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Silicon Photonics: A Review

Mr. Akshaykumar S. Hedaoo[1], Prof. Atul N. Shire[2] and Prof. Atul P. Shingade[3]

[1] Department of Electronics And Telecommunication, JDIET,
Yavatmal, (M.S.) - 445001, India

[2] Department of Electronics And Telecommunication, JDIET,
Yavatmal, (M.S.) - 445001, India

[3] Department of Electronics And Telecommunication, JDIET,
Yavatmal, (M.S.) - 445001, India

Abstract

Silicon photonics is the future of optical transmission. As researchers are more interested to replace copper wire with the optical technology. They are using photons instead of electron to carry out the transmission with in the silicon photonics chips. Due to photons the speed of data transfer will increase as compared to wired configuration. This paper reviews the growth of silicon photonics compared to last few years and a promising future of photonics. By taking advantage of silicon photonics, new products can scale bandwidth availability to meet the future demand.

Keywords: *Silicon, Modulators, Mach-Zehnder, SiGe, Detectors, Lasers, Avalanche Photodetector*

1. Introduction

Taking in mind silicon as the core material the new technology of producing optical devices and circuits has been introduce. Using standard CMOS fabrication process integration of optical and electronic components on single chip can be done. At mid wave Si or SiGe/Si components perform well, long wave and very long –wave infrared (THz) ranges. For optical communication the transparency at wavelengths (1270 nm to 1625 nm) and its intrinsic band gap of silicon (1.1 eV) typically favors and manipulates the light. Computers in present using copper wires to connect different peripherals which actually degrades the signal strength and constraints it to the maximum length.

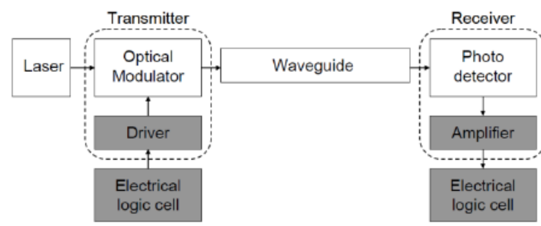

Fig. 1 Basic block diagram of optical link

Basic diagram of optical link is shown in fig (1). The on-chip laser source provides the pumping mechanism. Recently researchers focus on Hybrid Silicon Laser, as the silicon is bonded to a different semiconductor (InP/GaAs) which acts as the lasing medium. We require a Modulator to carry out the data in form of optical signals. Modulation is carried out through free carrier plasma dispersion effect in photonics. Optical medium between different chip and same chip has been provided by silicon waveguide. At the receiver end metal semiconductor junctions based photodetectors integrated into silicon waveguides for detection of light and converting back the data into electronic signals. Using optical interconnections with silicon as an optical medium, we can get the higher data rate over long distances. Signal information carried by the electrons in electrical medium but in optical medium information carried by the photons. Due to no charge and zero rest mass photons can travel at higher rate than electron. By using silicon photonics we can replace electrical circuits with optical circuits.

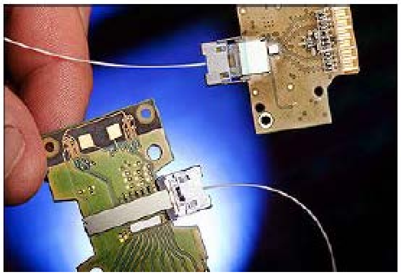

Fig. 2 50 Gbps silicon photonics transmit module

Figure above shows the 50gbps optical link module developed by Intel group. Firstly silicon chip provide laser light which travels through optical fibre and reaches to another silicon chip where it convert laser data in to electrical signals. Due to Optoelectronic systems integration on silicon on substrate (SOI) realizable with complementary metal-oxide semiconductor technology, allows large scale manufacturing and low cost for Si photonic device. Still the work is going on the development of integration methods of low loss waveguides, high quality resonators, high speed modulators and optically pumped lasers on silicon chip for effective photonic circuits with low cost and power consumption.

