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**REVIEW**

# A Review of the Building Blocks of Silicon Photonics: From Fabrication Perspective

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ABSTRACT

Silicon photonics is a disruptive semiconductor technology that taps into the extraordinary properties of light while taking full advantage of the already matured CMOS processes developed in the semiconductor industry. However, just like electronic industry in the 1970s, currently, silicon photonics is in its infancy. The fundamental building blocks of silicon photonics such as waveguides, lasers, modulators, etc. are yet to be fully optimized for low-cost-mass-manufacturing. In this paper, the current state-of-the-art related to developing and optimizing these aforementioned key components will be presented. The challenges of process integration regarding Silicon photonics will also be discussed.

## 1. Introduction

The success of today's semiconductor industry can largely be attributed to the exceptional process-friendly properties of the material – silicon. Its excellent native oxide ($SiO_2$) with high etching selectivity, outstanding mechanical and thermal properties and the availability of low-cost purification processes have led to a multibillion-dollar industry where groundbreaking innovations are taking place on a regular basis. Now, the transistors are smaller, faster and cheaper than ever before. The semiconductor processes have become so matured that the transistors just few atoms thick are currently being considered for mass manufacturing [1].

The same processes that have been developed to make complex electronic devices can be used to build silicon-based devices that manipulate light. The silicon photonic devices take full advantage of the already matured CMOS technology that no longer requires billion-dollar investments in the research and development (R&D). By combining the capabilities of electronics with high speed photonic circuits, it is possible to revolutionize computing, communication, sensor industries. However, just like any other new technology, silicon photonics is faced with lots of challenges ranging from availability of materials to process integration complexities related to photonic components. Remarkable R&D efforts are currently in place to optimize the performance of the fundamental building blocks of silicon photonics such as waveguides (WG), directional couplers, Bragg gratings, ring-resonators, modulators, photodetectors, lasers, and so on. CEA-LETI [2], IME [3], IMEC [4] are some

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of the R&D institutes that are constantly working to improve the performance of such components.

In this paper, the issues related to the design and fabrication of the most fundamental building blocks (waveguides, lasers, and modulators) of silicon photonics will be discussed. The material choice for these components and aspects of process integration will also be presented.

## 2. Silicon-on-Insulator (SOI) Waveguides

### 2.1 Waveguide Design

One of the most important component of a silicon photonic system is the waveguide. Most of the silicon photonics foundries fabricate their waveguides on SOI wafers. A 200 mm SOI wafer usually has 725 µm thick silicon substrate. On the top of the substrate, a 2 µm buried oxide (BOX) layer and a 220 nm thick crystalline silicon rests. This crystalline silicon serves as the core of the waveguide and is usually lightly doped ($1\times10^{15}$ cm$^{-3}$) [5]. Depending on the application, a cladding layer oxide is deposited on the top of Si core of these waveguides. Figure 1 illustrates the structure of a typical SOI waveguide.

The waveguide shown in Figure 1 is called strip waveguide. Depending on the system requirements, there are many other waveguide architectures available in the literature. Rib, ridge, strip-loaded, buried channel, suspended and slot waveguides are some of the most popular waveguide architectures currently available, as shown in Figure 2.

