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Integrating Silicon Photonics

Concept, Devices and Future Prospects

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Abstract —*This Silicon photonics is the adaptation of silicon integrated circuit technology and manufacturing processes to the design and manufacture of electro-optical transceivers to be used for short-haul optical data transport.The use of exotic materials has made optical technology an expensive solution. This prompted research for the construction of fiber-optic components from silicon.Silicon photonics has attained much attention in recent years owing to the maturity of silicon-based electronics industry and its possibility of monolithic integration of both photonic and electronic devices on one chip. It develops high-volume low cost optical components using standard CMOS process used today. Intel has recently come up with first silicon photonics integrated link, with integrated hybrid silicon lasers operating at 50 Gbps over a single fiber. The milestones in the development of Silicon Photonicsalong with its future prospects are discussed.*

Keywords-*Silicon Photonic; Raman Laser;Optical Modulation.*

I. INTRODUCTION

The silicon integrated technology has progressed from a few transistors in a circuit to billions in a span of a few decades. Along the way, entire computer processors were fabricated and then improved every year. The progress of Moore's law has led to the incorporation of integrated circuits into almost everything. Scaling is the engine of progress in silicon microelectronics. For many years, the ITRS has highlighted interconnect bottleneck as the one threat to continued scaling in particular that must be addressed in the short term future in order to avoid slowing down the pace of Moore's Law. As the number of transistors in an integrated circuit increases, more and more interconnecting wires must be included in the chip to link those transistors together. Sending information along these wires consumes significant power in various losses and introduces the majority of speed-limiting circuit delay in a modern integrated circuit. Scaling exacerbates both of these problems by decreasing the cross sectional area of each wire, proportionately increasing its electrical resistance. With further scaling the RC capacitive charging delays in the wires will increasingly dominate the overall performance of future integrated circuits.

The potential value of optical data transport for integrated circuit electronics systems has been known for decades. Compared to electrical wires, light can send data faster and over longer distances. The copper wires between regions of an integrated circuit would be replaced by a system of lasers, modulators, optical waveguides and photo-detectors. The metal interconnects at all levels starting from those within the ICs to that between ICs on boards and that with peripheral devices are replaced with optical links. The potential benefits of this approach include the virtual elimination of delay, cross talk, and power dissipation in signal propagation, although significant new challenges will be introduced in signal generation and detection.

It cannot be said for certain that Moore's Law rates of improvement and investment can be replicated with other technologies. Thus, the ability to leverage what has been developed for silicon integrated circuits for a cost efficient technology is a worthwhile prospect. It is no surprise, therefore, that researchers in the photonics sector have strived for years to create silicon-based optical devices that can exploit the benefits of silicon while also being fully compatible with electronics. Silicon photonics is now the most active discipline in integrated optics.

Besides the cost and use of available silicon integrated technology, the motivation for silicon photonics is the availability of high quality silicon on insulator (SOI) [1] wafers, an ideal platform for creating planer very low loss and high optical mode confinement waveguides, which enable a wave of new applications, including nano-optomechanics[2], biosensing[3], nonlinear optics[4] and very-long wavelength integrated photonics[5].

All of the constituent components of a photonic data transmission system built on electronics-compatible silicon wafers — including laser sources, modulators, detectors, waveguides , resonators, couplers, splitters and filters — have already been developed and are improved upon.

II. SILICON-ON-INSULATOR

The SOI forms the backbone of integrated photonics, providing the ability to integrate the various passive devices on a single chip. The wafer consists of a silicon substrate, oxide layer and crystalline silicon which acts as waveguide.Silicon is transparent for wavelength greater than 1.1 µm. The refractive indices of silicon and silicon dioxide are around 3.5 and 1.5, respectively. Thus the wafer forms a waveguide for optical transmission. The most common waveguide structure is the rib-waveguide. The size of the waveguide determines the operation of the waveguide and other photonic devices built upon it. All the optical components needed in photonics chips provide best performance at different waveguide thickness. Although, open access foundries have adopted 220nm thick device as standard, a foundry with flexible silicon thickness may become accessible for improved performance.