2. Literature Review

In 1958, Jack Kibly from Texas instrument demonstrated that it was possible to fabricate a resistor, capacitor, and transistor using single-crystal silicon[2]. Which led to first truly integrated circuit and was awarded by Nobel prize in year 2000. Due to which microelectronics industry witnessed a miraculous reduction in individual device size, and hence increases in chip functionality in five decades. And the trend has been set up that approximately after every 24 months world has witnessed the doubling of device density.

In 1962 Gordon Moore predicted Moore's law which remained pertinent to the present day, forming the motivation for the International Technology Roadmap for Semiconductors (ITRS) in 1993.

In 1980, using the design and manufacturing principles from microelectronics industries, taking in mind silicon as the base material for fabrication of photonics circuit researchers began to develop their projects and research. Silicon material proved to be an ideal material for planar light wave circuit (PLC) fabrication. Silicon is virtually transparent to wavelengths > 1100 nm, on the other hand silicon dioxide (SiO2) shares its chemical composition with glass fiber, providing a degree of interference with long-haul, fiber-optic technology. Silicon has a relatively high refractive index around 3.5 which leads to the fabrication of waveguides on the nanometer scale. Due to the size and nature of indirect bandgap, which prevents the deviating formation of efficient optical sources, and detectors compatible with subbandgap wavelengths which leads to limitation of silicon in photonics area[3][4].

A bit previous in the year 2000, primary correspondence for integrated silicon photonics was introduce in telecommunications, so-called first-generation. But due to the development of relatively large waveguide which were used in fiber optic network and optical switching has dominated silicon photonics. But in the late 1990's telecom industry has seen the abundance of technology touted as the favored tribune for integrated photonic circuit fabrication. At that time, Bookham Technology of the UK reached high level of competency in silicon photonics and showed that the methods used in the microelectronics industry to fabricate large volumes of devices in a economical manner could be applied to photonic circuits. Due to increase in engineers and scientists dedication to silicon photonic device design in the 1990s led directly to vast development in the field of silicon photonics in telecom sector.

Second-generation silicon photonics started in February 2004, led by Mario Paniccia and his group at Intel Corp. proclaim the demonstration of an optical device, fabricated wholly in silicon[5]. The potential for integration of photonic and electronic functionality as a method for reducing the excessive power dissipation in microelectronic circuits was thus demonstrated. The year 2004 also saw the publication of the first textbooks to deal with the subject of silicon photonics[6][7]. In the relatively short period, the field has expanded rapidly. Waveguide dimensions are now measured in square nanometers rather than square microns, and demonstration of modulation speeds in excess of 20 GHz have been done[8].

3. High-Speed Silicon Modulator

An Optical Modulator can be used to modulate a beam of light with respect to an information signal. Various factors decide the performance of the modulators: (1) modulation depth (2) modulation speed (3) bandwidth. In ideal cases, we prefer large bandwidth, high modulation speed and low power consumption.

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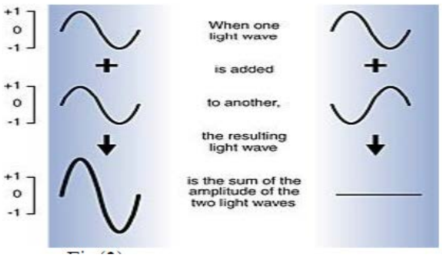

Fig. 3 Modulation process of wave

in the above fig (3) shows the modulation process of two wavelength. Here we can see that if two sine wave are completely matched then they are added and the output is twice the amplitude of individual waves. And if they are totally unmatched then they cancle each other out. Free carrier plasma dispersion effect is come through by silicon integration circuits modulation. Various constraints such as narrow waveguide, bandwidth, low power consumption, modulation efficiency is kept in mind while integrating optical modulators on silicon substrate.

