SILICON PHOTONICS

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ARAVIND SURESH KUMAR

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Department of Electronics Engineering
College of Engineering, Chengannur – 689121
Phone: (0479) 2454125, 2451424 **Fax:** (0479) 2451424

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ABSTRACT

Silicon Photonics can be defined as the utilization of silicon-based materials for the generation, guide, control and detection of light to communicate over distances. Optical technology suffered from a reputation as an expensive solution, based on high cost of hardware components, as they are typically fabricated using exotic materials that are expensive for manufacturing.

These limitations prompted Intel to research the construction of fibre-optic components from other materials, such as silicon (suggested since 1980's).Silicon Photonics has attained much attention in recent years owing to the maturity of silicon in the 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-the IC manufacturing process used today.

The various challenges as well as the milestones in the development of Silicon Photonic are discussed.The difficulty in fabricating optical devices such as laser source, modulators, detectors etc. on silicon for high switching speeds that provides high data rates for communication links as well as the solutions put forward by the Silicon Photonics research group at Intel are projected.With the developments up till now the devices available on silicon can form only a 40Gbps optical link.Tbps data rates has already been achieved in optics with Dense Wavelength Division Multiplexing technology. With further developments Silicon Photonics is expected to bring an optical revolution in Electronics and Communication industry with the realization of the above said Tbps data links using microelectronic silicon chips. The hopes and hurdles towards this development are discussed in detail

CONTENTS

1. INTRODUCTION……..……...…..2

1.1. MOORE'S LAW AND SILICON TECHNOLOGY……...3

1.2. OPTICAL INTERCONNECTS……..…….6

1.3. ENTER OPTOELECTRONICS……..……8

1.4. COMPONENTS OF AN OPTICAL SYSTEM……...9

2. DETAILED DESCRIPTION……13

2.1. SILICONIZE PHOTONICS……...……....13

2.2. HOW LASER OCCUR……...……..…13

2.3. RAMAN EFFECT……14

2.4. STIMULATED RAMAN SCATTERING & RAMAN SILICON LASER……...…….16

2.5. TWO PHOTON ABSORPTION & PIN DIODE CORRECTION……...……..17

2.6. APPLICATIONS OF RAMAN EFFECT…..……...……..……19

2.7. SILICON MODULATOR……...……20

2.8. ENCODING THE OPTICAL DATA…….……23

2.9. DEMODULATION……..24

2.10. SILICON INTERFACES……...……...26

2.11. SILICON CHALLENGES……..……..27

2.12. APPLICATIONS OF SILICON PHTONICS……..…….……..28

3. FUTURESCOPES AND CONCLUSION……...……..30

4. REFERENCES……..……33

INTRODUCTION

1. INTRODUCTION

Fiberoptic communication is well established today due to the great capacity and reliability it provides. . Fiber-optic communication is the process of transporting data at high

speeds on a glass fiber using light. However, the technology has suffered from a reputation as an expensive solution. This view is based in large part on the high cost of the hardware components. These components are typically fabricated using exotic materials that are expensive to manufacture. In addition, these components tend to be specialized and require complex steps to assemble and package. These limitations prompted Intel to research the construction of fiber-optic components from other materials, such as silicon. The vision of silicon photonics arose from the research performed in this area. Its overarching goal is to develop high-volume, low-cost optical components using standard CMOS processing the same manufacturing process used for microprocessors and semiconductor devices. Silicon presents a unique material for this research because the techniques for processing it are well understood and it demonstrates certain desirable behaviors. For example, while silicon is opaque in the visible spectrum, it is transparent at the infrared wavelengths used in optical transmission, hence it can guide light. Moreover, manufacturing silicon components in high volume to the specifications needed by optical communication is comparatively inexpensive.

Researchers at Intel have announced advancement in silicon photonics by demonstrating the first continuous silicon laser based on the Raman effect. This research breakthrough paves the way for making optical amplifiers, lasers and wavelength converters to act as light source and also switch a signal's color in low-cost silicon. It also brings Intel closer to realizing its vision of "siliconizing" photonics, which will enable the creation of inexpensive, high-performance optical interconnects in and around PCs, servers and other devices. There has also been developments which include the achievement of GHz range optical modulator and detector devices n silicon

Silicon's key drawback is that it cannot emit laser light, and so the lasers that drive optical communications have been made of more exotic materials such as indium phosphide and gallium arsenide. However, silicon can be used to manipulate the light emitted by inexpensive lasers so as to provide light that has characteristics similar to more-expensive devices. This is just one way in which silicon can lower the cost of photonics. Intel's silicon photonics research is an end-to-end effort to build integrated photonic devices in silicon for communication and other applications. To date, Intel has demonstrated laser production from external light source,

tunable filters, optical modulators, photo-detectors and optical packaging techniques using silicon that can establish optical links with Gbps datarates. Even more is yet to achieve.