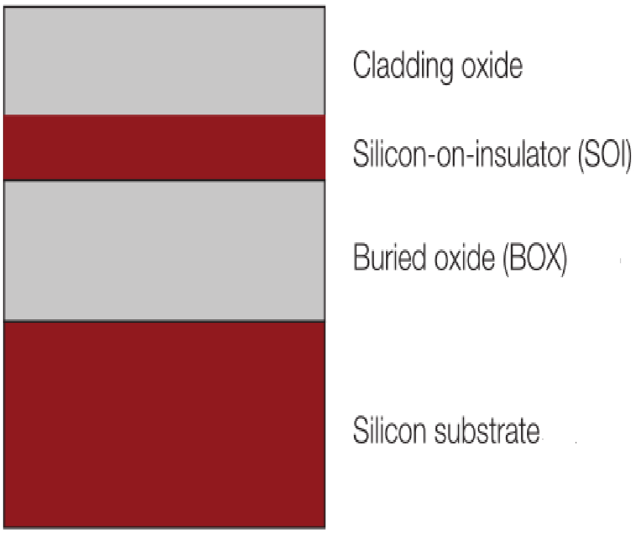

Figure 1. Cross-sectional view of Silicon-on-Insulator wafer.

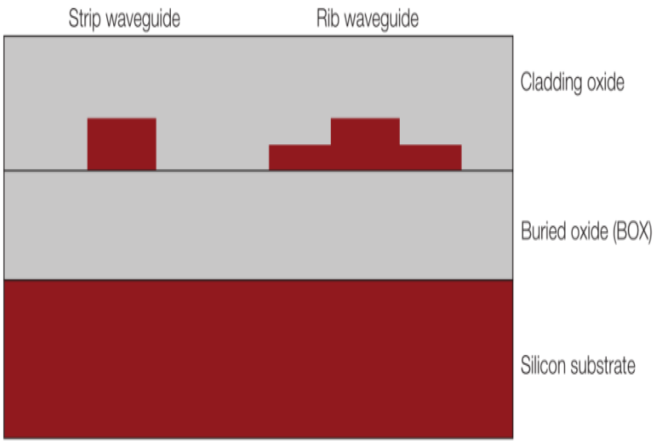

Figure 2. Common waveguides in silicon photonics. Rib waveguide (right) and Strip waveguide (left).

III. LASERS

Owing to its indirect band-gap, silicon, along with Ge, was never conceived for light emission. Free electrons tend to reside in the X valley of the conduction band, which is not aligned with free holes in the valence band (Fig. 3). Therefore if a recombination is to lead to emission of a photon, a third particle must be involved to carry away the excess momentum, which results in slow optical transition rates. A major non-radiative process is Auger recombination, in which an electron (or hole) is excited to a higher energy level by absorbing the released energy from an electron–hole recombination. The Auger recombination rate increases with injected free-carrier density and is inversely proportional to the bandgap. Free-carrier absorption (FCA) represents another major non-radiative process wherein the free electrons in the conduction band can jump to higher energy levels by absorbing photons. In high-level carrier injection devices (lasers and amplifiers, for example) or heavily doped layers, free-carrier loss is orders of magnitudes higher than the material gain[6]. For both Auger recombination and FCA, the electrons pumped to higher energy levels release their energy through phonons, rather than by emitting photons. They also have much shorter lifetimes (τ_{nonrad}) than those of radiative processes (τ_{rad}) in Si, resulting in an extremely poor internal quantum efficiency η_{i} of light emission, which is defined as

$$\eta_i = \frac{\tau_{nonrad}}{\tau_{nonrad} + \tau_{rad}}$$

and is generally of the order of 10^{-6}.