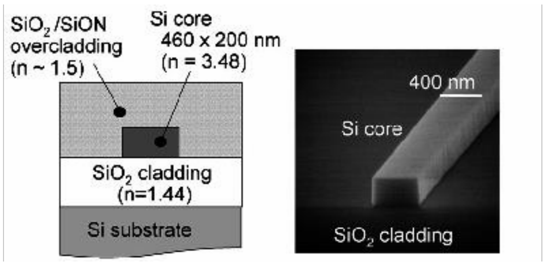

**Figure 1.** SOI waveguide with SiO$_2$ overcladding [6]

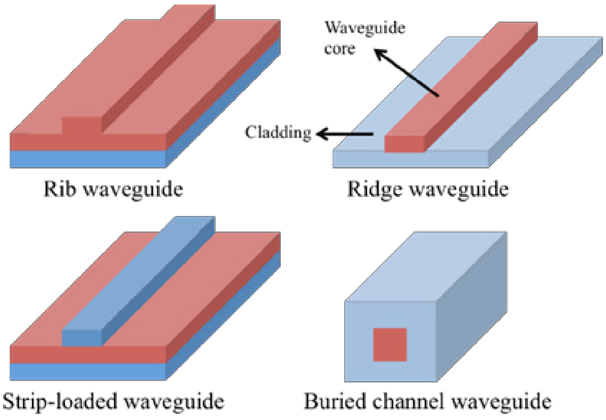

**Figure 2.** Popular SOI waveguide designs [7]

All these waveguide architectures follow the same fundamental principles of light propagation. When a high index material (HIM) is surrounded by a low index material (LIM), the HIM can confine and guide light. In SOI waveguides, the light is guided in the silicon core as Si has higher refractive index (3.5) than SiO$_2$ (1.45). Figure 3 illustrates how light is guided in the SOI waveguides.

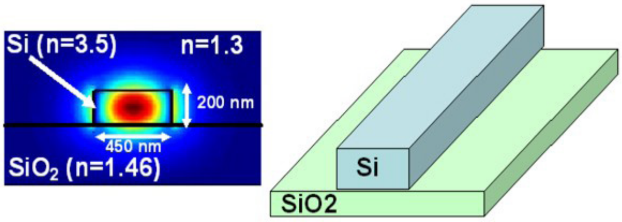

**Figure 3.** Mode propagation in the Silicon core of a SOI strip waveguide [8]

In the literatures, numerous waveguide architectures have been reported, and the R&D institutes like IMEC, IME, CEA- LETI and IHP have perfected the processes and recipes of fabricating excellent low-loss SOI waveguides. In Table 1, the properties of some of the commercially available SOI waveguides are presented.

**Table 1.** SOI waveguides in near-IR

| WG Type | Structure | Loss (dB/cm) | λ (nm) | Source |
|---|---|---|---|---|
| **Strip** | 220nm SOI | 2.5 | 1550 | Imec:iSiPP50G [9] |
| | 220nm SOI | <3 | 1550 | IHP [10] |
| **Rib** | Deep: 150nm partial SOI | 2.0 | 1550 | Imec:iSiPP50G [9] |
| | Shallow: 70nm partial SOI | 1.5 | 1550 | Imec:iSiPP50G [9] |
| | Multimode: 300/65nm SOI | <0.3 | 1550 | CEA-LETI [11] |
| | Monomode: 300/150nm SOI | <2.5 | 1550 | CEA-LETI [11] |
| | Deep: 120nm partial SOI | <2 | 1550 | IHP [10] |
| | Shallow: 70nm partial SOI | <1.5 | 1550 | IHP [10] |

These commercially available waveguides are mostly fabricated for guiding C-band wavelengths (telecommunication wavelength). However, for many applications, the mid-infrared (MIR) guidance is also required. Unfortunately, due to the high absorption losses of SiO$_2$ in the MIR regime, these aforementioned SOI WGs cannot be used for MIR. Therefore, several other waveguide architectures have been investigated to get rid of the proximity effects of SiO$_2$ on waveguide cores. Research has been carried out on platforms other than silicon dioxide such as sapphire [12]. Other researches include Ge-on-Si [13] or suspended structure [14] where the bottom layer (BOX) of the waveguide undergoes a HF removal to reduce

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the light absorption in that layer. A comparison is shown in Table 2.

**Table 2.** SOI waveguides in MIR

| WG Type | Structure | Loss (dB/cm) | λ (nm) | Source |
|---|---|---|---|---|
| **Slot** | Si-on- Sapphire Slot | 11 | 3400 | [12] |
| **Suspended** | - | 3.6 | 3800 | [14] |
| **Strip** | Ge-on-Si (2 μm) | 3 | - | [13] |

The losses in the waveguide is a strong function of the size of the core. The waveguide loss decreases with the increase of waveguide width. This trait has been demonstrated for a SOI waveguide fabricated with DUV lithography and dry etching [15], as shown in Figure 4.