	Ring Modulator	EAM		MZM			
Group	Cornell	UCSB	MIT	UCSB	Intel	IBM	IEF
Platform	Si	Hybrid Si	SiGe	Hybrid Si	Si	Si	Si
ER (dB) and driven bias (V_{pp})	17 (1.8 V)	10 (5 V)	10 (7 V)	12 (4V)	>20 (6V)	6 to 10 (1.8V)	14 (10V)
Bandwidth (GHz)	—	16.0	1.0	8.0	20.0	—	8.0
ER(dB) at high freq.(Gb/s)	9dB at 12.5G*	11dB at 10G	—	6.38 at 10G	1dB at 30Gb	? at 10G*	—
Optical bandwidth (nm)	<1	30	15	> 100	> 75 nm	—	> 30 nm
$V_{\pi}L$ (Vmm)	—	—	—	?	40	0.36	50
length (um)	10	100	50	500	1000	100	4000
loss(dB)/device	—	3	14.8	3	5.4	12	5

Table 1: Comparison of silicon modulators.

There are different types of modulators, Table 1 lists some of the important parameters for each specific modulator. The ring modulator is compact and operating at sub-voltage, but the optical and modulation bandwidth are both limited. It is suitable for high density and narrow bandwidth applications. In opposite, the Electro absorption Modulator (EAM) has slightly larger footprint, fair modulation efficiency and high modulation bandwidth up to 16 GHz. To meet large optical bandwidth reconfigurable communication system must be require for that EAM is a good candidate. The Mach-Zehnder Modulator (MZM) has a larger footprint and requires higher bias condition; however, it has a wider optical bandwidth, higher large signal modulation, and potential applications such as switches and routers make it very inhibiting for future all optical communication networks.

4. Metal-Oxide Semiconductor (Mos) Capacitor-Based Silicon Modulator

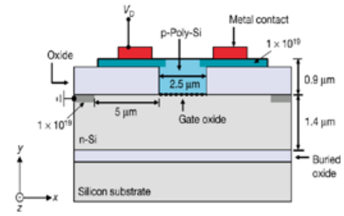

Fig. 4 Cross-section view of the MOS capacitor-based on silicon optical modulator.

Modulation can be achieved by driving MOS capacitor in accumulation mode in this type of modulator. When Positive voltage VD applied on the gate, it forms depletion and inversion layer across the waveguide region. Large amount of silicon charge carriers accumulate in the depletion region due to which there is change in the refractive index. It occurs mainly due to the positive charge. Due to Change in refractive index there will also be the changes in the phase shift and attenuation in one or both arms of interferometer.

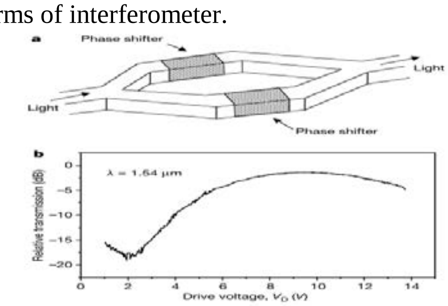

Fig. 5 (a) Phase shifter in both arms of MZI, (b) Drive voltage change with relative transmission

When light enters into MZI it will split up into two beams which travels through both arms of the interferometer. The relative phase shift can be change by Phase shifter between the two beams and modulation can be achieved on the output of interferometer**.** Due to plasma dispersion effect there will be change in the phase shift and attenuation in the arms of interferometer. MOS capacitor also improves the modulation efficiency. Speed of charge carriers in MOS capacitor is not dependent upon minority carrier's lifetime but depends upon the device resistance and capacitance. The optical loss of the phase shifter in high-speed section is 10 dB/cm and in low-speed section is 5.2 dB/cm. MZI modulator gives a total insertion loss of 19 dB consisting of 10 dB on-chip loss and 9 dB coupling loss. Out of 10 dB on-chip loss, 3.5 dB is due to the high-speed (RF) sections, 2.5 dB due to the low-speed (bias) sections. Phase efficiency can be further be improved by reducing the waveguide dimensions and reducing the gate

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dielectric width. Intel in 2004 made it's own MOS capacitor, with modulation bandwidth exceeding 1GHz.

5. Electro-Absorption Modulators

Electro absorption modulator is a type of semiconductor device that modulates the intensity of laser beam via electric voltage. Main principle of operation is based on the Franz–Keldysh effect. Absorption type modulators have high operating speed, low power dissipation and low operating voltage as compared to plasma dispersion-based modulators. Modulation bandwidth of 10 GHz can be achieved through these modulators. Electroabsorption modulators find their applications in high speed modulation, high extinction ratio, low drive voltage and integrability.