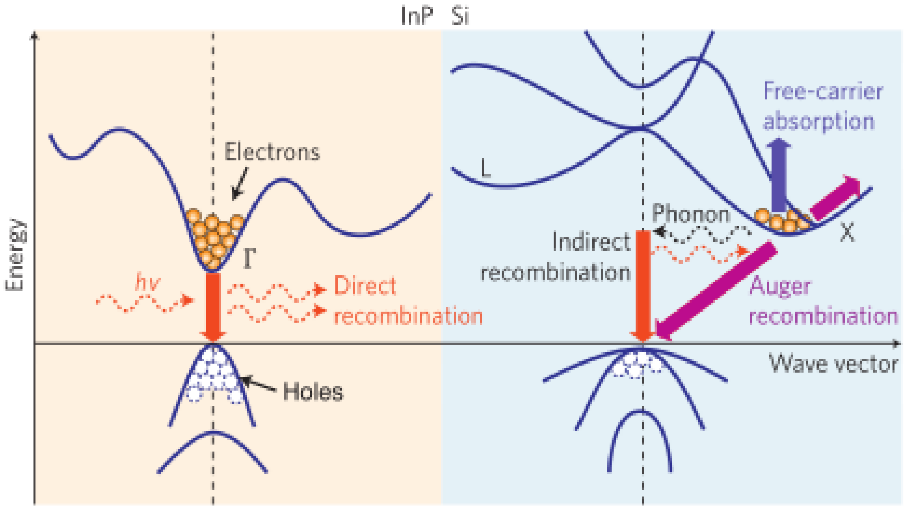

Figure 3. Energy band diagrams and major carrier transition processes in InP and silicon crystals.

In a direct band structure (InP), electron–hole recombination almost always results in photon emission, whereas in an indirect band structure (Si), free-carrier absorption, Auger recombination and indirect recombination exist simultaneously, resulting in little photon emission.

This is the reason why semiconductor laser research over the past has primarily focused on compound semiconductor substrates like GaAr, InP and GaN. These discrete lasers need careful alignment and assembly with high sophistication requiring more elaborate and complex assembly process. This prompted for research in silicon based lasers. Silicon Raman laser[13], Ge-on-Si laser, hybrid silicon lasers and the recent electrically pumped continuous-wave III–V quantum dot lasers on silicon[14] offer promising results.

3.1 Silicon Raman Laser

The Raman Effect refers to the inelastic scattering of a photon by an optical phonon. When incident light is absorbed by an atom or molecule at a vibrational state, the system energy is raised to an intermediate higher state. In most cases, the energy quickly drops back to the original vibrational state by releasing a photon with the same frequency, which is known as Rayleigh scattering, and is analogous to elastic scattering. Yet it is also possible to observe very weak (approximately one in ten million photons) additional components with lower and higher frequencies than the incident light due to the absorption or emission of optical phonons, namely the Stokes and anti-Stokes transitions, respectively.

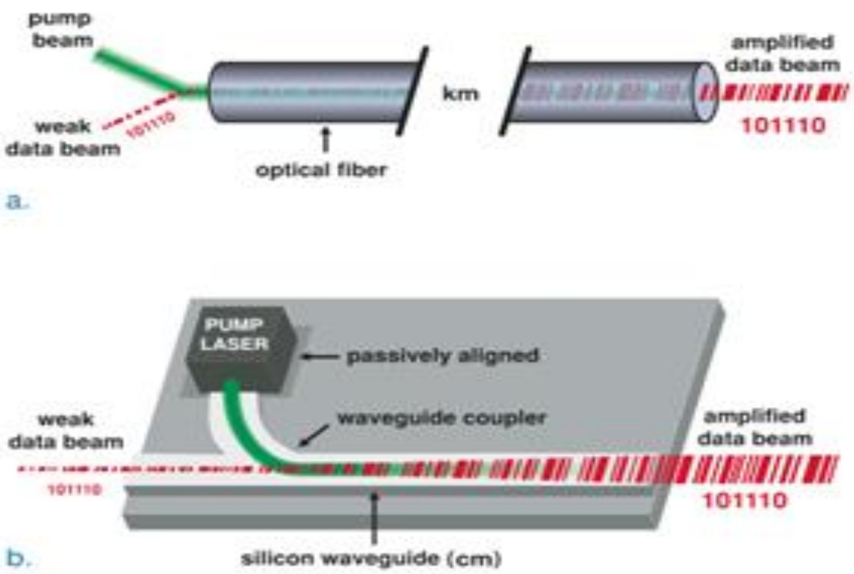

Figure 4. The Raman Effect allows energy form a pump beam to amplify data at longer wavelengths in glass fiber (a). This could now be dome in silicon as well (b).