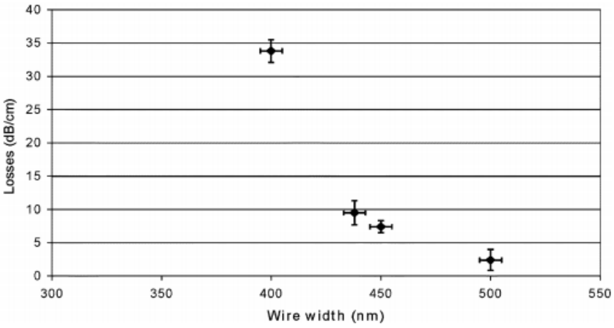

**Figure 4.** Loss vs WG widths [15]

### 2.2 Waveguide Materials

In most of the silicon photonic systems, the waveguides are designed to guide light within the chip at a very low loss. The key to achieve low propagation and material losses is to find the material with high refractive index and small free carrier absorption coefficient [16]. Extensive research has been carried out to find a CMOS compatible material with such traits.

In a CMOS platform, the first material of choice is silicon. Silicon is a very efficient waveguide material as it has a very high refractive index (3.5 at 1550 nm) and low absorption loss [16]. Silicon-based SOI waveguides are excellent choice in the near-infrared (NIR) as well as in the mid-infrared (MIR) regime (2-20 μm) as it is transparent up to 8 μm wavelength [17]. However, it is not possible to go beyond 4 μm in silicon-based SOI waveguides as absorption loss in $SiO_2$ reaches very high value at these wavelengths [17]. Therefore, other platforms or techniques are currently being investigated for MIR transmission.

Another popular material for waveguides is Ge-on-Si [13,18]. Since there is no $SiO_2$ involved, the optical transmission can be extended up to 15 μm in such waveguides [17]. A fabricated Ge-on-Si waveguide is shown in Figure 5.

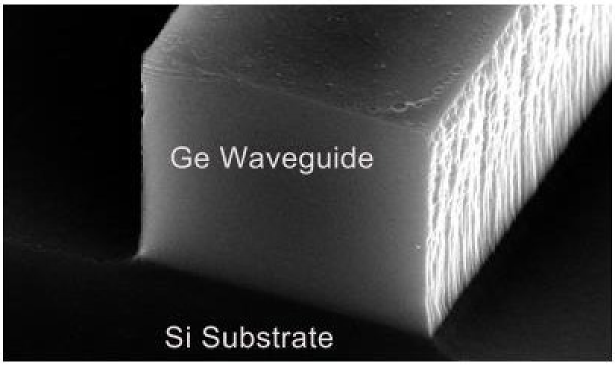

**Figure 5.** A fabricated Ge-on-Si Waveguide [18]

Currently, $Si_xN_y$ —another CMOS compatible material— is becoming popular in silicon photonics-based waveguides. Although SiN has a refractive index of 2, which is less than that of Si, its low material loss justifies its popularity. In the $Si_xN_y$- on-insulator configuration, losses less than 0.5dB/cm in the visible and NIR region have been reported in the literature [19].

### 2.3 Loss Compensation

Instead of finding different CMOS compatible materials with low loss, some researchers are trying to incorporate erbium (gain medium) into the SOI waveguide to compensate for the free carrier absorption and confinement losses in the core [20]. When erbium doped silicon waveguide is excited with NIR, the intra-4f shell atomic transition of $Er^{3+}$ ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) occurs, and it emits light at 1550 nm. Using this technique, losses in the waveguides can be compensated very effectively. This idea came from the optical fiber technology where fiber cores are doped with Erbium to amplify the optical signal without the presence of any active amplifier. Other compensation techniques include incorporating III-V materials with the waveguide to amplify the optical signal.

