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SILICON PHOTONICS: AN EVOLVING TECHNOLOGY

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ABSTRACT

This paper highlights recent progress and trends in the development of silicon photonics. Silicon photonics has been the subject of intense research activities in both industry and academia as a compelling technology paving the way for next-generation energy efficient high-speed computing, information processing, communications systems, and biosensing. The trend is to use optics in intimate proximity to the electronic circuit, which implies high level of optoelectronic integration. The goal is not only achieving high-performance in silicon photonics, but doing so at a price point that makes the technology a natural fit for all devices that consume bandwidth.

Great efforts have been dedicated and various impressive results achieved in passive and active silicon photonic devices, photonic circuit integration as well as various application exploration, including waveguide structures, modulators, switches, photo detectors, resonators, sensors, sub-wavelength structures, wavelength multiplexers, spectrometers, photonic crystals, nano plasmonics, light sources, and various subsystems.

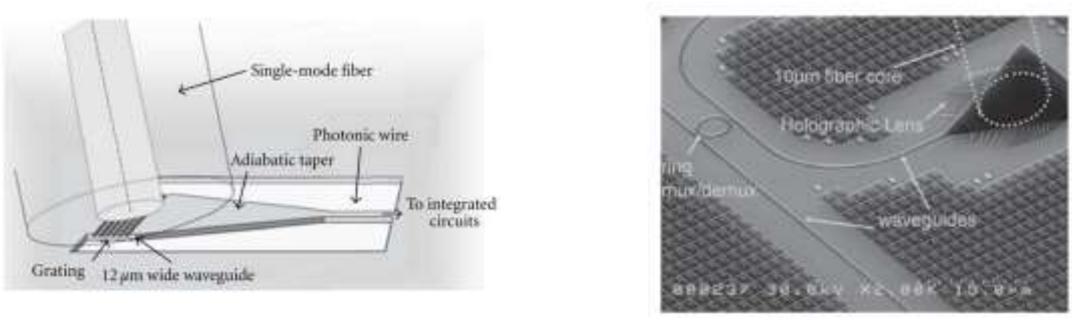
KEYWORDS: silicon photonics, modulators, heterogenous detectors, optical amplifiers.

INTRODUCTION

Creating low-cost photonics for mass-market applications by exploiting the mighty IC industry has been the traditional motivation for silicon photonics researchers. The wavelength range over which a Si-based photonic integrated circuit (PIC) or optoelectronic integrated circuit (OEIC) can operate depends upon whether the photonic waveguide material is silicon or another material. Intrinsic silicon is transparent from its 1.1 µm indirect bandgap wavelength out to about 100 µm, allowing a wide scope for silicon waveguide operation. Moreover, if the core layer of the silicon waveguide is very thin (several nanometers) and is quantum confined, then the Si bandgap widens and the Si transparency extends to shorter wavelengths, 800 nm or less, enabling visible and near-infrared waveguide transmission[1]. The strong optical confinement offered by the high index contrast between silicon(n=3.45) and SiO2(n=1.45) makes it possible to scale photonic devices to the hundreds of nanometer level. Such lateral and vertical dimensions are required for true compatibility with IC processing. In addition, the high optical intensity arising from the large index contrast (between Si and SiO_2) makes it possible to observe nonlinear optical interactions, such as Raman and Kerr effects, in chip-scale devices. Silicon has excellent material properties that are important in photonic devices. These include high thermal conductivity (~10×higher than GaAs), high optical damage threshold (~10×higher than GaAs), and high third-order optical nonlinearities.