If a scattering medium is irradiated with pump and signal beams simultaneously, the pump beam excites the constituent molecules or atoms to a higher vibration level, while the signal beam, which has a frequency resonant at the Stokes transition, triggers the generation of another Raman Stokes photon. Thus, amplification can be achieved through stimulation of the Stokes transition. This technique is known as stimulated Raman scattering and has enabled the realization of Raman glass fiber amplifiers with gain bandwidths of over 100 nm. The Raman gain coefficient in Si is around five orders of magnitude larger than that in amorphous glass fibers because of the well-organized single-crystal structure. However, Si waveguide loss is also several orders of magnitude higher than in glass fiber, making fabrication of a low-loss Si waveguide one of the keys to realizing net Raman gain in Si. A pump with energy well below the Si bandgap is typically used to avoid elevating the electrons up to the conduction band and also to suppress FCA — both of which prevent lasing in Silicon. High pump powers, however, induce another optical loss mechanism — two-photon absorption (TPA). TPA is a nonlinear loss mechanism in which two photons combine their energies to boost an electron in the valence band to the conduction band. Free carriers further induce FCA and dump more optical power inside the cavity. TPA increases with the number of photons in a waveguide, and therefore becomes a limiting factor when using high optical pump powers. The first demonstration of a pulsed Si Raman laser overcame TPA by using a long delay together with a short optical pulse, thus allowing the carriers generated during TPA to recombine prior to the next pass of the optical pulse. A p-i-n (p-type/intrinsic/n-type layers) structure is used in the waveguide to sweep free carriers away under a reverse bias, as this reduced the free-carrier lifetime to minimize TPA-induced FCA. The first successful demonstration of a CW Si Raman laser followed soon after[7], with a lasing threshold at an effective pump power of ~182mW for a reverse bias of 25 V.

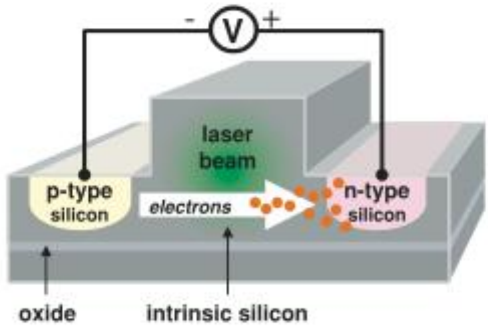

Figure 5. The electrons generated by TPA are removed and continuous amplification is obtained by using diode-like PIN device.

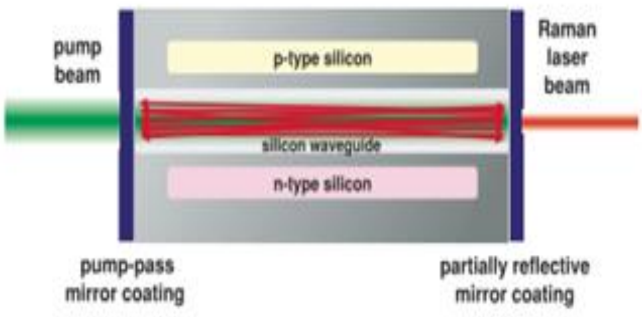

Figure 6. The breakthrough silicon laser uses a PIN device and the Raman Effect to amplify light as it bounces between two mirrors coated on the waveguide ends, producing a continuous laser beam.

The Raman Effect could also be used to generate lasers of different wavelengths from a single pump beam. As the pump beam enters the material, the light splits off into different laser cavities with mirrors made from integrated silicon filters (Figure 7). The use of lasers at multiple wavelengths is a common way of sending multiple data streams on a single glass fiber.

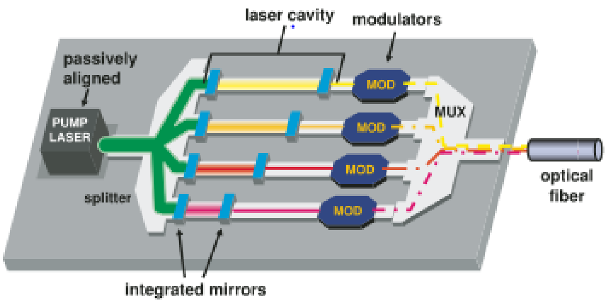

Figure 7 . A pump beam that contains multiple wavelengths could power four lasers of different wavelengths via Raman laser.