## 3. Optical Modulator

Optical modulators are one of the most import component of silicon photonics. These modulators take advantage of the refractive index or absorption change in silicon with the change in other externally controllable parameters. The modulators that use refractive index change to modulate optical signals are called electrorefraction modulators while the ones that use absorption change in material to modulate the signal are called electroabsorption modulator (EAM). To change the refractive index or absorption in silicon, external electric field or variation in free carrier density (plasma dispersion effect [21]) within silicon can be used. However, for silicon, changing external electric field has very weak effect on refractive index or absorption change [22]. Varying the free carrier density within silicon, on the other hand, has very strong effect on both refractive index and absorption. Therefore, this technique is commonly used to build silicon based optical modulators in the industry.

### 3.1 Modulator Designs

As mentioned above, varying the charge density within silicon by external means is the best way to build an optical modulator. The variation in charge density can be achieved in three different ways: carrier injection, depletion, and accumulation [23].

Using these three methods, countless new device structures have been proposed and realized. The first modulator design that utilized plasma dispersion effect was reported by Soref [24]. This device utilizes carrier injection method as a mean of varying carrier density. The schematics of the design of this modulator is presented in Figure 6. In this design, the rib waveguide was fabricated on $SiO_2$ which is similar to what we now call BOX in SOI devices. By controlling the voltage, the free carrier density within the waveguide could be changed, and thus, light propagating through the waveguide would experience a phase shift (due to refractive index change).

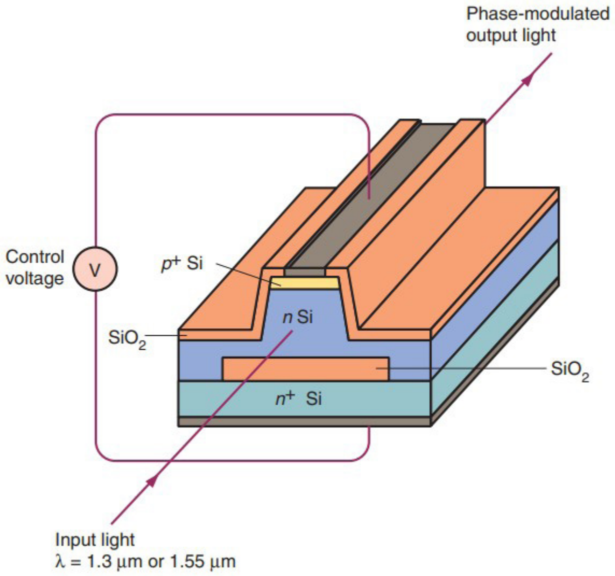

**Figure 6.** SOI $p^+$-n-$n^+$ rib waveguide modulator [23]

Perhaps, the revolution in silicon photonics industry was triggered by the first demonstration of a 1 Gbps modulator by Intel Corporation in 2004 [25]. The device architecture closely resembles the structure of a MOSFET. The rib-type waveguide consists of a p-Poly-Si layer and it is separated from the bottom n-Si layer by a thin oxide layer. By applying voltage at the p- polysilicon layer, small charge can be accumulated at the interface of p-Poly-Si and n-Si. These charges change the refractive index profile of the waveguide, and thus, achieves phase modulation. This phase modulation can later be converted to intensity modulation by means of Mach–Zehnder interferometer. The device proposed in [25] was further optimized, and a bandwidth of 10 GHz was achieved. These devices work on the basis of charge accumulation. A schematic of the first silicon modulator to exceed 1 Gbit/s is shown in Figure. 7.

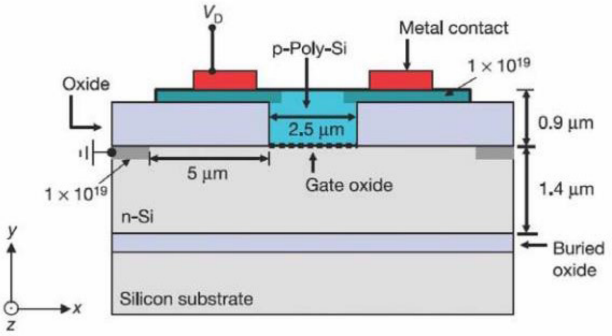

**Figure 7.** Schematics of the first silicon modulator to exceed 1 Gbit/s [23]

As discussed earlier, another means of varying carrier density within silicon known as depletion method is also possible. In this method, a p-n junction is formed and kept in the reversed biased configuration. The light is propagated through the depletion region of the device, and while propagating, the carrier density in the depletion region is changed by varying the external reversed biased voltage. This modulated carrier density results in modulated optical signal. The challenges related to optical loss is tackled by introducing highly doped $n^+$ and $p^+$ regions at the extreme sides of the device. Figure 8 illustrates the schematics of such device. This device has achieved an unprecedented data transmission rate of 30 Gb/s [26].