PASSIVE DEVICES

The basic requirement for virtually all integrated optical devices is low propagation losses in waveguides and cavities. Owing to the high index contrast between a silicon waveguide and its surrounding medium (air or SiO_2), surface roughness results in significant scattering losses. Thermal oxidation can be used to reduce the roughness on the waveguide sidewall, and its effect on the sidewall morphology has been studied extensively [2]. It has been found that oxidation at higher temperatures (~1100◦C) is preferred as it offers an extremely smooth sidewall without deformation of waveguide's cross-sectional profile [2]. The high refractive index of silicon makes it possible to reduce the optical mode size to approximately $0.1\mu m^2$ [3][4] i.e., on the same scale as typical dimensions encountered in CMOS VLSI. The high index contrast between silicon and the SiO_2 lower cladding layer makes it possible to create ultra compact waveguide bends, another requirement for creating real-estate efficient devices. Using such silicon wire waveguides, ultra small channel-dropping lattice filters have been fabricated [5]. Despite the severe modal mismatch between the silicon wire waveguide and a single-mode fiber, efficient fiber–waveguide coupling can be achieved using the inverse taper approach [4],[6]-[8]. Another approach for efficient fiber-to-waveguide coupling is using surface gratings etched onto silicon [24], [9][10].The fiber–waveguide coupling losses of 1 dB are obtained in experiments with a theoretical lower limit of 0.2 dB[10].



(a) ***(b)***

Figure 1: (a) Grating coupler for coupling between photonic wire waveguide and fibre. (b) Oblique view of a holographic lens connected to silicon waveguides. The optical fibre illuminates the holographic lens from a position normal to the surface. The core of the fibre is shown by the dashed lines. Figure (a) is taken from[11,12]. Figure (b) is taken from[13].

MODULATORS

Silicon is not an ideal material for electro optic modulation. The linear electro optic effect, the so-called Pockel effect that is the basis of traditional LiNbO3 modulators, is absent in silicon due to its centro symmetric crystal structure. This leaves the plasma dispersion effect as the only viable mechanism to achieve fast modulation [32]. This widely employed approach can be traced back to the classic work of Soref et al.[14],[15]-[18] followed by the early work of Tang et al.[19]-[21]. They demonstrated that waveguide switches and modulators can be fashioned in silicon by taking advantage of the linear dependence of refractive index and absorption coefficient on carrier density.

The basic mechanism is well understood and is described in excellent review articles about this topic[22]. Researchers from Intel Corporation have demonstrated a silicon-based optical modulator that can operate at 10 Gb/s [23]. Luxtera Inc., which is a start-up company, has also announced a 10 Gb/s silicon carrier-depletion modulator [24]. The device exhibits 5 dB of modulation depth with 2.5 V of voltage swing with a waveguide propagation loss of 1–3 dB/cm. It uses grating couplers with a loss of 3 dB for the pair of couplers. commercial $LiNbO_3$ optical modulators exhibit 2.5 dB of total fiber-to-fiber loss (fiber coupling plus waveguide propagation losses) with a switching voltage of about 4 V (for∼20-dB modulation depth) and a bandwidth of 20 Gb/s [25]. The weak electro optic effect in silicon requires long devices and hinders high integration levels, thus increasing the cost. Cavity enhancement can, in principle, lead to efficient modulation[26]-[29].

A compact device using a ring resonator (10μm diameter) has recently been demonstrated by Lipson et al. at Cornell University [28],[29]. Free-carrier modulation of Raman gain has been proposed and demonstrated as a means to achieve optical modulation[30]. A Raman laser 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. Industry, most notably Intel, has lead the way into the GHz domain with a 1 Gb/s MOS accumulation modulator device43 (2.5 mm-long phase shifters within a longer MZI), and their modeling shows extension to 10 GHz, conservatively.[27]

GROUP-BASED MODULATORS

Based on the potential of integration with electronics in a cost-effective manner, silicon has been one main candidate for modulator fabrication. However, some primary electrical field effects, including the Pockels effect, the Kerr effect, and the Franz-Keldysh effect, are weak in pure silicon at telecommunication wavelengths of 1.3 μm and 1.55 μm, due to the centro -symmetric crystal structure of Si[31,32,33]. Owing to the large thermal-optic coefficient of Si (1.86×10−4/K) [33], thermal modulation, which is based on the temperature dependent of the material refractive, is realizable in Si. Recently, tunable thermal-optic switches and modulators have been demonstrated [34], and the power consumption of this type of modulators is reported being similar to that of plasma dispersion-based modulators [33]. There are two options available for converting a change in refractive index into intensity modulation. One common method is to shift the relative phase of two propagating waves by changing the refractive index of one or both arm waveguides, so that they interfere either constructively or destructively [35]. Typically, a Mach-Zehnder interferometer (MZI) is used to achieve this. The other one is using cavity enhancement with resonant structure. Since the change in the refractive index also affects the resonant condition, this allows the device to be switched between on- and off-resonance states at any given wavelength[32,36]. The structures of both kinds of modulators are shown in Figure 2.

