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Review on Silicon Photonics

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Abstract: As a promising technology in optoelectronic integration for computing, communication, sensing, and solar harvesting, Silicon photonics has attracted tremendous attention and research effortMainly due to the combination of its excellent material properties and the complementary metal – oxide semiconductor (CMOS) manufacturing processing technologies, silicon has become the substrate option for low-cost, ultra-compact device footprint and high-density integrated photonic and optoelectronic circuits. This review paper provides an overview of silicon photonics by highlighting the early work of the mid-1980s on the fundamental building blocks such as silicon platforms and wave guides, as well as the major milestones achieved in the field so far. A summary of reported work on functional elements in both passive and active devices is identified, as well as the technology applications in interconnect, sensing, and solar cells. With the increasing requirement for bandwidth in computing and signal processing, the inherent limitations of metallic interconnection seriously threaten the future of traditional IC industries. Silicon photonics can provide a low-cost approach to overcome the bottleneck of high data-rate transmission by replacing the original integrated electronic circuits with integrated photonic circuits. Although the commercial promise has not been fulfilled, these years this perspective gives enormous impetus to the development of silicon photonics. This paper provides an overview of each component's progress and state of the art in silicon photonics, including waveguides, filters, modulators, detectors, and lasers, mainly over the past five years.

Keywords: Active devices, Fabrication, Passive devices, Silicon photonics

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INTRODUCTION

For more than 40 years, Silicon (Si)[1] has been the pillar of the electronics industry and once revolutionized the way the world functions. The development of processors can still barely follow the law of Moore by using more precise lithography technology and multicore structures. However, with increasing bandwidth requirement, the parasite effects in current metallic interconnection have gradually become a major obstacle to further improvements, as attenuation of electrical signals and dissipation of power increases dramatically with higher data rate. One possible solution to overcome the bottleneck of high data rate transmission could be the use of optical interconnection, in which the information signals are carried by photons instead. Photons have zero rest mass and zero charge when compared to electrons. In other words, they can travel at light speed without interference with the electromagnetic field, so that optical systems can achieve theoretical signal transmission with much higher data rates and better stability than the electrical system. It is therefore highly desirable to replace traditional electrical circuits with optical circuits, and under these motivations is a popular subject, called the Optoelectronic Integrated Circuit (OEIC)[2], built since the late 1980s.

Si has an apparent 1100 nm to approximately 7000 nm wavelength window, which is far from being limited to the 1300–1550 nm near-infrared (IR)[3] communication band. Some excellent optical properties, such as large threshold for optical damage and thermal conductivity; Appear also in Si. In addition, today's mature, complementary metal-oxide semiconductor (CMOS)[4] techniques could also enable Si photonic devices to be manufactured at low cost, on a large scale. All of these reasons select Si as a notable photonics candidate. The Si photonics development can be tracked back to the pioneering work done in the mid-1980s, from which technology boom in this field focused primarily on Si-based waveguides, switches, and modulators. It wasn't until mid-2000s that the momentum in this field was significant. Until now, both quick Si modulators and high responsivity have been achieved in epitaxial Germanium (Ge) detectors. In addition, Great breakthroughs, such as Raman Si lasers, Mid-IR Si sources, epitaxial GaAs diodes grown on Si at room temperature, and even Ge-on-Si lasers, were made as light sources, a major obstacle in traditional Si photonics. Surely these technical advances boost the promise that Si can be seen as an optical material for OEIC system.

Rather than reviewing the history of this field, this paper aims to assess the potential impacts of silicon photonics by describing recent breakthroughs; Novel devices, and current challenges, mainly over the last five years. There will also be a review of some current commercialized devices and long-term projects of several large corporations in this field.

1. Passive Devices:

Passive devices are the key components of silicon PICs where no energy source is required to operate. Research has focused on the development of discrete passive devices like waveguides, Directional couplers, multi-mode interference couplers, interferometers Mach – Zehnder, Bragg gratings, ring resonators, etc. In this section we describe the details on waveguide advances, and splitters and rotators for polarization.