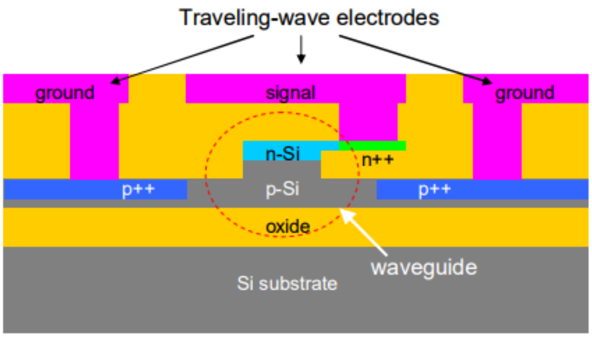

**Figure 8.** Schematics of the modulator utilizing carrier depletion method [26]

Many other designs are currently being investigated and realized. A summary of some contemporary research is presented in Table 3.

**Table 3.** Optical Modulators [23]

| Structure | Modulation Principle | Speed (Gbps) | Energy/bit (fj/bit) |
|---|---|---|---|
| **MZI** | Depletion | 30 | 30000 |
| **MZI** | Forward Biased | 10 | 5000 |
| **Ring** | Forward Biased | >12.5 | 300 |
| **Disk** | Forward Biased | 10 | 85 |
| **Ring** | Forward Biased | 3 | 86 |
| **Ring** | Reverse biased | 10 | 50 |

### 3.2 Modulator Materials

Currently, other methods of modulation are being investigated for better speed and energy/bit performance in optical modulators. The quantum confined Stark effect (QCSE) is a very good candidate for modulation. It utilizes electric field induced changes in the material absorption. However, as mentioned above, electric field induced effects are very weak for silicon. Therefore, alternative materials other than silicon are needed to be experimented with.

For optical modulators, materials such as Ge [27], GeSi [28] have already been used to develop devices, and their superior performance justifies the process complexities introduced by multiple material system. In Figure 9, a schematic of a 50 GHz waveguide EAM has been presented. This modulator has recently been fabricated by IMEC [27].

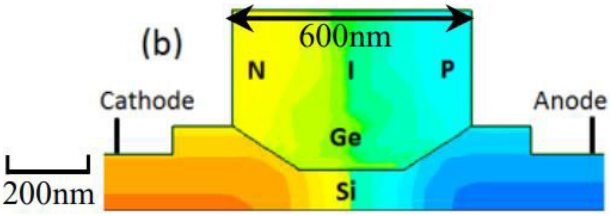

**Figure 9.** Schematics of 50 GHz Ge waveguide EAM [27]

## 4. Semiconductor Laser

Lasers have been the most challenging aspect of silicon photonics due to the inferior photon generation properties of silicon. As silicon is an indirect bandgap material, it generates phonons (heat) instead of photons while configured for stimulated emission. Although, several research works have managed to make silicon based light emitters work, the entire process remains very inefficient. Therefore, different material systems have been explored, and tremendous R&D efforts have been placed to make those materials CMOS compatible.

### 4.1 Materials

The materials that are excellent as optical gain medium, are group III-V materials. Group III-V materials such as GaAs, AlGaAs, GaP , InGaP, GaN, InGaAs, GaInNAs, InP, GaInP, etc are heavily used in the industry for LED and lasers fabrication. However, these materials are not CMOS compatible as their lattice constants are not matched with that of silicon. The growth of these materials on silicon substrate results in interfacial states and dislocations due to the lattice mismatch. Therefore, the resulting laser/LED will be of very low quality with extremely low efficiency.