1.1 MOORE'S LAW AND SILICON TECHNOLOGY

It is an understatement to remark that we live in a world made possible by silicon technology. Modern life has been shaped and defined by innumerable products that rely on integrated electronic circuits fabricated in mind-boggling number and precision on silicon wafers. The grand success of silicon technology is not only the dramatic improvements that have been achieved in performance, but also the exponentially decreasing per-component manufacturing costs that have kept that performance affordable. In fact, Gordon Moore's famous law(1962) describing progress in the semiconductor industry was originally stated in similar economic terms:

" The complexity for minimum component costs has increased at a rate of roughly

a factor of two per year. . . , this rate can be expected to continue"

Complexity is usually equated to transistor count, and by that measure the exponential progress predicted by Moore's Law has been maintained through the present day (figure1.1). It has become cheaper over time to pack more and more transistors into integrated circuits because each individual transistor is continually being made smaller. This scaling process allows more powerful chips with more transistors to be made for a reasonable price. Smaller transistors also drive down the price of previous generation chips of any given complexity, because more functionally identical copies can be simultaneously made on the surface of a silicon wafer for nearly the same cost. Scaling is the engine of progress in silicon micro electronics. It is sustained only by intensive research and development in the face of perpetual technology challenges always looming on the horizon

Goals and benchmarks for scaling are established and monitored in the International Technology Roadmap for Semiconductors (ITRS), a public document.

Figure 1.1-moore's law

In Figure 1.1, transistor counts for integrated circuits showing the historical accuracy of Gordon Moore's prediction of exponentially increasing integrated circuit complexity with year by a consortium representing the global semiconductor industry. The roadmap is intended "to provide a reference of requirements, potential solutions, and their timing for the semiconductor industry" over a fifteen -year horizon. For many years, the ITRS has highlighted 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.

The anticipated problem is often referred to as the "interconnect bottleneck." 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. Today's chips already contain well over one kilometer of wiring per square centimeter of chip area . 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 interconnect bottleneck has threatened Moore's Law before. In the late 1990s, integrated circuits contained aluminum wires

that were surrounded by silicon oxide. As interconnect cross sections decreased, mounting circuit delay in capacitive charging of these aluminum wires began to effect chip performance. A solution was found in a change of materials. Copper was introduced in place of aluminum, which cut the resistance of the wires nearly in half. Eventually low dielectric constant ("low-κ") doped silica infill materials were also phased in to reduce the capacitance.

Figure 1.2-technology vs delay

In Figure 1.2, according to the ITRS, there is no known manufacturable global or intermediate interconnect solutions for the 45 nm technology node. In the roadmap, such challenges are highlighted on a spreadsheet in red, forming the "red brick wall."

Incorporating these new materials into existing fabrication processes posed significant integration challenges. Copper can diffuse quickly through silicon and create short circuits in the transistors of a chip unless care is taken to avoid contact between the copper wires and the silicon substrate. Additionally, the nonexistence of any suitable gas phase etching process for copper requires additive deposition techniques to be used. The silicon industry invested heavily in research and development to find diffusion barriers and to perfect "Damascene" deposition processes relying on chemical-mechanical planarization (CMP) . These technologies made copper interconnects possible and have allowed scaling to continue through the present day.

Further evolutionary progress through materials research in very low-κ dielectrics may postpone the return of the interconnect bottleneck, but a new approach to information transfer within integrated circuits will inevitably become necessary if transistors are to continue shrinking into the next decade. According to the latest update of the ITRS chapter on interconnects, traditional interconnect scaling is not expected to satisfy performance requirements after approximately 2010 (figure 1.2).

1.2 OPTICAL INTERCONNECTS

Many expect photonics to provide the long term solution. In so-called optical interconnect schemes, 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.

The current integration level of about 1.7 billion transistors is responsible for the high processing capability of todays processors. More transistors means more switching power. Since switching decides digital signal processing power the very high integration of transistors is responsible for the processing power of todays processors.But the maximum performance power of systems with these processors is limited by the heat loss in metal connections, inductive losses due to nearby conductors, proximity effect, i.e expeltion of current from inner conductor when conductors are in close proximity, skin effect i.e concentration of current flow to the surface of conductor due to its suppression at the interior due to the formation of eddy currents(loop currents) at the interior whose flux linkage opposes the flux of the main current that caused them. There are also losses due to metallic imperfections (impurities, lattice mismatch etc.). Due to all these a speed grater than 10Gbps has never been possible with metal interconnections. Even the core series processors from Intel has databus speed around 5Gbps

The integration density and data rate that can be achieved using conventional electrical interconnects set very high performance requirements for any optical interconnect

system to be viable. We can anticipate that optical interconnects will make the chip-scale integration of the very best photonic technologies available today. Stable laser sources, interferometric modulators, dense wavelength division multiplexing (WDM), and low loss planar waveguides will all be necessary components of an optical interconnect system that can reach an acceptable per-wire information bandwidth-per-watt figure of merit.

These photonic technologies are now applied primarily in the long-haul telecommuting actions industry, where individual component cost and size do not drive the market. Data transfer rates and the cost per transmitted bit through optical fiber networks have improved dramatically in performance over the last few decades, following exponential progress curves that can compound even faster than Moore's Law. These advances underlie the infrastructure of the internet and are responsible for fundamental changes in our lives, particularly in our experience of distance around the globe. However, while millions of miles of fiber optic cable now stretch between cities and continents, the photonic components they connect are still typically packaged separately. Obviously this must change if optical networks are to be replicated in microcosm within millions of future chips.

Micro photonics refers to efforts to miniaturize the optical components used in long-distance telecommunications networks so that integrated photonic circuits can become areality. Work in this field spans many subjects, including planar waveguides and photonic crystals, integrated diode detectors, modulators, and lasers. In more recent years, research focused on the sub wavelength manipulation of light via metal optics and dispersion engineered effective media has begun to explore the anticipated limits of scaling in future photonic integrated circuits. Advances in the related and often overlapping field of "nanophotonics" suggest the possibility of eventually controlling optical properties through nanoscale engineering.