1.1 Waveguides:

One basic passive device in photonics is the waveguides[5], through which you can transfer optical signals from one point to another. In general, loss of both size and propagation should be considered when assessing the performance of a particular type of waveguide. Propagation loss can be divided into two parts, which are inherent losses (such as carrier absorption) and extrinsic losses (such as sidewall dispersal and substrate radiation). The former is the main source of loss for doping-based waveguides, while the later becomes significant when the sizes of waveguides are relatively small (such as SOI waveguides), due to the Silicon surface field density and the interface roughness.

There are many kinds of materials related to Si that can be applied to make the waveguides. Silica is one of the most commonly used wave-guide materials. The refractive index of the material will change by doping III / V ions into the silica (typically around 0.1 to 0.75 %), This results in a contrast between the refractive index of the core and the cladding. For silica waveguide one advantage is that the refractive index contrast can be flexibly adjusted by changing the doping density. However, for silica waveguides, the low refractive index means a weak confined structure resulting in both thick cladding layer (typically average 50µm) and wide spacing between waveguides. So it isn't really compatible with electronic IC technology. Fortunately, a fortuitous Silicon-on-insulator (SOI) discovery has provided an excellent platform for Si / SiO2 waveguides. Because of the large refractive index contrast between Si (n = 3,45) and SiO2 (n = 1,45), the waveguides form a strong confinement, This allows the size of the waveguides mode to be scaled down to around 0.1 µm2. Such lateral and vertical dimensions are in line with the demand for economic compatibility with today's CMOS technology (Figure 1). As devices are downsized however, deviations from ideal manufacturing profiles will become prominent. In particular, roughness of the sidewall introduced by imperfect etching; will result in the interface scattering between the waveguide core and the cladding which becomes a major source of loss of propagation. This scatter loss, typically around 0.2–3.0 dB / cm, is related both to the roughness of the sidewall and to the size of the waveguide.

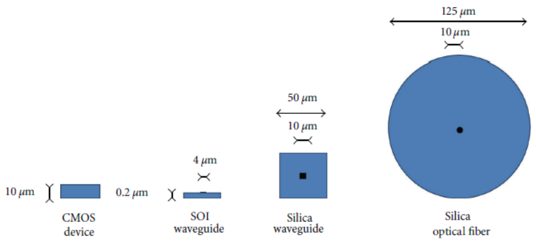

Figure1: Comparison of the Cross-Sections of a CMOS Chip, a typical SOI Waveguide, a Silica Waveguide, and a Silica Mono-mode Optical Fibre

1.2 Filters:

With the wavelength multiplexing (WDM) and de-multiplexing applications, optical filters[6] have been a crucial part of modern optical network. Early work can be tracked back to the late 1990s and early 2000s using waveguide grating and, more recently, because of their potential for high-density integration, microdisk and micro-ring have gained increasing interest in the same application. For a common micro-ring-based add-drop filter, light travels in close proximity to a ring through a wave guide, so that the optical modes ' evanescent fields overlap, and the optical energy can be transferred to the ring. The gap between the wave-guide and the ring will determine the coupling strength. The wavelength of the signal must meet to achieve resonance

$$\lambda = n_{eff}L/m$$

Where$L$ is the ring diameter, n_{eff} is the effective index of the mode propagating in the ring, and m is the resonance order. The free spectra range (FSR), which is the wavelength separation between resonances, is given by

$$FSR = \lambda^2_R/n_gL$$

Where n_g is the group index of the propagating modes. Therefore, the resonance frequency will be blue-shifted if reducing the diameter of the ring L or the refractive index. The resonance depth, which is also called the extinction ratio (ER), is another crucial parameter for ring filter, which is defined as

$$ER = 10 \log (P_{on}/P_{off})$$

Where P_{on} and P_{off} are the optical power on-resonance and off-resonance.

1.3 Couplers:

A crucial issue in developing SOI-based commercial microphotonics products is effective fibre-to-waveguide coupling. There is a significant mode mismatch between the waveguides and the input / output fibre due to the submicron dimensions of the silicon waveguides. Using an inverted taper with a polymer or silicone oxide cladding[7] is one efficient solution. The inverted taper dislocates the core mode profile, where the taper's narrow tip expands the optical mode to match the fiber's modal size (as seen in Figure 2). Furthermore, the back-reflections can be minimized since the effective index at the tip of the taper is close to that of the fiber. For the inverted taper the reported coupling loss is below 1 dB. The disadvantage, though, is that it can be placed only at the edges of a chip.