6. Hybrid Silicon Modulator

High speed operation, large bandwidth and good modulation efficiency are the main requirement of an efficient modulator. MZI based modulator has the bandwidth near to 100nm while electro-absorption modulators are less than 30nm. Due to requirement of high speed operation, hybrid silicon modulators are developed, where the III-V material epitaxial layer appear on silicon-on-insulator (SOI) wafer by wafer bonding techniques. LiNbO3 is the most widely used material as electro-optic modulators. Electro-optic coefficient is high and mature fabrication technology making it suitable for modulation applications. Earlier, LiNbO3 modulators have modulation speed of 20Gbps but now ultrafast LiNbO3 of 60Gbps have been developed by titanium (Ti) diffusing.

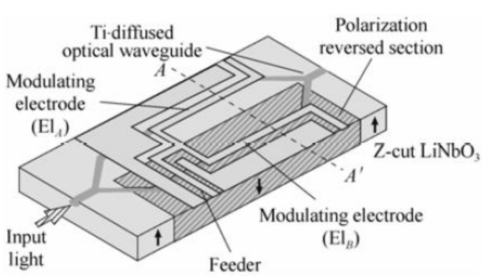
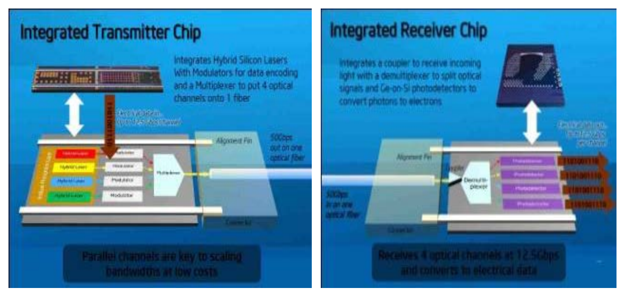


Fig. 6 LiNbO3 modulator with Ti diffusing

Feeder provides the input signal with same phases and amplitude which is further divided in to two signals on the modulating electrodes E1A and E1B. Phase shift provided by the arms of MZ interferometer in opposite direction. polarization reversal technique is used to fabricate this type of modulators. Modulators based on Electro-Absorption (EA) or MachZehnder (MZ) provides data rate higher than 10Gbps whereas MachZehnder structures on Lithium-Niobate (LiNbO3) give us data rate up to 60Gbps. Modulation format such as OPSK (Quadrature Phase Shift keying), DQPSK (Differential Quaternary Phase-Shift Keying) are under progress to achieve higher data rate. Lately, these formats based LiNbO3 modulator give us 80Gbps data rate. To achieve the data rate of 100Gbps or beyond researcher's are working on the multi-level modulation format based on MQAM (Quadrature-Amplitude Modulation). Another approach supporting the higher data rate is the division of transmitted signal into sub carriers. These sub carriers are aligned orthogonally with the same symbol rate. Recently, Intel has also proposed 50Gbps optical link and their future work of achieving 1Tbps based on the sub carrier's modulation.



(a) (b)
Fig. 7 Showing (a) Transmitter (b) Receiver with wavelength division multiplexing

At the Transmitter chip there has four hybrid silicon lasers (InP) which generates four different colors of continuous-wave laser light or wavelengths. Wavelength division multiplexing (WDM) is the reason of increasing the number of channels in the fiber which increases the bandwidth. From the four hybrid silicon lasers, light beams travel into an optical modulator that encodes data on to them at 12.5Gbps. Afterwords these four beams further combined to a single optical fibre for overall data rate of 50Gbps. At the receiver link, chip separates the four optical beams and directs them into photo detectors to convert them back into electrical signals. Research has been going on to achieve data rate of 100Gbps or further based on these model.