Between the long-haul telecommunications industry and research in micro photonics lies a small market that will undoubtedly aid in driving the integration of on-chip optical networks: high performance supercomputing. Modern supercomputer performance is typically dominated by the quality of the interconnecting network that routes information between processor nodes. Consequently, a large body of research exists on network topology and infrastructure designed to make the most of each photonic component. This knowledge is ready

to be applied to future optical interconnect networks that connect sub processor cores within a single chip.

If optical interconnects become essential for continued scaling progress in silicon electronics, an enormous market will open for integrated photonic circuit technology. Eventually, unimagined new products will be made possible by the widespread availability of affordable, high-density optical systems. Considering the historical development of computing hardware from the relays and vacuum tubes of early telephone networks, it is possible that optical interconnects could someday lead to all-optical computers, perhaps including systems capable of quantum computation.

Unfortunately, there is at present no clear path to practical on-chip optical data transfer and scalable all-photonic integrated circuits. The obstacles that currently stand in the way of optical interconnects are challenges for device physics and materials science. Break through are needed that either improve the set of materials available for micro photonic devices or obviate the need for increased materials performance through novel device designs.

1.3 ENTER OPTOELECTRONICS

Fiber optics use light to transmit data over a glass or plastic fiber(silica),and a seed of about 1.7Gbps was achieved in 1980s itself. Though plastic fibres are also used silica(glass fibre), i.e Silicon dioxide, that we use as insulator in CMOS fabrication is most commonly used. The primary benefit of using light rather than an electric signal over copper wiring is significantly greater capacity, since data transmission through fibres is at light speed.But this alone cannot make high speed transmission possible, it aso requires the end devices like modulators, demodulators etc where convertion between optical and electrical data takes place, also to work at such high speeds. The Bell Labs in France currently holds the record of transmission with muxing of about 155 different data streams each on its own light wave and each with a capacity of about 100Gbps that constitute in total a 14Tbps data link using a fibre pair with Dense WDM technology. In addition, glass fiber has desirable physical properties: it is lighter and impervious to factors such as electrical interference and crosstalk that degrade signal quality on copper wires. Hence optic fibres can be used even at places of high lightning with all

dielectric cables.The high electrical resistance of fibres makes them usable even near high tension equipments. Hence repeaters are placed at ranges over 100Kms.

Photonics is the field of study that deals with light, especially the development of components for optical communications. It is the hardware aspect of fiber optics; and due to commercial demand for bandwidth, it has enjoyed considerable expansion and developments during the past decade. During the last few years, researchers at Intel have been actively exploring the use of silicon as the primary basis of photonic components. This research has established Intel's reputation in a specialized field called silicon photonics, which appears poised to provide solutions that break through longstanding limitations of silicon as a material for fiber optics. In addition to this research, Intel's expertise in fabricating processors from silicon could enable it to create inexpensive, high-performance photonic devices that comprise numerous components integrated on one silicon die.

1.4 COMPONENTS OF AN OPTICAL SYSTEM

To understand how optical data might one day travel through silicon in your computer, it helps to know how it travels over optical fiber today. First, a computer sends regular electrical data to an optical transmitter, where the signal is converted into pulses of light. The transmitter contains a laser and an electrical driver, which uses the source data to modulate the laser beam, making beam on and off to generate 1s and 0s. Imprinted with the data, the beam travels through the glass fiber, encountering switches at various junctures that route the data to different destinations. If the data must travel more than about 100 kilometers, an optical amplifier boosts the signal. At the destination, a photo detector reads and converts the data encoded in the photons back into electrical data. Similar techniques could someday allow us to collapse the dozens of copper conductors that currently carry data between processors and memory chips into a single photonic link.

The core of the internet and long-haul telecom links made the switch to fiber optics long ago. A single fiber strand can now carry up to one trillion bits of data per second, enough to transmit a phone call from every resident of New York City simultaneously. In theory, you could push fiber up to 150 trillion bits per second—a rate that would deliver the text of all the books in the U.S. Library of Congress in about a second.

Today's devices are specialized components made from indium phosphide, lithium niobate, and other exotic materials that can't be integrated onto silicon chips. That makes their assembly much more complex than the assembly of ordinary electronics, because the paths that the light travels must be painstakingly aligned to micrometer precision. In a sense, the photonics industry is where the electronics industry was a half century ago, before the breakthrough of the integrated circuit.

The only way for photonics to move into the mass market is to introduce integration, high-volume manufacturing, and low- cost assembly—that is, to "siliconize" photonics. By that we mean integrating several different optical devices onto one silicon chip, rather than separately assembling each from exotic materials. In our lab, we have been developing all the photonic devices needed for optical communications, using the same complementary metal oxide semiconductor (CMOS) manufacturing techniques that the world's chip makers now use to fabricate tens of millions of microprocessors and memory chips each year.

A source that can produce narrow coherent beam of light is the prime necessity in optical communication. Hence lasers are the first choice. However LEDs are also used for some low cost applications. Also for lasers a 1000 times more power output may be obtained compared to LEDs, based on how we set the gain medium. However optical communication has limitations due to scattering effects at discontinuities or imperfections in fibre and also very slight variations in refractive index along the fibre that can affect the wavelength of signal transmitted. When such limiting factors persist a coherent narrow beam from source, i.e a beam of light with each photon at equal lengths along the fibre as well that at a singe cross section showing the same wave properties(frequency, phase, polarization etc.) , is a must otherwise the dispertion and diffraction phenomenon may occur in a different way to each photon in the beam and this can severly distort or destroy the light signal.

