with oscillation of the susceptibility (ω_v) produces induced polarizations at the sum frequency, $\omega_p + \omega_v$ (which is an anti-Stokes frequency), and at the difference frequency $\omega_p - \omega_v$ (a Stokes frequency). In the stimulated scattering that is responsible for amplification and lasing, the interaction of the pump and Stokes waves produces a driving force for atomic vibrations that enhances the transfer of power from the pump to the Stokes wave. In an amplifier, an incident beam is amplified at the expense of the pump beam. In a laser, the spontaneously generated Stokes photons are resonantly amplified inside a cavity and produce a strong beam of light at the Stokes wavelength when the gain equals or exceeds the round-trip loss.

The Raman approach to silicon photonics has been extremely successful since its inception. It has recently produced the first silicon lasers and optical amplifiers [13]–[15]. The main contribution of the Raman approach in the near term will be optical amplification.

Owing to the high index contrast between a silicon waveguide and its surrounding medium (air or SiO_2), any finite surface roughness results in significant scattering losses. Consequently, silicon waveguides are characterized by losses in the range of 0.1–3 dB/cm depending on dimensions and processing conditions. These, along with the fiber-to-waveguide coupling losses, have limited the extent of on-chip integration that can be achieved. With the ability to amplify the light, many optical devices could be cascaded, bringing the field closer to the vision of photonics circuits that boast a respectable level of complexity.

Silicon-Based PDs and Next-Generation Devices

Photodetectors

Silicon-based PDs are commonly used for applications that operate in the visible spectrum (i.e., 0.4–0.7 μm) due to their near-perfect efficiency at these visible wavelengths. However, most communication wavelengths are centered in the near-infrared wavelengths of 1.31 and 1.55 μm , a region where silicon is a poor detector. Figure 4 shows the experimentally determined absorption coefficients for various bulk materi-

als [16], [17]. Since silicon doesn't absorb well in the near-IR range (i.e., 1.1–1.6 μm), typically indium GaAs (InGaAs)-based devices are preferred for communication applications. To improve the performance of silicon-based detectors, the most common approach is to introduce germanium (Ge) to the material system to reduce the bandgap. The effect on the absorption coefficient and penetration depth, defined as the distance that light travels before the intensity falls to 36% ($1/e$), is also shown in Figure 4. Note that the data in Figure 4 represents unstrained bulk material with no voltage applied. By introducing strain or electrical bias, it is possible to extend the curves to longer wavelengths. This is very important for detection at 1.550 μm , where even a pure Ge film with the appropriate strain or bias could potentially be shifted to reduce the penetration depth to acceptable values.

There are various types of PDs, including p-i-n-based devices and Schottky or metal-semiconductor-metal (MSM)-based detectors [17]. Both offer different performance tradeoffs and processing requirements that, depending on the application, will determine the type of device that should be used. MSM-based devices, because of the metallization patterning, offer a more planar-based design, which could lead to higher yield. In addition, MSM-based devices, due to the metal finger spacing being smaller than for a vertical p-i-n device, allows for much shorter transit times and thus much higher bandwidths. However, the metal fingers of the MSM device often occupy 25–50% of the surface area, which leads to lower effective responsivity.

There are three key parameters for Ge on Si PDs. They are the tradeoffs between dark current, bandwidth, and responsivity [18]–[20].

Dark Current

Silicon, due to its pure crystalline material quality and excellent passivation properties, results in high-quality, very-low-dark-current PD devices. However, the introduction of Ge with silicon will add some significant complications. Since the lattice constant of Ge is 4% larger than that of Si, this lattice mismatch will introduce strain in the Ge film when it is grown epitaxially on Si. This strain, when relaxed, will lead to misfit dislocations that in turn lead to threading dislocations (TDD) and will degrade device performance.