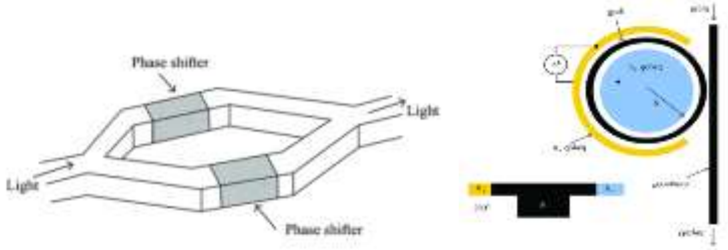


Figure 2: Schematic layout of (a) an MZI modulator and (b) a ring resonator-based modulator. Figure (a) is taken from [35]. Figure (b) is taken from[36].

DETECTORS

Photodetectors are perhaps the oldest and best understood silicon photonic devices. Commercial products operate at wave-lengths below 1000 nm, where band-to-band absorption occurs. Among various 1.55 μm-photodiode contenders for CMOS-compatible integration on silicon OEICs, the germanium photodiode (typically under tensile strain) appears to be the winner. Several research groups have demonstrated the direct integration of Ge photodiodes upon silicon, and that process appears to have major importance for 1.55 μm applications.

MATERIALS HETEROGENEOUS DETECTOR

In comparison with silicon, III-V-based detectors usually have a much wider absorption bandwidth, with relative low dark currents. Current InGaAs PIN photodetectors can operate at a responsivity of more than 1 A/W and very low dark current of around several picoamperes [37]. recently, some of them, like InGaAs detectors, have been successfully built on the SOI substrate with excellent performance using heterogeneous integration approach [37,38]. An example of a vertically built InGaAs detector is shown in Figure 3, in which benzocyclobutene (BCB) layer is applied to support the top detector [38]. Alternatively, two-photon absorption behaviour in III-V materials can also be used for low-speed detection of below-bandgap radiation, and such devices can be used as auto correlators in lasers for pulse generation [39].

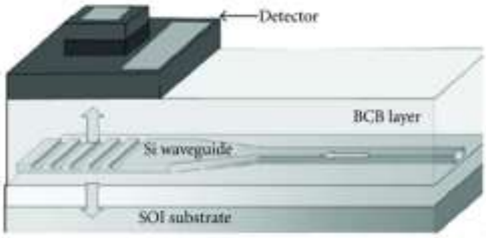


Figure 3: Schematic view of an SOI waveguide-integrated detector. Arrayed grating is used to achieve low loss vertical coupling. Figure is taken from[38].

Several groups, among them MIT and Luxtera, have investigated this with promising results on responsivity and detectivity. For application in fiber-optic communication, silicon is not the right material since it is transparent in the 1300- and1550-nm operating wavelengths of these networks[40]. With its smaller bandgap, germanium has strong absorption at these wavelengths—a motivation for the early work on photodetectors with an active layer made of GeSi[41]-[43] as well as SiGeC alloys [44].The lattice constant of Ge is 4% larger than that of Si. The strain resulting from lattice mismatch modifies the bandstructure and causes dislocation defects that increase the leakage current of the p-i-n photodetector. Ge does not form stable oxide, and the lack of a high-quality passivation layer for Ge also makes it difficult to achieve a low dark current. Interestingly, by scaling the device to smaller dimensions, a higher dark current can be tolerated. For a given dark current density (in amperes per square centimeter), the dark current decreases with detector area. Hence, to the extent that the signal can be coupled into the smaller device, a given signal-to-noise ratio can be achieved with a higher dark current density. Strain limits the thickness of Ge layers that can be epitaxially grown on silicon. A thin Ge layer is preferred from the bandwidth point of view as it minimizes the carrier transit time, but it comes at the expense of reduced absorption and diminished responsivity. A waveguide p-i-n geometry is preferred over a normal incidence design since it allows independent optimization of absorption volume and transit time. With solid understanding of material and device related issues, excellent progress is being made toward Ge on silicon detectors[45] that are approaching III–V detectors in performance[46]-[50]. TPA can be used for low-speed detection of below bandgap radiation. Such detectors have been used as autocorrelators [51], [52] and as phase detectors for clock recovery using an optical phase-locked loop [53]. Using helium implantation as a means of enhancing the absorption (photoresponse) of Si below the bandgap, photo detection in1440–1590 nm has been recently proposed and demonstrated for power-monitoring purposes[54].