Optical communication operates on the short wave or IR region of EM spectrum (i.e from 1260-1675nm). The operating range of wavelength is divided into 6 bands. Among them the C-band(Conventional band), i.e from 1530-1565nm is most commonly used, since it has showed the least scattering. Most optical devices have been developed to work in this range. For communication single mode fibres are preferred, where mode represents the angles of incidence

at the core-cladding interface for which transmission is possible. Multimode fibres (cross-section diameter>50um) are avoided due to intermodal dispertion, and even LEDs can b used. However single mode fibres require high stability for the light source used.

WDM started with muxing of 2 channels and now you can pack dozens of channels of high-speed data onto a single mode fiber with cross-section as low as 9um,separating the channels by wavelength, a technique called wavelength-division multiplexing, similar to frequency division multiplexing in radio communication. Arrayed waveguide grating structures that can perform both muxing and demultiplexing are used to implement WDM(Figure 1.3).

In AWG shown in Figure1.3, from 1 to 5, it acts as mux and demux the otherway. Regions 2 and 4 are free space segments and section 3 forms the array of waveguides with a constant length increment. Whereever light comes out of waveguide to free space, it diffracts, i.e spreads. A multiwavelength beam coming from section 1 after diffraction at section 2 passes to each of the waveguides of the array. The phase shift between the waves coming to section 4 will be such that the waves after diffraction constructive interference of the composed waves occur where they are received by different waveguides as shown in Figure 1.3. It has the advantage of integrated planar structure, low cost, low insertion loss and ease of network upgradation, since with increasing demand for bandwidth instead of laying new fibres, it only requires this device replaced with a higher capacity structure. As in any optical devices, changes in refractive index with temperature that can affect wavelength is a problem, and hence precision temperature control within +/-2 degree Celcius is required.

Figure 1.3-Arrayed Waveguide Grating(AWG) structure

DETAILED DESCRIPTION

2. DETAILED DESCRIPTION

2.1 SILICONIZE PHOTONICS

To siliconize photonics, we need six basic building blocks:-

- An inexpensive light source.
- Devices that route, split, and direct light on the silicon chip.
- A modulator to encode or modulate data into the optical signal.
- A photo detector to convert the optical signal back into electrical bits.
- Low-cost, high-volume assembly methods.
- Supporting electronics for intelligence and photonics control.

It's a tall order. Nevertheless, researchers at Intel's Photonics Technology Lab have been working on these building blocks for several years. Their achievements are actually the devices described below in detail:-

2.2 HOW LASER OCCUR

Lasers generate a beam of a single wavelength by amplifying light. As shown in (Figure 2.3) electrical or optical energy is pumped into a gain medium which is surrounded by mirrors to form a "cavity." Initial photons are either electrically generated within the cavity or injected into the cavity by an optical pumpm may be a Light Emitting Diode. As the photons stream through the gain medium, they trigger the release of duplicate photons from an electron in high energy orbital by disturbing it .The emitted photon will have the same optical properties (wavelength, phase and polarization), and travelling in the same direction as the incident photon. This same direction of motion and wave characteristics of every phton that constitute the laser beam is responsible for the directional narrow beam and coherent properties of the light emitted. As the photons move back and forth between the mirrors, they gather additional photons. This

gain has the effect of amplifying the light. An external chemical, electrical or optical pump source will be provided to maintain population invertion, i.e the state of electrons in the gain medium such that more number of electrons will be present in higher energy levels than at low levels. This is necessary to facilitate continous laser emission to occur. Ultimately, the light is sufficiently strong to form a "coherent" laser beam in which all the photons stream in parallel at the same wavelength. This laser beam is shown exiting the cavity by the red beam at the right of the figure below.

Figure 2.1-Basic laser working

2.3 RAMAN EFFECT

The term "laser" is an acronym for Light Amplification through Stimulated Emission of Radiation. The stimulated emission is created by changing the state of electrons the subatomic particles that make up electricity. Electrons in conduction band may fall to valence band with the emission of a photon, a process stimulated by another photon. This generation of photons can be stimulated in many materials, but not in silicon due to its material properties. Silicon and Germanium are indirect bang gap materials where a recombination of electron in conduction band with a hole in valence band is least probable or does not occur at all. It has some momentum consideration as shown in Figure2.2. However there are recombinations that result in phonon emission(heat) as is seen in ordinary silicon diodes. In case if photonic recombination occur they are associated with phonon emissions and such large transitions of electron energy that cause this may cause lattice instability.

Figure 2.2-The indirect bandgap

Using an external laser source coupled with waveguide has significant problems due to sub-micron misalignments of laser and fibre and also reflections of laser back to source that result in source instability of operation and variations in emitted wavelength that will distort the data being transmitted. However, an alternate process called the Raman effect can be used to amplify light in silicon and other materials, such as glass fiber, where laser formation occurs within waveguide. Named for the Indian physicist Chandrasekhara Venkata Raman, who first described it in 1928, this effect causes light to scatter in certain materials to produce longer or shorter wavelengths. These scattering is associated with energy transitions i.e during scattering of light the incident photon is absorbed which cause an electron excitation, which is immediately followed by the fall of the excited electron to lower energy state (a process stimulated by an immediately following photon), with the emission of a second photon. The energy and characteristics of the emitted photon depends on the atomic or molecular vibrational energy state of the atom or molecule that caused the scattering.