This typically presents itself as dark current (noise) in the PD. Figure 5 is a schematic of how lattice mismatch between Ge and Si leads to misfit dislocations. In addition to strain, there exists no good passivation material, which further adds to the likelihood of increased dark current. Significant processing techniques combining temperature

Figure 4. Absorption coefficient and penetration depth of various bulk materials as a function of wavelength. The green lines mark typical wavelengths for telecommunications windows of 1.310 and 1.550 μm .

Figure 5. Diagram showing lattice mismatch of 4% between Si and Ge leads to misfit dislocations that degrade detector performance.

anneals and passivation processes will be needed to produce high-quality, low-dark-current devices.

Bandwidth

The bandwidth of a PD can be limited by the transit time required for the photocarriers to travel from the junction region to the contacts or the RC time constant of the device. Typical PDs do not have a deep extending electric field, so the carriers will slowly diffuse up, causing a significant low-frequency component to the response. Key to detector design is to eliminate the slow diffusion current by using very thin films that can be fully depleted to prevent the generation of diffusion current or effectively reducing the diffusion length of minority carriers. This is often done by using a second (and deeper) p-n junction to pull out the slow carriers before they can reach the junction or by introducing recombination sites near the depletion region to eliminate the slow carriers. The collection of the much faster drift current is then optimized by keeping the depletion width as thin as possible, as determined by the penetration depth. If the penetration depth can be kept below 2 μm , the transit time alone could support a bandwidth of 10 Gb/s or higher [21].

Responsivity

The responsivity is the ratio of collected photocurrent to the optical power incident on the detector. Responsivities for commercial III-V PDs are typically close to 0.8 to 0.95 A/W. Responsivity typically increases as the absorption coefficient increases. Ge-based PDs can have responsivities as high as III-V PDs but usually at the expense of bandwidth and dark current performance.

For normal incidence PDs, the electrical and optical parameters are coupled. Maximizing the absorption by making the layers thicker results in a reduction in bandwidth due to transit time needed to travel through the absorption material. If one produces a waveguide-based PD (see Figure 6), one can minimize the transit time but at the expense of lengthening the detector to increase the responsivity. This inherently results in a larger capacitance device, which must be carefully optimized for bandwidth. However, the big advantage of the waveguide-based approach is the fact that it is a planar device, so it is very suitable for integration with other photonic devices in a silicon-on-insulator (SOI) platform.

Issues Related to Integration of Ge with Silicon

The amount of Ge required for efficient photodetection is dependent on the wavelength. If detection at 1.31 or 1.55 μm is desired, then very high (>50%) Ge concentrations are needed. This concentration is significantly higher than those found in SiGe heterojunction bipolar transistors (HBTs), and as a result, new integration issues have to be overcome within the fab.

Chemical stability will be an issue for films with high Ge concentration. Since Ge does not form a stable

oxide like silicon when exposed to oxidizing chemicals, the SiGe films tend to be susceptible to corrosion during wafer cleaning and polishing. Thus, special processing modules will need to be developed to accommodate for the difference and maintain the integrity of the SiGe films.

Furthermore, since most useful strained $\text{Si}_{1-x}\text{Ge}_x$ films are metastable with respect to defect formation, exposing the wafer to high temperatures after growth can be problematic. Certainly, long times at temperatures above the growth temperature (550–650 $^{\circ}\text{C}$) should be avoided. Higher temperatures might be possible for short times, such as in rapid thermal annealing, but this is conditional on the film quality. Amorphous, polycrystalline, or relaxed single-crystal films will not have this temperature limitation.

A survey of the latest literature highlights the fact that pushing performance in one parameter comes at the expense of lower performance of the others. Jutzi et al. have shown very high B/W in excess of 39 GHz but with poor responsivity [20]. High responsivity can be achieved, but at the expense of bandwidth. For SiGe detectors to be competitive, one must achieve bandwidths of 10 GHz or higher, a responsivity near 0.5 A/W, and dark current ideally below ~ 100 nA. Achieving all these performance requirements simultaneously will be a key challenge for the commercial viability of SiGe-based PDs.