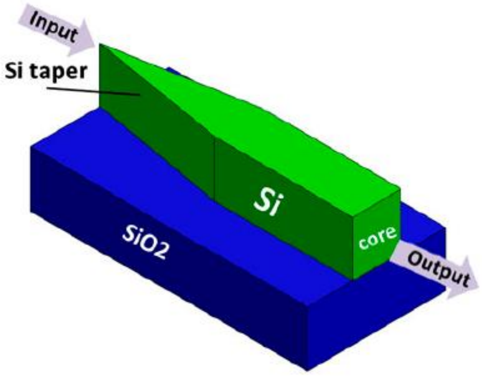

Figure2: Schematic Diagram of an Inverted-Taper-Based Coupler

2. Active Devices:

An active device requires an external energy source for its operation and has an output connected with the input signal(s). The key components of silicon PICs are active devices, such as silicon-based lasers, silicon modulators, and detectors.

2.1 Lasers:

Due to silicon's indirect band gap structure, free electrons tend to recombine with holes by emitting phonons (heat) instead of photons; this results in extremely poor internal quantity efficiency for the silicon light emission (on the order of one photon per million electrons). The realization of a silicon laser in silicon photonics remains a challenging issue to date.

Optical transitions must obey the conservation of energy and momentum to realize stimulated emission. In materials with direct band gaps, recombination of electron – hole pairs can emit photons quickly and efficiently, as shown in Figure 3. The conduction and valence bands extreme (lowest and highest) energy points share the same crystal momentum by lining up vertically along the axis of the wave vector. For this reason, the dominant semiconductor lasers are III – V, such as GaAs-, InP- and GaN-based materials.

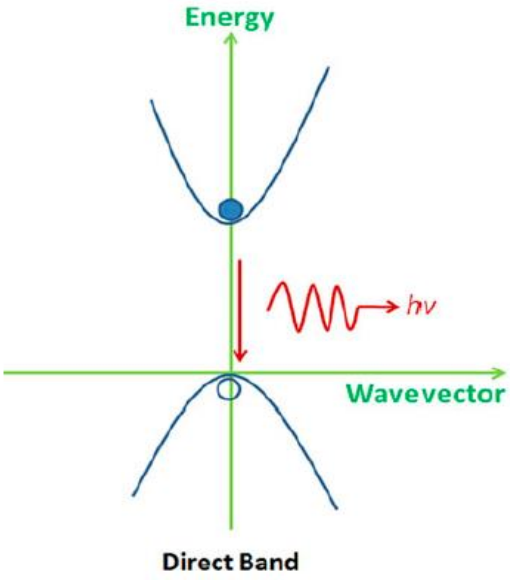

Figure 3: Schematic Energy Band Diagram of a Direction Band Gap Material, Such as GaAs

Free electrons reside in the lower valley of the conduction band in an indirect band gap material such as silicon or germanium (Figure 4), which is not aligned directly over the free holes in the valence band. Stimulated emissions are normally achieved through phononon-mediated processes, in which electrons are required to absorb phonons to fulfill the condition of momentum conservation and to emit photons. In direct band gap materials, the probability of a phonon-mediated process is much lower than that of a single-step recombination. There are usually two kinds of non-radiation processes associated with the recombination of the electron – hole in a silicone material: (i) Auger recombination in which a free electron is excited to a higher energy level by absorbing the released energy from a recombination of an electron-hole; and (ii) free-carrier absorption (FCA) in which the free electrons in the conduction band jump to a higher energy level by absorbing photons. Auger recombination and FCA have a much shorter lifetime than those in a radiation process, resulting in poor internal light emission quantity efficiency.