3.2 Hybrid Silicon Laser

The SOI substrates used in Si photonics are usually made by wafer bonding an oxidized Si wafer onto another Si carrier wafer. By wafer-bonding compound semiconductors to SOI substrates, this same approach can be used to combine the superior gain characteristics of compound semiconductors with the superior passive waveguide characteristics of Si waveguides. This idea has been demonstrated for wafer sizes of up to 150 mm in diameter. Intel, in its first electro-optical transceiver chip, has used hybrid silicon transceivers.

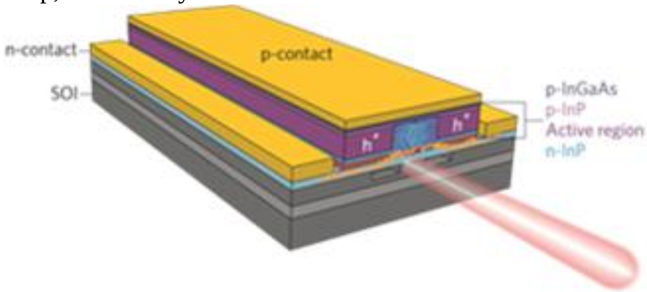

Figure 8. Hybrid Si device platform

IV. MODULATORS LASERS

Optical modulation is one of the main required functionalities for any optical interconnect solution. An optical source can be either directly or externally modulated. External modulation has advantages over direct modulation. The optical source can be relatively inexpensive and its operation does not need to be compromised by direct modulation, modulation speeds can be higher, and optical isolation and wavelength stabilization need to be performed only once for the entire system. Furthermore, a single light source can feed multiple channels via individual modulators, thus reducing the total power budget of the system.

An optical modulator is a device that is used to a light beam propagating either in free space or in an optical waveguide. These device can be categorized as either amplitude, phase or polarization modulators. In addition, modulators can be also classified as either electro-refractive or electro-absorptive.

Applying an electric field to a material may change its real and imaginary refractive indices. A change in the real part of the refractive index (Δn) with an applied electric field is known as electro-refraction, whereas a change in the imaginary part of the refractive index ($\Delta\alpha$) is known as electro-absorption.

The most common method of achieving modulation in silicon devices so far has been to exploit the plasma dispersion effect, in which the concentration of free charges in silicon changes the real and imaginary parts of the refractive index. This is described by the Drude-Lorenz equations that relate the concentration of electrons (N_e) and holes (N_h) to the absorption coefficient α and refractive index n. For a modulator, the most convenient way of expressing this is as the change in these parameters, $\Delta\alpha$ and Δn, with the change in electron and hole densities, (ΔN_e) and (ΔN_h). Soref and Bennett[8] evaluated changes in the refractive index Δn from experimentally produced absorption curves for a wide range of electron and hole densities, over a wide range of wavelengths. They also quantified changes in both the refractive index and absorption[8], and produced the following expressions to evaluate changes in the carrier densities in silicon at a wavelength of 1.55 μm:

$$\Delta n = \Delta n_e + \Delta n_h = -[8.8 \times 10^{-22} \times \Delta N_e + 8.5 \times 10^{-18} \times (\Delta N_h)^{0.8}]$$
$$\Delta\alpha = \Delta\alpha_e + \Delta\alpha_h = 8.5 \times 10^{-18} \times \Delta N_e + 6.0 \times 10^{-18} \times \Delta N_h,$$

whereΔn_e and Δn_h are changes in refractive index resulting from changes in the free-electron and free-hole carrier concentrations, respectively, and $\Delta\alpha_e$ and $\Delta\alpha_e$ are the changes in absorption resulting from changes in the free-electron and free-hole carrier concentrations, respectively. Similarly, at a wavelength of 1.3 μm:

$$\Delta n = \Delta n_e + \Delta n_h = -[6.2 \times 10^{-22} \times \Delta N_e + 6.0 \times 10^{-18} \times (\Delta N_h)^{0.8}]$$
$$\Delta\alpha = \Delta\alpha_e + \Delta\alpha_h = 6.0 \times 10^{-18} \times \Delta N_e + 4.0 \times 10^{-18} \times \Delta N_h$$

Using these expressions, to calculate, for example, that a change in carrier density of the order of 5×10^{17} cm^{-3} results in a Δn of -1.66×10^{-3} at a wavelength of 1.55 μm. However, this is accompanied by a detrimental change in intensity due to the absorption of free carriers[11].