Next-Generation Devices

We now look ahead at two next-generation optical devices in silicon, which focus on size reduction and possibly new functionality: RRs and photonic band gap (PBG) devices. Optical RRs are useful components for multiplexing, switching, wavelength filtering, and modulation. The key performance characteristics of the RR include the free-spectral range (FSR), the finesse (or Q factor), the resonance transmission, the extinction ratio (ER), and polarization performance. Figure 7 is a simple diagram explaining how a RR operates.

For such designs, resolution and optical lithographic critical dimension (CD) control are all important to the success of the devices. In the case of Si-based RRs,

Figure 6. Cross section of waveguide-based SiGe p-i-n PD.

one of the critical parameters to control is the coupling efficiency between the RR and the input/output waveguide. As a compact waveguide (for example, $220\text{ nm} \times 500\text{ nm}$ strip waveguide) is usually used in the RR to obtain a large FSR, the gap between the ring and bus waveguide is $100\text{--}200\text{ nm}$. Since the device operates through evanescent coupling, the coupling is exponentially dependent on the size of the separating gap. Thus, in order to reliably process high-Q RR devices, dimensional tolerance of a few nm demands CD control. This is readily achieved by modern $0.13\text{-}\mu\text{m}$ or $0.09\text{-}\mu\text{m}$ processes currently in production.

Going to even smaller devices, one gets into a new regime. For example, photonic crystals are the optical analog to electronic semiconductor crystals. Photonic

crystals have been gaining considerable attention since reports by researchers working in silicon were brought to mainstream attention. Their dispersive properties and nonlinear optical effects, combined with the promise to drastically reduce the dimensions of common optical designs, are fueling many currently active research efforts, such as those on the super prism devices [22]–[24].

Through the periodic arrangement of two materials with dissimilar dielectric constants, a photonic crystal will exhibit a band of forbidden frequencies of propagation. This PBG is analogous to the forbidden energy gap of semiconductors, just as forbidden electronic states are due to the periodic arrangement of atoms in a crystalline lattice. The periodic arrangement of dielectrics on the order of the wavelength of light creates an optical gap (see Figure 8). The most common example of a photonic crystal is a one-dimensional Bragg grating for which a forbidden optical gap or stop-band is achieved. For most two-dimensional planar SOI-based PBG waveguides, a triangular lattice of holes in silicon is used [25].

Compared with standard waveguide-based devices, PBG's benefits are that the physics of operation allow for much smaller bending radii with negligible loss. This could lead to very-small-form-factor photonic devices. Smaller form factors could lead to a much higher level of integration on a single chip. However, all this comes with increased coupling loss into and out of these very small devices. A conventional optical waveguide cannot have a sharp bend without significant loss of power. PBG-based waveguides can have 120° bends with radii near $1\text{ }\mu\text{m}$ [26]. However, PBGs will require better processing and control of CDs. Another challenge of PBG-based devices is the relatively high optical transmission losses. Photonic crystal waveguides device performance has markedly improved in recent years, as highlighted by the recently announced propagation losses of 3 dB/mm in a waveguide [27]. One of the key developments in the field is the

Figure 7. Simple description of how an RR works.

Figure 8. Examples of (a) electrical energy band gap for a semiconductor (silicon) and (b) a photonic band gap for a photonic crystal, where a is the pitch of the lattice.

use of numerical optimization techniques for the design of microcircuits, as demonstrated by the combination of an injector, waveguide, Y-junction, and bends that closely matched the predicted results [28]. As to functionality, the control of the dispersive properties of a waveguide, such as group velocity dispersion and the group velocity itself, is a unique feature of photonic crystals, as recently highlighted by the direct observation of ultraslow light in photonic crystal waveguides [29].

Modulators

Background

Photonic modulation has traditionally been associated with the Pockels effect in ferroelectric materials such as lithium niobate (LiNbO_3) and III-V semiconductors, with the former boasting a larger electro-optic coefficient [30]. Silicon is inherently restricted as an optical modulation material because the centrosymmetric crystal structure of silicon means that it does not exhibit a linear electro-optic (Pockels) effect. This leaves the plasma dispersion effect and thermal modulation as the only viable mechanisms [31]. Thermal modulation is inherently slow, so the plasma dispersion effect is favored for most applications. The plasma dispersion effect is related to the density of free carriers in a semiconductor, which changes both the real and imaginary parts of the refractive index.