The Raman effect is widely used today to make amplifiers and lasers in glass fiber. These devices are built by directing a laser beam known as the pump beam – into a fiber. As the light enters, the photons collide with vibrating atoms in the material and, through the Raman effect, energy is transferred to photons of longer wavelengths. If a data beam is applied at the appropriate wavelength, it will pick up additional photons. After traveling several kilometers in

the fiber, the beam acquires enough energy to cause a significant amplification of the data signal. By reflecting light back and forth through the fiber, the repeated action of the Raman effect can produce a pure laser beam (figure 2.1). However, fiber-based devices using the Raman effect are limited because they require kilometers of fiber to provide sufficient amplification. The Raman effect is more than 10,000 times stronger in silicon than in glass optical fiber, making silicon an advantageous material. Instead of kilometers of fiber, only centimeters of silicon are required. By using the Raman effect and an optical pump beam, silicon can now be used to make useful amplifiers and lasers.

Raman scattering is used today, for example, to boost signals traveling through long stretches of glass fiber. It allows light energy to be transferred from a strong pump beam into a weaker data beam. Most long-distance telephone calls today benefit from Raman amplification. Typically, a Raman amplifier requires kilometers of fiber to produce a useful amount of amplification, because glass exhibits very weak scattering.

Figure 2.3-Raman effect in optical fiber and silicon waveguide

2.4 STIMULATED RAMAN SCATTERING & RAMAN SILICON LASER

Unlike in ordinary scattering, in stimulated raman scattering the energy of weak data beam to be amplified is coupled to light from pump source(Figure 2.3), where, as the pump laser power travels across the fibre, along with amplification through stimulated emission a wavelength shift also occurs. Here the energy of data beam being weak is passed to molecular vibrational energy. The light from pump photons with sufficient energy to excite electron undergoes scattering and Stimulated Raman Scattering (SRS) occurs without the need of a state of population invertion as in ordinary lasers. Since the energy of weak data beam passed to molecular vibrational energy, which decides the wave characteristics of the emitted photon. This finally result the production of a final laser beam with characteristics of the weak data beam, or it can be said that energy is passed from amplified form of pump beam to weak data beam. This is similar to technique in microwave amplifier-The Travelling Wave Tube(TWT). The final wavelength will be in the usable range(i.e least scattering region: 1260-1675 nm). Further amplification limited by scattering outside this range.

To build a Raman laser in silicon, we first need to create a conduit, also known as a waveguide, for the light beam. This can be done using standard CMOS techniques to etch a ridge or channel into a silicon wafer. In any waveguide, some light is lost through imperfections, surface roughness, and absorption by the material. The trick, of course, is to ensure that the amplification provided by the Raman effect exceeds the loss in the waveguide. The back and forth reflections within a small waveguide section creates laser within silicon, a process initiated by light from a superior material like GaAs or InP (the direct bandgap materials that are used to create LEDs). With the Raman amplifier between the two dielectric mirrors, we had the basic configuration needed for a laser. After all, laser stands for “light amplification by stimulated emission of radiation,” and that’s what was going on in our device. Photons that entered were multiplied in number by the Raman amplifier. Meanwhile, as the light waves bounced back and forth between the two mirrors, they stimulated the emission of yet more photons through Raman scattering. The photons stimulated in this way were in phase with the others in the amplifier, so the beam generated will be coherent.

Figure 2.4-Raman silicon laser

In mid-2004, intel discovered that increasing the pump power beyond a certain point failed to increase the Raman amplification and eventually even reduced it. The culprit was a process called two-photon absorption, which caused the silicon to absorb a fraction of the pump beam's photons and release free electrons. Almost immediately after we turned on the pump laser, a cloud of free electrons built up in the waveguide, absorbing some of the pump and signal beams and killing the amplification. The stronger the pump beam, the more electrons created and the more photons lost.

2.5 TWO PHOTON ABSORPTION & PIN DIODE CORRECTION

The realization of continous wave all-silicon laser was a challenge due to the existence of two photon absoption. Intel has achieved a research breakthrough by creating an optical device based on the Raman effect, enabling silicon to be used for the first time to amplify signals and create continuous beams of laser light. This breakthrough opens up new possibilities for making optical devices in silicon.Usually, silicon is transparent to infrared light, meaning atoms do not absorb photons as they pass through the silicon because the infrared light does not have enough energy to excite an electron. Occasionally, however, two photons arrive at the atom at the same time in such a way that the combined energy is enough to free an electron from an atom. Usually, this is a very rare occurrence. However, the higher the pump power, the more

likely it is to happen. Eventually, these free electrons recombine with the crystal lattice and pose no further problem. However, at high power densities, the rate at which the free electrons are created exceeds the rate of recombination and they build up in the waveguide. Unfortunately, these free electrons begin absorbing the light passing through the silicon waveguide and diminish the power of these signals. The end result is a loss significant enough to cancel out the benefit of Raman amplification.