7. Photodetectors

Photodetectors converts optical signals into electrical signals. It should have high sensitivity in operating wavelength, low noise, high response speed, high

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reliability and low biasing across the detector. Photoconductor is the plain and essential detector consists of single semiconductor slab across which electric field is applied. Due to which it has high dark current noise and high response speed. Also reverse biased pn junction has low dark current noise. Hence photo detectors consist of p-n junction which works under a reverse bias voltage. reverse current and width of the depletion region increases due to reverse bias voltage across the pn junction. Also thickness of the depletion region adds to increases the quantum efficiency but the response time increases. Performance of photo detector depends upon (1) Responsivity (2) Bandwidth (3) Dark current.

Under no input light signals detector shows small electric current which is known as Dark current. It is also referred as reverse leakage current in detectors. the receiving efficiency of the detectors is determined by Responsitivity and is calculated as

$$R = \eta \frac{e}{hv}$$

Where hν is the photon energy, η is the quantum efficiency, and e is the elementary charge. By adding an intrinsic area in pn junction efficiency can be increased. The width of depletion region becomes equal to the intrinsic region when device operates in reverse biased condition. Due to which it increases the light absorption area and increases the quantum efficiency. Quantum efficiency can also be increased by using Anti-reflection coating on the surface. Bandwidth of the photo detectors depends upon junction capacitance and the generation of carriers across the junction. Bandwidth related to junction capacitance (Cj) given as

$$f_{BW} = 1/(2 * \pi * R_{LOAD} * C_j)$$

With the increase in depletion width due to reverse, capacitance of the depletion region increases due to which bandwidth increases. In most cases, detectors can have larger responsivity, but it will also increase both the dark current and the capacitance and hence reduces the sensitivity and the bandwidth, respectively. Semiconductor materials, such as Ge, Si, and III-V material, like GaAs, InP, have been used for the manufacturing of hetrojunction photodetectors. Figure(8) describe the comparison of the absorption coefficients of different semiconductors including Silicon. From this fig(8) it can be seen that Si and GaAs have very low absorption coefficient while Ge and some other III-V materials have considerable absorption coefficient.

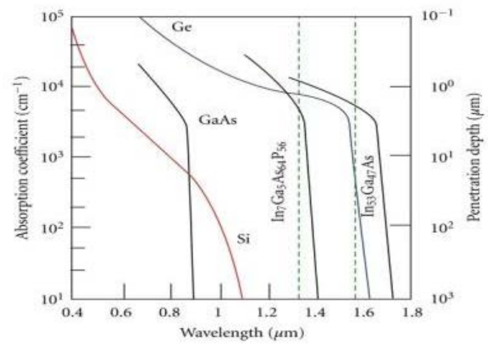

Fig. 8 Absorption coefficient as a function of their wavelength. The green dashes mark typical wavelengths for telecommunications windows of 1310 and 1550 nm

7.1 Silicon Detector

From the fig (8) it is clear that Si exhibit transparency in the 1300–1550 nm operating wavelength range due to its low absorption coefficient it is not a satisfiable material for fiber-optic communication application. But it carry out well under 1000nm, where band-to-band absorptions happen. To solve this problem, we can approach to three structures; III-V heterogeneous detectors, Schottky structure or Ge detectors built on silicon substrates.

8. Schottky Detectors

Schottky detectors consists of a thin metal layer (~ 100 Å) on a lightly doped p-type Si, forming a Schottky barrier at the material interface which is also known as metal semiconductor diode. The depletion layer between the metal and semiconductor junction due to Schottky barrier also known as the absorption region. The barrier is usually 0.2–0.6 eV for p-Si, while the value is a bit smaller for n-Si with the same contact metal. Main advantages of Schottky detectors that it is majority carrier device, independent on minority carrier's lifetime therefore no delays problems. It speedy i.e response time is good (150GHz) and compatible with standard CMOS technology. But its drawback is the low quantum efficiency. Quantum efficiency can be improved by mixing the dielectric waveguide using transparent conducting electrodes and employing surface Plasmon polarizations (SPP). Fig (9) shows below symmetric and asymmetric surface Plasmon Schottky contact detector. Scales et al. demonstrated symmetric structure with responsivity of 0.1 A/W and dark current of 21nA. In the symmetric structure, fabrication process is complex as it involves the realization of thin metal films buried in semiconductor in order to simpler the fabrication process Berini`s group proposed

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the asymmetric Surface Plasmon polaritions photodetectors.