Electrical manipulation of the charge density interacting with the propagating light is achievable through mechanisms such as carrier injection, accumulation or depletion. These schemes are represented schematically by waveguide cross-sections in Fig.9.

There are essentially two options available for converting a change in refractive index into intensity modulation. First, the refractive index change can be used to shift the relative phase of two propagating waves such that they interfere either constructively or destructively. Typically, a Mach–Zehnder interferometer (MZI) is used to achieve this. Second, including a resonant structure in the device allows the refractive-index change induced in the modulator to change the resonant condition, thus allowing the device to be switched between on- and off-resonance states at any given wavelength.

The early years of the research into optical modulators based on silicon waveguides saw devices that were generally slow (~megahertz data rates), with seemingly little prospect for applications in high-speed systems. Most monolithic devices exploited carrier injection, using the plasma dispersion effect for modulating either the refractive index or the absorption coefficient of the material. In most cases p-i-n (p-type/intrinsic/n-type layers) diode structures were formed around the waveguide to electrically control the injection of electrons and holes into the path of the propagating light. Performance enhancements have been made over the years by optimizing the structure and reducing device dimensions; device bandwidths in the gigahertz regime had already been proposed by the mid-2000s. The schematic of one such device is shown in Fig. 10

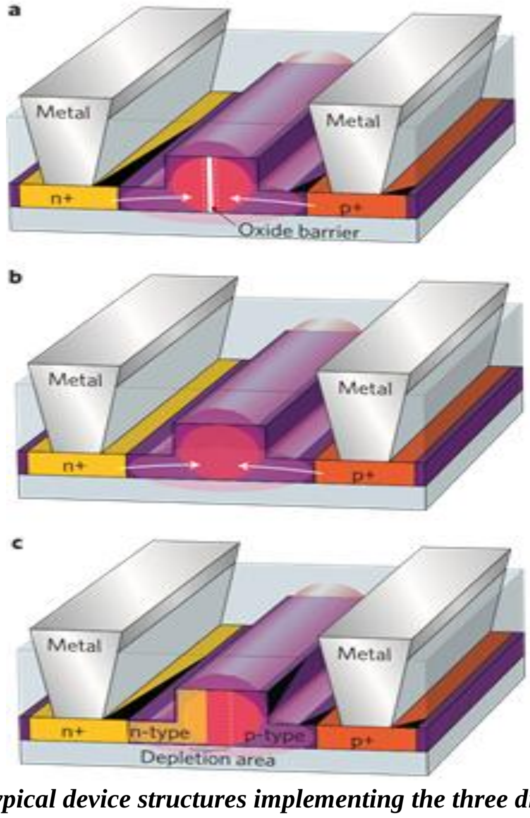

Figure 9 | Cross-sections of typical device structures implementing the three different mechanisms commonly used to electrically manipulate the free-carrier concentrations in plasma-dispersion-based silicon optical modulators. a), Carrier accumulation; a thin insulating layer of SiO_2 is used to isolate twohalves of the waveguide to form a capacitor structure. b), Carrier injection; highly doped p- and n-regions are separated by an 'intrinsic region' in which thewaveguide is formed. Forward-biasing the device causes free electrons and holes to be injected into the 'intrinsic' waveguide region. c), Carrier depletion; lightlydoped p- and n-type regions abut in the waveguide to form a p–n diode. The depletion area of the diode becomes larger with increasing reverse bias voltage.

The breakthrough came in 2004 when the first monolithic silicon modulator capable of operating at speeds of >1 GHz was experimentally demonstrated by the Intel group. The device, shown in Fig. 2b, functioned by accumulating free carriers on either side of a dielectric layer inside a micrometer-sized waveguide (much like in a capacitor), rather than by carrier injection.The performance of this carrier-accumulation device was later optimized, and data rates of 10 Gbps were achieved.

Carrier depletion is another technique that manipulates free-carrier densities in a modulator to avoid the speed limitation posed by the minority carrier lifetime. Devices based on carrier depletion operate by allowing the propagating light to interact with the junction region of a p–n diode operated at reverse bias. The diode's depletion width, and therefore the free-carrier density in the waveguide, varies with the applied reverse bias. In 2005, the first modulator using this technique in a sub-micrometer waveguide was proposed, with theoretical models predicting an unprecedented intrinsic bandwidth of 50 GHz. The device featured a horizontal p–n junction across the waveguide with the highly doped regions required for the formation of resistive contacts placed at the extremities of the waveguide to avoid excessive optical loss.