Starting from the Drude-Lorenz model [32], Soref and Bennett [31] produced the following extremely useful empirical expressions, which are now used almost universally to evaluate changes due to injection or depletion of carriers in silicon. At an optical wavelength of $\lambda = 1.55 \mu\text{m}$,

$$\begin{aligned}\Delta n &= \Delta n_e + \Delta n_h \\ &= - \left[8.8 \times 10^{-22} \Delta N_e + 8.5 \times 10^{-18} (\Delta N_h)^{0.8} \right],\end{aligned}\quad (1)$$

$$\begin{aligned}\Delta \alpha &= \Delta \alpha_e + \Delta \alpha_h \\ &= 8.5 \times 10^{-18} \Delta N_e + 6.0 \times 10^{-18} \Delta N_h,\end{aligned}\quad (2)$$

where Δn_e = change in refractive index resulting from change in free electron carrier concentrations; Δn_h = change in refractive index resulting from change in free hole carrier concentrations; $\Delta \alpha_e$ = change in absorption resulting from change in free electron carrier concentrations; and $\Delta \alpha_h$ = change in absorption resulting from change in free hole carrier concentrations.

An interesting feature of the silicon electroabsorption modulator that is central to microwave systems is the inherent linearity evident in (2). The absorption is directly proportional to electron and hole densities, which themselves are linearly proportional to the device current. This results in an intrinsically linear static electro-optic transfer function, a welcome behavior in analog applications. However, one should be cognizant of the phase modulation, described by (1), which accompanies

the amplitude modulation. In optical links in which fiber dispersion is significant, dispersion-induced phase-to-amplitude conversion, an inherently nonlinear process, will be a source of dynamic nonlinearity.

Progress in Silicon Modulators

Silicon modulators and switches were among the first silicon photonic devices to be studied and have been the subject of extensive research ever since. While it is impossible to provide comprehensive coverage of modulators here, several examples are discussed in the following. A more comprehensive review of modulators can be found in [33].

The first plasma dispersion modulator in silicon was proposed by Soref et al. [34]. This $p^+ - n - n^+$ modulator was based on a single-mode silicon rib waveguide. It was found by modeling that the interaction length of the modulator required for a π -radian phase shift was less than 1 mm. The corresponding loss was less than 1 dB at $\lambda = 1.3 \mu\text{m}$ for both orthogonal polarization modes. The buried block of SiO_2 below the waveguide acts as the lower waveguide boundary.

In 1987, Lorenzo et al. [35] reported the first 2×2 electro-optical switch in silicon. The switch was fabricated as a vertical $p^+ - n$ diode. The injection of holes into the intersection of the crossing waveguides caused a change in refractive index, resulting in some limited switching. For an input current density of $J = 1.26 \text{ kA/cm}^2$, applied at the p^+n junction, the device experienced an on state that switched 50% of the optical power from the output straight-through channel port 3 to the output cross-channel port 4. Although this device was not optimized, it reaffirmed the feasibility of the plasma dispersion effect.

In the late 1980s, Friedman et al. [36], [37] proposed and theoretically analyzed phase modulators in a series of transistor structures integrated into rib waveguides. The devices were based around MOSFETs, utilizing injection of single carrier types (holes or electrons) or dual injection field effect transistors (DIFET). The injected charge in the DIFET was to be controlled by the junction field effect in which a voltage variable depletion width controlled the effective cross-sectional area of the conducting channel. The authors predicted effective refractive index changes of the order of 1×10^{-3} for applied gate voltages of 10–20 V. They also proposed dual gate devices, which offered better overlap of the modal field with injected carriers, although fabrication of two gates is impractical for potential SOI structures. They concluded that because the refractive index changes occurred over thin layers, the devices would be optimal in small waveguides, on the order of $0.1 \mu\text{m}$ in height. At the time, this was regarded as unreasonably small, but as the recent trend to smaller cross-sectional dimensions continues, and nanophotonic devices are becoming more seriously considered, some of these early devices are being reconsidered.