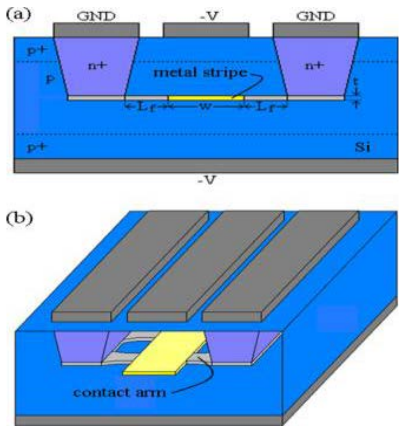

Fig. 9 Scheme diagram of examples of (a) symmetric and (b) asymmetric surface Plasmon Schottky contact detector.

9. Heterogeneous Detector

Compared to silicon III-V-based detectors III-V semiconductors have direct band gap and have wider absorption bandwidth as well as relative low dark currents. The lattice structures of III-V materials are different from the Si semiconductor hence these semiconductor materials cannot be directly grown on silicon. A solution to this problem is the heterogeneous to use a integration of III-V layers on silicon substrate by using advanced wafer bonding technique. In earlier the III-V detectors (GaAs,) are not compatible with CMOS (Complementary metal oxide semiconductor's) technology approach. But in now a days some of them, like InGaAs/InP built on the SOI substrate using heterogeneous integration approach. This integration process achieved by using the DVS-BCB by adhesive die-to-wafer bonding process. In figure the metal-semiconductor-metal photo detector (MSM) using an InGaAs absorption layer were envision. The vertical directional coupling between the SOI waveguide and the lossy III-V waveguide mode Coupling is formed between the SOI waveguide and photo detector. At a bias voltage of 5v the dark current was formed of 3.0nA while the responsivity of detector was at 1.0A/W at 1.55 μm and bias voltage of 5V.

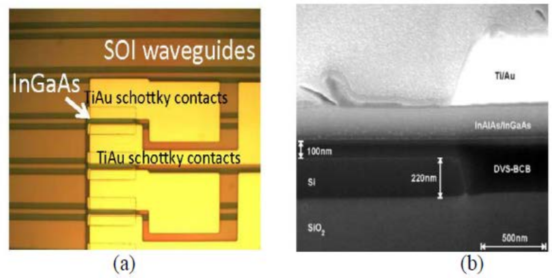

Fig. 10 (a) Top view of the fabricated III-V metal-semiconductor-metal photodetectors integrated on an SOI waveguide platform (b) cross-section of the device.