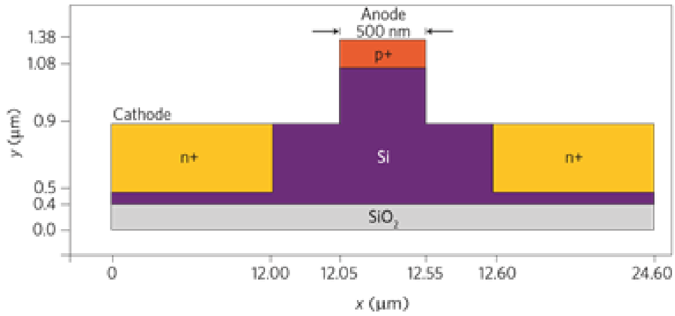

Figure 10 | Cross-section of the first proposed gigahertz modulator, which was based on carrier injection

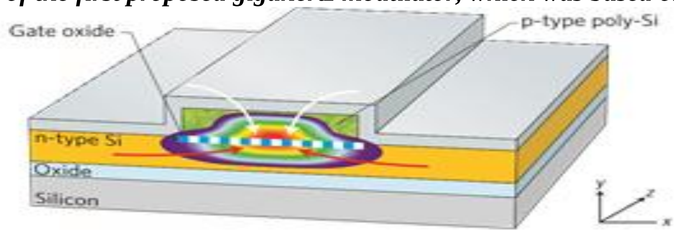

Figure 11 | Cross-section of the first experimentally realized gigahertz modulator based on carrier accumulation

Two years later a design a similar was realized by Intel. The authors reported initial data transmission rates of 30 Gbits^{-1} but later improved this figure by demonstrating data transmission at 40 Gbps. The challenge remains to improve efficiency while maintaining other performance metrics.

V. PHOTODETECTORS

The non-absorbent nature of silicon at the operating wavelength of silicon photonics required photo-detectors which could be integrated into SOI. In 2008 Intel came up with the fastest Si-Ge based APD with a 340 GHz gain-bandwidth product. Today Ge photo-detectors are considered to be the most mature devices in the silicon-based photonics technology. Most of the results on Ge photo-detection have been obtained in 130 to 160nm. Detection in mid-infrared range is desirable in order to exploit a broader wavelength region for other applications as well.

VI. FUTURE OF SILICON PHOTONICS

During the past few years silicon photonics has grown through leaps and bounds with new ways being discovered and tried. But it is still a challenger of the InP based discrete-component solution. The electro-optical transceivers for data centers have now been in the market for a while. Intel's has come-up with integrated link which is said to operate at a speed of 50 Gbps. It consists of a fully integrated silicon photonic transmitter chip with hybrid silicon lasers and a fully integrated receiver chip based on germanium photo-detectors. Both chips are fabricated using CMOS silicon manufacturing techniques, with passive optical connector. The transmitter chip consists of four hybrid silicon lasers operating at wavelengths of 1351, 1331, 1311 and 1291 nm. These four lasers are fabricated by bonding a layer of indium phosphide to the silicon photonic chip. Each of the four laser outputs is directed towards its own silicon modulator, which transforms the incoming electrical data stream into an optical signal. A multiplexer is then used to combine the optical channels and launch them into a fiber via an on-chip fiber coupler. On the receiver chip, optical signals coupled to the connecting fiber are separated into the four initial wavelengths by a de-multiplexer. They are then directed into four monolithically integrated germanium photo-detectors that convert the photons back into electrical data streams. The driver for the integrated circuit was designed specifically for the low-voltage (~1.35 V) silicon modulators, and is based on the 65 nm CMOS process. The link provides 50 Gbps with12.5 Gbps per channel.

The solution for monolithic integration of electronics and photonics with separation of electronics and photonics processes like Cu-Cu bonding, and Back-end technology for bonding seems promising. When maturity of silicon photonics will be high enough it will be possible to build the photonic devices on top of the electronic layers.

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