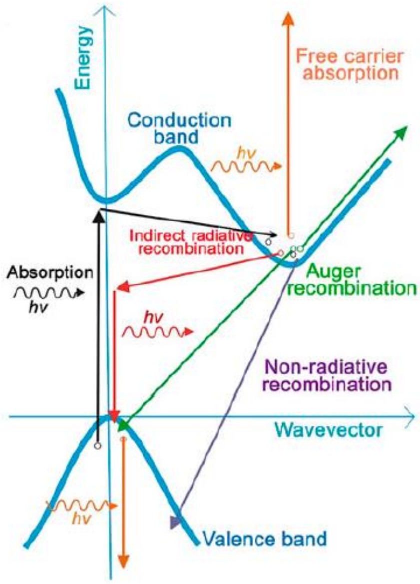

Figure4: Schematic Energy Band Diagram of the Indirect Band-Gap in Silicon

2.2 Silicon Modulators and Switches:

Other important components of silicon PICs include the silicon modulators[8] and switches[9]. A modulator is a device that can vary one or more of the transmitting light beam properties (i.e., an optical carrier). On the other hand, a silicon switch allows an optical carrier to be selectively switched from one circuit to another in a silicon PIC[10]. The performance parameters such as speed and extinction ratio are normally characterized by a modulator / switch. The modulation / switching speed measures the maximum data rate modulated onto an optical carrier before reducing the amplitude of modulation / switching to 3 dB. The extinction ratio (ER), or the modulation / switching depth, defines the ratio between maximum and minimal transmission of optical power. An ER > 7 dB is desirable; however an ER of 4–5dB is usually sufficient, as long as the individual components are optimized throughout the optical system. In designing a modulator / switch, additional performance parameters including insertion loss, power consumption and footprint are often taken into account.

Modulators and/or switches use either non-optical (e.g. electric field, heat, etc.) or optical signals to control the optical carriers. The application of an electric field to a material can alter its actual and imaginary refractive indices. When optical signals control the optical carriers, all-optical modulators or switches are executed. Until now, all-optical modulation / switch can be performed either by the two-photon absorption or the Kerr effect.

2.3 Silicon Photo-detector:

Located in a silicon PIC at the end of the optical interconnect, a photo-detector converts an optical signal into an electronic form. The process of working can be depicted as shown in Figure 5.The photo detector absorbs the photons of the incident, generating free electron-hole pairs, which are then swept by an electric field to the electrodes. The output is a photocurrent, or electrical current. The energy of incident photons must be equal to or greater than that of the band gap to generate electron-hole pairs; i.e.

$$E_{photon} = h\upsilon \geq E_g$$

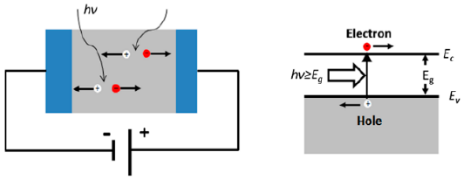

Figure5:Physical Principle of a PhotoDetector: (left) Photon Absorption and Generation of an excited

Mobile Electron–hole pair;(right) Schematic of Energy Level Transition of an Electron Induced by a Photon

Parameters used to assess a photo detector's performance include quantum efficiency, responsivity, response time, and noise from the detector. Quantum efficiency measures the electrical sensitivity of a photo detector to light which refers to the ratio of the number of electron-hole pairs generated to the number of photons incident. Responsiveness is dependent on wavelength and can be calculated by the ratio of the photocurrent generated to the total optical incident power. The response time is the time it takes for a Photo Detector to react to a light incident. A photo detector's response time is limited by both the free carrier transit time as well as the RC time constant associated with the detector and its circuitry. Generally speeding up response time means the photo detector has a broader operating bandwidth (BW). Detector noise includes shot noise from the production's statistical nature as well as dark current noise from the free carriers that are generated thermally.

CONCLUSION

This paper provides an overview of the rapidly evolving field of silicon photonics, including the highlight of the early work of the mid-1980s, the main milestones achieved in both passive and active devices, integration and packaging, as well as interconnection, sensing and solar cell applications. The silicon photonics technology offers the monolithic integration capability with electronic devices at low cost and on a large scale. Successful demonstrations of state-of - the-art silicon photonic devices and systems have further demonstrated the potential economic benefit where advanced functionality and improved performance with ultra-compact size, low power consumption and low cost can be achieved. Silicon photonics is ideally situated to play a leading role in devices and systems of the next generation.

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