OPTICAL AMPLIFIERS AND LASERS

In silicon photonics, light sources, including lasers, light emitting diodes (LEDs), and optical amplifiers, are always the most challenging part in the whole silicon-based OEIC networks, hence attracting heavy research interests these years. As shown in Figure 4, unlike III-V materials such as GaAs or InP, Si has an indirect bandgap structure, which means the valley on conduction band where free electrons stay is not aligned with the free holes in the valence band. Since visible and IR photons have negligible momentum, in order to fulfill momentum conservation, radiative recombination will need the assistance of a phonon. This in turn reflects the very long lifetime in millisecond level for radiative recombination in Si. In comparison, the lifetime for nonradiative recombination in Si is only around several nanoseconds, so most of the excited electron-hole pairs will recombine nonradiatively, resulting in very low electroluminescence efficiency in bulk silicon. Despite this natural challenge, a number of excellent breakthroughs have recently been made on the light sources on Si platform. Although numerous approaches have been explored to this issue, most belong to the four categories: (1) employing quantum confinement effect to overcome the indirect band structure in Si, (2) introducing rare-earth impurity as luminescence centres, (3) using Raman scattering to achieve net optical gain, and (4) applying epitaxy and hybrid integration with III-V-based lasers or Ge lasers. All of these methods are reviewed in detail below. In order to understand more fully the requirements for each approach, the optical emission problem in crystal Si is discussed first.

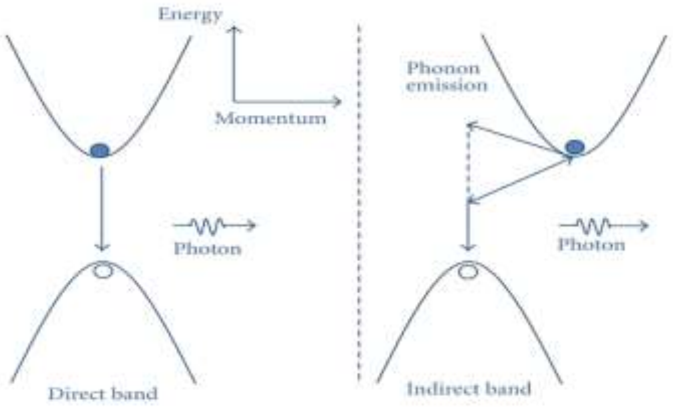


Figure 4: Energy band diagrams and major carrier transition processes in GaAs (left) and bulk silicon (right).Epitaxial III-V-Based Lasers On Silicon

Recently, numerous approaches have been used to integrate III-V layers on SOI substrates. Both direct molecule wafer bonding[55,56] and di-vinyltetramethyldisiloxane-benzocyclobutene (DVS-BCB) adhesive bonding [57] can be applied to grow high-quality InP layers on Si in low temperature, and several examples of InP lasers on SOI with good performance have been reported [57,58]. The details of these two methods have been reviewed in [59]. Room temperature InGaAs quantum dot laser grown directly on Si was demonstrated by Bhattacharya's group in University of Michigan [60] as early as 2005. In addition, another exciting idea for epitaxial lasers is to employ materials like GaNAsP, which have the same lattice constant with Si[61]. Another challenge for III-V epitaxy methods is the compatibility of CMOS processing.

Ge-On-Si Lasers

Another novel approach for epitaxial lasers is using Ge-on-Si structure. The idea of Ge-based lasers was first theoretically demonstrated by Liu et al.[62], suggesting that efficient light emission and optical gain at 1550 nm could be obtained in Ge with proper band structure engineering. Since then, there have been intensive researches on light emission in Ge. Basically, there are three kinds of methods to realize direct bandgap transition in Ge, including quantum confinement, strain, and high concentration n-type doping. Although quantum confinement effect between Ge and Si can raise the indirect bandgap of Ge to match 1550 nm wavelength, the confinement is only effective for holes due to the type II junction between Ge and Si. As a result, with unconfined electrons, Ge/Si quantum structure still preserves the property of the materials with indirect band, which results in a low light emitting efficiency.