In 2005, Intel disclosed the development of a way to flush out the extra electrons by sandwiching the waveguide within a device called a PIN diode; PIN stands for p-type–intrinsic–n-type, where the waveguide forms a part of the intrinsic region of the waveguide. When a reverse voltage is applied to the PIN structure, the free electrons move toward the diode's positively charged side; the diode effectively acts like a vacuum and sweeps the free electrons from the path of the light. This is due to the initial high electric field that setup across the PIN structure. Using the PIN waveguide, we demonstrated continuous amplification of a stream of optical bits, more than doubling its original power. Once we had the amplification, we created the silicon laser by coating the ends of the PIN waveguide with specially designed mirrors. We make these dielectric mirrors by carefully stacking alternating layers of no conducting materials, so that the reflected light waves combine and intensify. They can also reflect light at certain wavelengths while allowing other wavelengths to pass through. With the implementation of this technique intel built the first continuous silicon laser(Figure 2.5).

Figure 2.5-Waveguide PIN structure

2.6 APPLICATIONS OF RAMAN EFFECT

Fundamentally, Intel researchers have demonstrated silicon's potential as an optical gain material. This could lead to many applications including optical amplifiers, wavelength converters, and various types of lasers in silicon.

An example of a silicon optical amplifier (SiOA) using the Raman effect is shown in Figure 1b. Two beams are coupled into the silicon waveguide. The first is an optical pump, the source of the photons whose energy will cause the Raman effect. The spectral properties of this pump determine the wavelengths that can be amplified. As the second beam, which contains the data to be amplified, passes through the waveguide, energy is transferred from the pump into the signal beam via the Raman effect. The optical data exits the chip brighter than when it entered; that is, amplified.

Optical amplifiers such as this are most commonly used to strengthen signals that have become weak after traveling a great distance. Because silicon Raman amplifiers are so compact, they could be integrated directly alongside other silicon photonic components, with a pump laser attached directly to silicon through passive alignment. Since any optical device (such as a modulator) introduces losses, an integrated amplifier could be used to negate these losses. The result could be lossless silicon photonic devices.

The Raman effect could also be used to generate lasers of different wavelengths from a single pump beam(Figure 2.6). As the pump beam enters the material, the light splits off into different laser cavities with mirrors made from integrated silicon filters. Here the resonant wavelength of each cavity exist and others cancel by destructive interference during multiple back and forth reflections. The length of the cavity must be an integral multiple of the wavelength that sustains. The use of lasers at multiple wavelengths is a common way of sending multiple data streams on a single glass fiber. In such a scenario, Intel's silicon components could be used to generate the lasers and to encode the data on each wavelength. The encoding could be

performed by a silicon modulator un veiled by Intel in early 2004. This approach would create an inexpensive solution for fiber networking that could scale with the data loads of large enterprises.

Figure 2.6-Creating multiple laser sources from single pump

Optical amplifiers such as this are most commonly used to strengthen signals that have become weak after traveling a great distance. Because silicon Raman amplifiers are so compact, they could be integrated directly alongside other silicon photonic components, with a pump laser attached directly to silicon through passive alignment. Since any optical device (such as amodulator) introduces losses, an integrated amplifier could be used to negate these losses. The result could be lossless silicon photonic devices.

2.7 SILICON MODULATOR

Beyond building the light source and moving light through the chip, you need a way to modulate the light beam with data. The simplest option is switching the laser on and off, a technique called direct modulation. An alternative, called external modulation, is analogous to waving your hand in front of a flashlight beam blocking the beam of light represents a logical 0; letting it pass represents a 1, without disturbing the source. The only difference is that in external modulation the beam is always on.(figure 2.7)

For data rates of 10 Gbps or higher and traveling distances greater than tens of kilometers, this difference is critical. Each time a semiconductor laser is turned on, it "chirps" i.e a pulse broadening occurs due to device heating that result in variation in refractive index. The initial surge of current through the laser changes its optical properties, causing an undesired shift in wavelength. A similar phenomenon occurs when you turn on a flashlight: the light changes quickly from orange to yellow to white as the bulb filament heats up. If the chirped beam is sent through an optical fiber, the different wavelengths will travel at slightly different speeds, which warps data patterns. When there's a lot of data traveling quickly, this distortion causes, errors in the data. Also, the phenomenon of chirp worsen as sorce power increase. Hence a high source power cannot be used, so range is limited to 10 kms.

With an external modulator, by contrast, the laser beam remains stable, continuous, and chirp-free, hence comparatively a high power source can be used. The light enters the modulator, which shutters the beam rapidly to produce a data stream; even 10 Gbps data can be sent up to about 100 km with no significant distortion. Fast modulators are typically made from lithium niobate, which has a strong electro-optic effect—that is, when an electric field is applied to it, it changes the speed at which light travels through the material, as a result of variations in refractive index of the material which varies inearly with modulating voltage applied (Figure 2.8).

A silicon-base modulator, as mentioned before, has the disadvantage of lacking this electro-optic effect. To get around this drawback, we devised a way to selectively inject charge carriers (electrons or holes) into the silicon waveguide as the light beam passes through. This used a PIN diode type structure where waveguide forms the intrinsic region. Because of a phenomenon known as the free carrier plasma dispersion effect, the accumulated charges change the silicon's refractive index and thus the speed at which light travels through it. The silicon modulator splits the beam in two, just like the lithium niobate modulator. However, instead of the electro-optic effect, it's the presence or absence of electrons and holes that determines the

phases of the beams and whether they combine to produce a 1 or a 0.The trick is to get those electrons and holes into and out of the beam's path fast enough to reach gigahertz data rates. Previous schemes injected the electrons and holes into the same region of the waveguide. When the power was turned off, the free electrons and holes faded away very slowly (by lattice recombinations etc.). Hence the maximum speed was limited to about 20 megahertz.