10. Germanium Detector Built On Silicon

Ge has an indirect bandgap structure which similar to Si but having less band gap energy (0.7ev versus 1.1ev for Si) compared to Si. Hence it has a higher absorption coefficient up to the wavelength of 1550nm. The present period of time most of the researchers are working on Ge-on-Si photodetectors because of its high responsivity behavior in near IR wavelength and its optoelectronic properties and compatibility with CMOS fabrication. Chemical vapour deposition processes (CVD) can deposit Ge/GeSi. But in these photodetectors main difficulty comes in growing o epitaxial films of Ge on Si. Because of the high lattice constant of Ge which is 4% greater than the silicon, hence there is always mismatched in their structures. Due to this the defects such as dislocations in their densities arrangement and high power loss will cause while growing Ge layers on Si. Such defects greatly affect the performance of the photodetectors. To get over with this problem we have two different approaches these are (1) selectively growing of Ge on Si (2) two step method of growing Ge. In this discriminatory approach we generally use Si3N4 as the dielectric mask by which the Ge layers grow on the silicon. In the Deposition of layers of Ge through the exposed areas develop over the dielectric mask Chemical vapour deposition (CVD) is use. Ge layers grow epitaxially on Si under controlled temperature in the two step method. At frist, on Si at a temperature of 320–360°C Ge layer of 30 nm grows. Continuous growth of Ge desired over the Si at a higher temperature greater than 600°C occurs in second step. Later on Loh et al.As demonstrated the modified two step approach, which includes growing of ultrathin (2~30 nm) at Low Temperature SiGe buffer layer prior to the deposition of Low Temperature Ge layer and High Temperature Ge layer. There are two structures of Ge-on-Si p-i-n photo detectors (1) normal-incidence type (2) waveguide type. Waveguide based photo detectors is better than normal-incidence photo detectors on the basis of quantum efficiency and bandwidth. (1) normal-incidence type (2) waveguide type this are the two structures of Ge-on-Si p-i-n photo detectors. On the basis of quantum efficiency and bandwidth waveguide based photo detectors are better than normal-incidence photo detectors. The induced type detectors have larger area, about ten times that of the waveguide detectors. The large progress is going on Ge on Si photo detectors. Vivien et al. gives the Ge detector with bandwidth of 42 GHz and responsivity at 1 A/W operating at 1550 nm wavelength. Ge detector with 17.5GHz bandwidth is showed by Feng et al. The bias voltage across the detectors, reduce the dark current, power absorption and operating voltage of chip are lowered by theCMOS integration process. Ge detectors of 130 nm and 180 nm respectively integrated with CMOS technology Currently has, a zero bias Ge detector with 17.5 GHz has been recently demonstrated by demonstrated by Luxtera and MIT. Ge detector with high sensitivity at 4 dB and speed at 10Gb/s is reported by Kang group in 2010.

11. Avalanche Photodetector

Avalanche photodiode detectors (APD) have great sensitivity and they exhibit larger gain bandwidth product as compare to that of the p-i-n type detectors. As compare to the the III-V detectors Ge-on-Si APD gives us better performances. Due to multiplication of charge carrier's number of charge carriers increases by 10-100 factor in an avalanche based photodetectors. Thus it helps in the increases the sensitivity, bandwidth and helpul in long distance transmission. For low cost with Ge-on-Si APD at data rate of 40Gbps Progress work going on the development. 340 GHz gain–bandwidth with Ge–Si avalanche photodiode using CVD growth of Ge and Si layers at 850°C has been demonstrated by the Intel-UCSB team in the recent events.

12. Applications and Future Aspects

Recently Silicon photonics is extremely powerful technology which fulfills the demands for efficiency, higher speed, and low power consumption at lower costs. In silicon technology, using narrow waveguides various opto-electronics devices alliance on a single substrate connected with each other. Such circuits could be used to establish increased bandwidth, high speed transmission, reduced power consumption and decreasing latency problems. by providing micro-scale, ultra low power devices it can potentially increase the bandwidth capacity. Optical data transmissions increase the data rate and exclude the complication of electromagnetic interference. With these data rates one could imagine the videoconferencing with a high resolution. Optical link can transfer data to longer distances and faster than today's copper technology; up to 50 GB of data per second. Recently, Intel Corporation launched their optical link connection operating at 100Gbps. Fujitsu Laboratories recently create four wavelength integrated silicon laser for optical transrecievers. Work is in the progress for the new optic-interconnection of external devices to PCs. Intel announced Light Peak, 2009 which substitutes the USB and communicates the data at up to 10Gbps. Breakthrough in the field of silicon nanophotonic technologies leads new ideas in future computing systems and their architectures.

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First Author Mr. Akshaykumar S.Hedaoo is pursuing his full time bachelor's degree in Electronis & telecommunication from JDIET Yavatmal. His area of interest is in Photonics system.

Second Author Prof. Atul N.Shire Received M.Tech degree in Electronics from G.H.Raisoni, Nagpur, India in 2010. He has in all experience of 10 years in teaching & industry. He also served as Head of department for three years in DBNCOET in Electronics & Telecommunication, yavatmal, Maharashtra. Till date he has published 18 research paper in various International Journals/ Conference. His area of intrest is signal/image processing. He is also a life member of ISTE and IETE.

Third Author Prof. Atul P.Shingade has completed his masters from SGBAU Amravati. He has more than five years of experience in teaching and industrial area. He has interest in Digital Image Processing and VLSI Design.