The second method to modify the band structure of Ge is to introduce strain. It has been shown that Ge becomes completely direct bandgap material at a tensile strain of 1.8%. Usually thermal expansion mismatch is preferred to introduce the tensile strain between Ge and Si, since this type of strain is not limited by critical thickness of Ge layer [63]. However, when the required 1.8% is applied, the corresponding emission wavelength shifts to around 2300 nm due to the shrinkage of the bandgap under strain, which is out of the wavelength range for telecommunication. Instead, it is demonstrated that 0.25% tensile strain is preferred to make Ge lasers [64,65], and a very low threading dislocation density of 2 × 107 cm−2 appears for epitaxial Ge layer on Si[64].

Figure 5: Design of the Ge-based light emitting diode. (a) Isometric schematic of the device structure showing the Ge mesa on top of a p-type Si substrate with Al ring contacts. (b) Cross-section schematic of the device structure. Figures are taken from [68].

A milestone work was made in 2009 by MIT when actual 1590 nm PL lasing was realized in an n-doped Ge on Si channel-waveguide resonator with pumping at the wavelength of 1590 nm[66]. Since then, several types of Ge-based EL LEDs grown on Si emitting around 1600 nm were realized [67,68]. An example of Ge LED achieved by Cheng et al. is shown in Figure 5 [68].

THE OPTICAL FUTURE

As Moore's Law continues to push microprocessor speeds and as increasing volumes of data are sent across the Internet, the demands placed on network infrastructure will increase significantly. By taking advantage of silicon photonics, new products can scale bandwidth availability to meet this demand. In addition, due to the low cost of silicon solutions, we can expect that servers and high-end PCs might one day come standard with an optical port for high-bandwidth communication. Likewise, other devices will be able to sharein the bandwidth explosion provided by the optical building blocks of silicon photonics.The SOI platform by itself offers an almost complete suite of photonic components, including filters, (de)multiplexers, splitters, modulators, and photodetectors. However, electrically pumped efficient sources on silicon are a challenge due to silicon's indirect bandgap.

ADVANCES IN SCIENCE AND TECHNOLOGY TO MEET CHALLENGES

The SOI platform by itself offers an almost complete suite of photonic components, including filters, (de)multiplexers, splitters, modulators, and photodetectors. However, electrically pumped efficient sources on silicon are a challenge due to silicon's indirect bandgap. A way to introduce efficient electrically pumped sources is to utilize III–V gain regions placed directly on silicon[69,70] . There are three approaches to achieve this[71,72]. One approach uses III–V chips bonded on silicon with coarse alignment and subsequently processed on the Si wafer scale. A second approach is the direct epitaxial growth of III–V layers on silicon or SOI using intermediate buffer layers, typically Ge and strained superlattices, to minimize dislocations propagating into the active region. A third approach is to combine the first two approaches: one can grow III–V gain material on silicon and then bond it to patterned SOI wafers for efficient waveguide coupling and PIC fabrication. The problem with growing III–V directly on silicon is threading dislocations due to lattice and thermal mismatch. Quantum dots (QDs) reduce the epitaxially grown InAs/GaAs lasers on silicon is currently quoted at approximately 4600 h [73]. Other possibilities for generating light in silicon include strain-engineering of silicon and germanium or by using rare-earth-ions, but all these approaches still face considerable challenges in building high-performance lasers. Currently, the majority of light sources in silicon photonics use either III–V to silicon wafer bonding (heterogeneous integration) or butt-coupling with precise assembly (hybrid approach).

CONCLUSION

This paper has been an attempted overview of silicon photonics, including current novel technology and devices, the challenges, and some future plans for the commercialization in this field. The progress in waveguides, filters, modulators, detectors, and lasers has been reviewed in details. The final version of this subject is to have Si optoelectronic devices participating in global applications, like computing, telecommunication, imaging, energy conversion, and biomedical sensing. It is proposed that Si will play a leading role for the realization of the next generation of photonics devices.

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