In 2005, Intel disclosed the development of a silicon modulator that uses a transistor like device rather than a diode both to inject and to remove the charges. Electrons and holes are inserted on opposite sides of an oxide layer at the heart of the waveguide, where the light is most intense. Unlike ordinary transistors which is a combination of PN junction diodes connected back to back, here the structure has PIN diodes connected back to back, where the waveguide on either side of the oxide layer forms the intrinsic regions. Rather than waiting for the charges to fade away, the transistor structure pulls them out as rapidly as they go in. To date, this silicon modulator has encoded data at speeds of up to 10 Gbps fast enough to rival conventional optical communications systems in use today.

A speed of 18 Gbps was demonstrated with an optical ring modulator that uses a circular waveguide structure with multiple inputs, in which the resonant wavelength of the ring will sustain and is modulated using a PIN diode structure. A 40 Gbps silicon modulator demonstrated in 2007 and an 8-channel integrated 200 Gbps detector demonstrated in 2008 are the recent achievements.

Figure 2.7-Direct and external modulation

Figure 2.8-External modulation in silicon chip

2.8 ENCODING THE OPTICAL DATA

By splitting the laser beam into two using semitransparent surface within the waveguide and then applying phase shifts to either waves using electro-optic modulator incorporated within the waveguides (Figure 2.9). If the phase (speed) change is such that beams will be out of phase resulting in a destructive interference at where they recombine. If, on the other hand, no voltage is applied to modulators, then beams remain in phase, and they will add constructively when recombined, encoding the beam with 1s and 0s (Figure 2.10).

Figure 2.9-The MachZender interferometric structure for data encoding

Figure 2.10-Encoding the optical data

2.9 DEMODULATION

Once the beam is flowing through the waveguide, photo detectors are used to collect the photons and convert them into electrical signals. They can also be used to monitor the optical beam's properties—power, wavelength, and so on—and feed this information back to the transmitter, so that it can optimize the beam. Silicon absorbs visible light well, which is why it appears opaque to the naked eye.

Infrared Rays, however, passes through silicon without being absorbed, so photons at those wavelengths can be neither collected nor detected. This problem can be overcome by adding germanium to the silicon waveguides. Germanium absorbs infrared radiation at longer wavelengths than does silicon, germanium being a lwer bandgap material than silicon. So using an alloy of silicon and germanium in part of the waveguide creates a region where infrared photons can be absorbed. Our research shows that silicon germanium can achieve fast and

efficient infrared photo detection at 850 nanometers and 1310 nm, the communications wavelengths most commonly used in enterprise networks today.(figure 2.11).

A PIN diode structure in which waveguide forming intrinsic region is used with reverse bias for improved depletion region width into the intrinsic region. This will enhance the detection since the electron-hole pairs created at intrinsic region is swept by the electric field in depletion region and forms diode current, and also the depletion capacitance decreases. However, increased depletion region increases transit time delay and hence an optimization is necessary.

Figure 2.11-Demodulation of optical data

The detector devices commonly used are the above said PIN diode detector and Avalanche photodiode detector. InGaAs and germanium are the preferred materials to be used with silicon. In Avalanche detectors(Figure 2.12) a strong built in electric field exist at the pn junction due to heavy dopping on either side. This will give an additional advantage of built in amplification.

These devices however suffer from noise problems due to low bandgap and output current fluctuations due to variations in the occurrence of photons at the detector. Another problem is the dark current- the reverse leakage current in the absence of photon. However typical response time is found to be 0.5ns (a switching speed of about 2GHz). A 40Gbps PIN

detector demonstrated in 2007 and Avalanche photodetector with 340GHz Gain*BW demonstrated in 2008 are the recent achievements.

Figure 2.12-Avalanche Photodiode detector

2.10 SILICON INTERFACES

One step that's often overlooked in discussions of optical devices is assembly. But this step can account for as much as a third of the cost of the finished product. Integrating all the devices onto a single chip will help reduce costs significantly; the fewer discrete devices, the fewer assembly steps required. We're not yet at the point of full integration, however, and in the mean time, we still need a way to assemble and connect the silicon optical devices to external light emitters and optical fibers.

Optical assembly has long been much more challenging than electronics assembly. First, the surfaces where light enters and exits each component must be polished to near perfection. Each of these mirror like facets must then be coated to prevent reflections, just as sunglasses are coated to reduce glare. With silicon, some of these extra assembly steps can be greatly simplified by making them part of the wafer fabrication process. For example, the ends of the chips can be etched away to a mirror-smooth finish using a procedure known as deep silicon etching, first developed for making micro electro mechanical systems. This smooth facet can then be coated with a dielectric layer to produce an antireflective coating.

Because a fiber and a waveguide are different sizes, a third device—typically a taper—is needed to connect the two. The taper acts like a funnel, taking light from a larger optical fiber or laser and feeding it into a smaller silicon waveguide; it works in the opposite direction as well. Obviously, you don't want to lose light in the process, which can be tricky when hooking up a waveguide 1 micrometer across to a 10-µm-diameter optical fiber.