Throughout the 1990s, significant progress was made in the optimization of optical modulators, mostly based on a progression to SOI waveguides, rather than silicon on a doped silicon substrate.

The work of Tang et al. in 1994, in support of an earlier simulation paper in 1993 [38]–[40], showed that it was possible to obtain a 30% increase in the concentration of injected carriers into the waveguiding region of a phase modulator by changing the sidewall angle of the rib from vertical to the naturally occurring 54.7° (Figure 9). Also, reducing device dimensions [41] and introducing trench isolation [42] were found to be the key means of increasing performance. In 2000, Dainesi et al. reported a CMOS-compatible fully integrated Mach-Zehnder interferometer (MZI) in SOI technology [43]. A cross-finger type of p- and n-doping regions was used to modulate the optical phase through plasma dispersion effects.

The weak electro-optic effect in silicon requires long devices and hinders high integration levels, increasing

the cost. Cavity enhancement of the effect can, in principle, lead to efficient modulation [44]. The microcavity facilitates confinement of the optical field in a small region, and the transmission of the device near its resonance is highly sensitive to small index changes in the cavity. Barrios et al. [45] modeled a modulator based on a Fabry-Perot resonator with Bragg reflectors. The device required a low concentration of injected carriers to switch to a nonresonant position. The $20\text{-}\mu\text{m}$ -long device was predicted to require a dc power of the order of $25\text{ }\mu\text{W}$ at an operating wavelength of $1.55\text{ }\mu\text{m}$ to achieve 31-MHz operating bandwidth with transmittance of 86% and a modulation depth of 80%.

A similar device but using an RR ($10\text{ }\mu\text{m}$ diameter) has recently been demonstrated [46]. The highly scaled devices used waveguides 450-nm wide and 250-nm high. Instead of electrical injection, free carriers were introduced optically via two-photon absorption using ultrashort pulses. The enhancement of the power in

the resonant structure reduces the power requirement for switching. Modulation depths up to 94% were measured with switching times less than 500 ps, suggesting a repetition rate of $\sim 700\text{ MHz}$. In general, resonator-based devices make use of high optical Q factors to enhance the interaction efficiency between free carriers and the optical field. Fundamentally, this comes at the expense of reduced bandwidth and in most cases, also results in polarization-dependent behavior. Further enhancements were produced by the same group in a subsequent paper [47].

Recently, researchers from Intel Corporation experimentally demonstrated a silicon-based optical modulator with a bandwidth that exceeds 1 GHz [48]. A schematic of the reported device, which

operates via the plasma dispersion effect, is shown in Figure 10 and bears a resemblance to a CMOS transistor. The device structure consists of *n*-type crystalline silicon with an upper rib of *p*-type polysilicon. The *n*-type and *p*-type regions are separated by a thin insulating oxide layer. Upon application of a positive voltage to the *p*-type polysilicon, charge carriers accumulate at the oxide interface, changing the refractive index distribution in the device. This in turn induces a phase shift in the optical wave propagating through the device.

Figure 9. An early proposal for silicon electro-optical phase modulator [39].

Figure 10. Schematic diagram of the silicon-based optical modulator demonstrated experimentally to exceed 1 GHz bandwidth [48].