On the other hand, the materials such as InP or GaAs have similar lattice constants as the other III-V materials. Therefore, the growth of optically active III-V materials on InP or GaAs substrate will result in lesser number of dislocations and defects. The resulting device on these substrates will be highly efficient. III-V materials grown on InP substrate is shown in Figure 10.

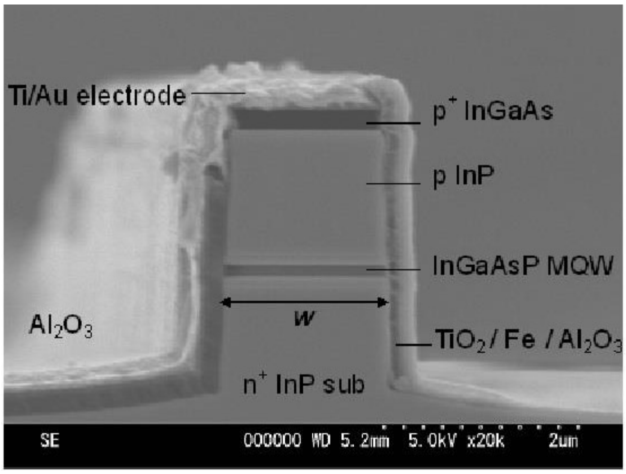

**Figure 10.** III-V materials grown on InP substrate [29]

Therefore, lasers, LEDs and photodetectors are usually grown on the InP or GaAs substrate. Afterwards, in the backend process, the devices fabricated on InP or GaAs substrates are integrated to the SOI wafer using techniques knows as hybrid integration [30]. The process of fabricating lasers directly onto the silicon substrates is known as monolithic integration which is not very popular due to the process complexities involved.

### 4.2 Hybrid Integration

As explained earlier, hybrid integration is a technique to integrate non-CMOS-compatible devices to the CMOS SOI devices. For lasers, several hybrid integration techniques are currently being used in the industry. The most popular one is wafer bonding. Depending on the requirements, several types of wafer bonding techniques are currently being used. For example, wafer-to-wafer (W2W) molecular bonding, die-to-wafer (D2W) molecular bonding, BCB-assisted D2W adhesive bonding (benzocyclobuten), and metal-assisted adhesive bonding (AuGeNi) [30].

A simple schematic diagram is presented in Figure 11 to demonstrate the wafer bonding technique used in the industry to integrate lasers onto SOI waveguides. Here, first, the III-V epi layer is fabricated onto the InP substrate. Afterwards, an O2 plasma assisted wafer bonding process is carried out at low temperature. Then, the InP substrate is etched out, and the standard photolithography and etching techniques for III-V devices is implemented for further processing.

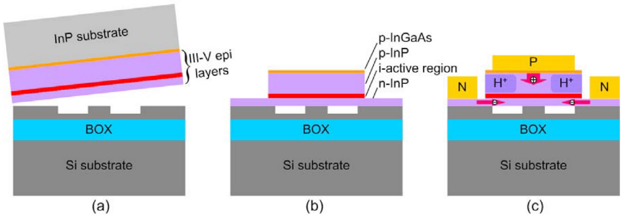

**Figure 11.** Process flow of a simple wafer bonding of III-V Semiconductor on SOI substrate [32]

### 4.3 Monolithic Integration

Extensive researches have been carried out to monolithically grow laser devices on SOI platforms. These researches explore aspects ranging from doping of silicon with rare earth ions and exploring silicon nanocrystals to applying tensile strain to engineer the bandgap of silicon. Recently, a Ge-on-Si structure has been realized that is capable of emitting light. This has been done by employing tensile strain technique on silicon [33].

## 5. Conclusions and Discussion

In this article, the three fundamental building blocks of silicon photonics (waveguides, lasers, and modulators) have been thoroughly investigated, and the current state-of-the-art regarding these devices have been presented. The process integration and material related challenges have also been summarized, and the future direction of the R&D activities related to silicon photonics has been pointed out. Judging by the pace at which the silicon photonics industry is currently progressing, the authors believe that the silicon photonics industry will soon overtake many of the technologies we presently are using.

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