Connecting optical fibers to optical devices on a chip requires attaching the fiber directly to the chip somehow. One approach we are pursuing is micromachining precise grooves in the chip that are lithographically aligned with the waveguide. Fibers placed in these grooves fall naturally into the proper position. Our research indicates that such passive alignments could lose less than 1 decibel of light as the beam passes from the fiber through the taper and into the waveguide. An index-matching gel material may be used sometimes.

To passively couple a laser to a silicon photonic chip, you start by bonding the laser onto the silicon. Silicon etching can be used to produce mirrors, to help align the laser beam to the waveguides. You can also etch posts and stops into the silicon surface, to control the vertical alignment of the laser to the waveguide, and add lithographic marks, to help with horizontal alignment.

When we lay silicon optic links on silicon chip, it must be optically independent from the rest of the substrate. For this an interleaving material is used, commonly silica, i.e silicon dioxide which has a refractive index 1.44 which is less than 3.4 of silicon and hence facilitates light transmission by total internal reflection.

2.11 SILICON CHALLENGES

The various challenges at each stage in the development of silicon photonics, include the difficulty to develop a continous wave all-silicon laser, GHz range modulator and detector devices etc. However there are also some other effects seen in silicon that has adverse effect at lower micrometer scale fibre transmissions. These include Kerr nonlinearity effect and

Four wave mixing phenomenon. These are significant, since we deal with micrometer or nanometer range fibres in silicon photonics.

Kerr nonlinearity variation in refractive index proportional to the square of electric field intensity. When multiplexed waves of different intensities are transmitted, this will lead to separation of waves and destroy the transmission.

Another phenomenon is the four wave mixing. In case when three photons of different wavelength meet at an atom or molecule in the fibre, such that one photon will cause an electron excitation, a second photon brings stimulated transition of excited electron to a lower energy state, again a third photon cause excitation of the same electron to a much heigher energy state, from where a spontaneous transition to initial actual energy state of electron occur, with the release of a photon of a fourth different wavelength (Figure 2.13).

Figure 2.13-Energy level transitions of an electron during four-wave mixing

2.12 APPLICATIONS OF SILICON PHTONICS

The high modulation-demodulation rates along with Dense Wavelength Division Multiplexing with which Tbps data transmission has been achieved in optical communication, that has never been achieved in any other forms of communication, is expected to come on computer systems, corporate datacenters and in high end servers. With the developments in silicon photonics where the electronic and optical components comes on a single integrated platform, this can be achieved at reduced cost and with the elimination of wired connections. Routers, signal processors etc. that forms the internet backbone will become more simple and powerful at low cost.

Another achievement with developments in silicon photonics will be the faster and more compact medical equipments like imaging machines, lasik surgical instruments etc. There will also be reduction in cost, the same thing that we seen in electronics industry with the developments in integrated circuits.

3D ICs (Figure 2.14) an emerging technology. With the developments in silicon photonics there will be developments 3D IC technology which consist of various layers of electronic and photonic components or circuits. In figure 2.14, a 100-core processor layer is at the bottom. The communication between cores of the processor and that of the chip with external devices (off-chip traffic) is handled by a superfast photonic or optical link layer at the top. The research in this area is going on at the IBM's research centre.

Figure 2.14-3D ICs (An artistic view)

FUTURESCOPE AND CONCLUSIONS

3 FUTURE SCOPES AND CONCLUSION

As Moore's Law continues to push microprocessor performance, and as increasing volumes of data are sent across the Internet, the demands placed on network infrastructure will increase significantly. Optical communications and silicon photonic technology will allow enterprises to scale bandwidth availability to meet this demand. In addition, due to the low cost of silicon solutions, servers and high-end PCs might one day come standard with an optical port for high-bandwidth communication. Likewise, other devices will be able to share in the

bandwidth explosion provided by the optical building blocks of silicon photonics. Intel's research into silicon photonics is an end-to-end program that pushes Moore's Law into new areas. It brings the benefits of CMOS and Intel's volume manufacturing expertise to fiber-optic communications. The goal is not only achieving high performance in silicon photonics, but doing so at a price point that makes the technology a natural fit.

The ultimate goal in siliconize photonics is to integrate many silicon optical devices onto a low-cost silicon substrate using standard CMOS manufacturing techniques. Parts of this scheme already exist. Intel's modulator, for example, relies on the same deposition tools and doping techniques used to mass produce transistors. Silicon and oxide etching tools, which are also standard in the industry, are used to define optical wave guides. Even the deposition machines needed for silicon-germanium photo detectors are becoming more commonplace in today's state-of-the-art CMOS fab facilities.

The next phase of development is to build a "hybrid" silicon photonic platform using a mix of silicon and nonsilicon devices attached to a silicon substrate. Over time, we will be able to replace the nonsilicon components with silicon devices. This integration could bring about enough of a cost reduction to make these hybrid devices attractive for corporate data centers and high-end servers. The final phase is to integrate a majority of the devices into silicon and to begin integrating electronics with the photonics the convergence of communications and computing on a single silicon chip. At that point, we will start to see the emergence of completely new kinds of computing applications and architectures, afforded by the availability of low-cost photonic devices.

Momentum is building in silicon photonics. During the past 12 months, there have been significant leaps in silicon device performance in the areas of modulation and lasing. Government funding in this field has been accelerating, as has the dissemination of research publications. A few optical start-ups have even been choosing silicon as their device

Figure 3.2-Silicon photonic transceiver chip

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