The bandwidth of the device (a single 2.5-mm-long phase modulator) was characterized in two ways in an integrated asymmetric MZI. The first technique was to drive the device with a 0.18 V_{rms} sinusoidal source at 1.558 μm , using lensed fibers for coupling into and out of the device. The second test was the application of a 3.5-V digital pulse pattern with a dc bias of 3 V. A 1-Gbit/s pseudorandom bit sequence was applied to the device, and a high-bandwidth photoreceiver was used for detecting the transmitted optical signal. However, the on-chip loss for this device was high, at ~ 6.7 dB, and the device is also highly polarization dependent due to the horizontal gate oxide. Phase modulation efficiency for TE polarization is larger than TM polarization by a factor of seven. All measurements reported were made for TE polarization. The authors subsequently improved their device by replacing the lost/lossy polysilicon layer by crystalline silicon, by optimizing the doping, and by shrinking the device dimensions, resulting in a faster device [49]. This was demonstrated by implementing data transmission at 6 Gb/s (4.5 dB extinction ratio) and 10 Gb/s (3.8 dB extinction ratio). They also suggested that by further optimization they could achieve extinction >12 dB and chip loss of only 2 dB.

Another recent paper has suggested that silicon modulators are set to be pushed even faster. Gan et al. have provided modeling of a small p-i-n device suggesting an intrinsic bandwidth in excess of 20 GHz [50]. This is achieved by using a combination of an insulating layer and thin contacts to provide carrier confinement. It is helpful to compare the recently reported modulators (Table 1) to see the trend to improving device speed. This followed from modeling of Png et al. [51], which also suggested p-i-n modulators could be relatively fast.

Luxtera Inc., a start-up company, recently also announced a silicon modulator capable of operating at 10 Gb/s, although few details of the device have been made available [52].

Finally, an interesting modulator has recently been reported by Boyraz et al. [13]. The Raman laser reported by the same authors as the previous section was combined with a p-i-n silicon modulator, which was used to inject free carriers to suppress lasing in the device, and hence, introduce modulation. A relatively large separation of the p and n regions of 8 μm was used to perform the function, resulting in a modulation bandwidth of only 1 MHz, although the novel demonstration of a modulated silicon laser was significant. The CW laser reported by Rong et al. [53], and also discussed previous-

ly, includes a p-i-n structure, this time in reverse bias to suppress carriers. This device has been used to demonstrate a lossless modulator by combining Raman amplification with removal of free carriers.

Conclusions

The silicon chip has been the mainstay of the electronics industry for the last 40 years and has revolutionized the way the world operates. Today, a silicon chip the size of a fingernail contains nearly 1 billion transistors and has the computing power that only a decade ago would take up an entire room of servers. As the relentless pursuit of Moore's law continues, and Internet-based communication continues to grow, the bandwidth demands needed to feed these devices will continue to increase and push the limits of copper-based signaling technologies. These signaling limitations will necessitate optical-based solutions. However, any optical solution must be based on low-cost technologies if it is to be applied to the mass market. Silicon photonics, mainly based on SOI technology, has recently attracted a great deal of attention. Recent advances and breakthroughs in silicon photonic device performance have shown that silicon can be considered a material onto which one can build optical devices. While significant efforts are needed to improve device performance and commercialize these technologies, progress is moving at a rapid rate. More research in the area of integration, both photonic and electronic, is needed.

The future is looking bright. Silicon photonics could provide low-cost opto-electronic solutions for applications ranging from telecommunications down to chip-to-chip interconnects, as well as emerging areas such as optical sensing technology and biomedical applications. The ability to utilize existing CMOS infrastructure and manufacture these silicon photonic devices in the same facilities that today produce electronics could enable low-cost optical devices, and in the future, revolutionize optical communications.

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TABLE 1. Silicon plasma dispersion modulators recently reported in the literature.

Year	Author	Electrical structure	Optical structure	Dc power (mW)	Switching time (ns)	Length (μm)
2003	Png et al. [51]	p-i-n	MZI	~ 0.56	0.51	>500
2004	Liu et al. [48]	MOS	MZI	~ 0	~ 0.6	10,000
2005	Liao et al. [49]	MOS	MZI	~ 0	~ 0.1	3,500
2005	Xu et al. [47]	p-i-n	RR	~ 0	~ 0.35	14
2005	Gan et al. [50]	p-i-n	MZI	~ 500	~ 0.042	1,000

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