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On-chip Optical Communication Using Graphene

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ABSTRACT
Advancement in technology is increasing day by day. Accordance to Moore’s Law, the number of transistors per square inch on integrated circuits had doubled every year. In this way, Graphene research so far has focused on electronics and photonic applications, in spite of its impressive optical properties, graphene can be used as optical communication devices which are more efficient than any other materials. It has as unique photonic and electronic extraordinary properties. This leads to remarkable high bandwidth, zero source-drain bias, better modulation of light, and good internal quantum efficiency.

Keywords: Graphene, Moore’s Law, Optical communication, Photonics.

I. INTRODUCTION

The growing demand for instant and reliable communication means that photonic circuits are increasingly finding applications in optical communications systems. One of the prime candidates to provide satisfactory performance at low cost in the photonic circuit is silicon. Silicon photonics is less well developed as compared to some other material technologies, it is poised to make a serious impact on the telecommunications industry, and silicon photonics explains the concepts of the technology, taking the reader through the introductory principles, on to more complex building blocks of the optical circuit. It is currently a very active and progressive area of research, as silicon and grapheme optical circuits have emerged as the replacement technology for copper-based circuits in communication and broadband networks.

Silicon photonics is a term given to the science of optical communications, a science that is now looking to do what has been done with so many other electronic devices; make them smaller, faster, and cheaper. Advance to this silicon photonics is Graphene Photonics. Replacing silicon with grapheme is more efficient. “Graphene enables us to make modulators that are incredibly compact and that potentially perform at speeds up to ten times faster than current technology allows. This new technology will significantly enhance our capabilities in ultrafast optical communication and computing.” At present optical communications is used between devices and between the exchanges but not in the integrated circuits and not between the integrated circuits. This paper gives way to integrate optical communication in integrated circuits. Graphene Photonics is a powerful example of how scientific discoveries can unexpectedly emerge in the course of technology development.

Graphene Photonics is an essential tool for photonics engineers and young professionals working in the optical network, optical communications and semiconductor industries.

Photonics is the technology of signal processing, transmission and detection where the signal is carried by photons (light) and it is already heavily used in photonic devices such as lasers, waveguides or optical fibers. Optical technology has always suffered from its reputation for being an expensive solution, due to its use of exotic materials and expensive manufacturing processes. This prompt research using most common materials, such as graphene and silicon for the fabrication of photonic components. Although fiber-optic communication is a well-established technology for information transmission, the challenge for graphene photonics is to manufacture low cost information processing components. Rather than building an entirely new industrial infrastructure from scratch, the goal here is to develop graphene photonic devices manufactured using standard CMOS techniques. The big companies like IBM and Intel, that are making headway in combining optical and electrical elements on a single silicon CMOS chip only. Smaller players such as kotura, Lightwire and Luxtera are already introducing silicon photonics components to market place. IBM for instance showcases its silicon Integrated Nanophotonics project on its website. The limit goal of this project is to develop a technology for on-chip integration of ultra-compact nanophotonic circuits for manipulating the light signals, similar to the way electrical signals are manupulatated in computer chip using graphene. The limitations in silicon photonics can be overcome Graphene photonics.

II. OPTICAL COMMUNICATION

The root for graphene photonics is optical communication. Optical communication networks consist of three key building blocks: optical fiber, light sources, light detectors and optical modulators.

Optical fibers are now ubiquitous. They are the long, thin glass or Teflon fibers used to propagate a light signal down their length. This signal can be manipulated at both ends so as to code and decode the 1s and 0s that comprise the digital data domain. While initial use of optical fiber involved a single stream of data, this was soon improved upon with Multimode Fibers (MMFs). These fibers can support several light sources by using slightly different angles when propagating light down the length of the fiber, thus dramatically increasing a single fiber's bandwidth. With such improvements in the ability to manipulate the digital signal (called modulation), data speeds are now at 10 Gb/s and could theoretically reach 20 Tb/s. Extrapolate this out to the bundle of fibers that typically run down most residential avenues today delivering voice, TV, and data and one starts to believe in the theory of 'more than we could ever use'. These fibers have made their way beyond the large deployments of the cable and telecommunications providers and into even small data centers. For instance, it is not at all uncommon to find mass storage systems attached to high end computing systems via an optical fiber link. Fiber is even finding its way into 'the last mile', being offered by some cable providers delivering optic communications all the way to your home.

Light sources are needed to generate the signal which travels down the optical fiber. These are typically the most costly element in optical communications. Most widely used are the Laser Diode (LD) and the Light Emitting Diode (LED). These are both semiconductor devices, but as will be later explained, not on the miniaturized scale needed for Silicon Photonics. Key to the use of any light source is ensuring it is aligned with the optical fiber so that light entering the fiber is propagated down its length with minimal loss. Of particular impact is loss related to back-reflection at the point of entry. If the light source is not aligned perfectly, some light will catch the edges of the fiber and reflect back into the source, causing loss in signal strength, as well as creating potential problems for the light source itself in the form of interference and built up of heat.

The final component necessary for optical communication is the light detector that as its name suggests, 'detects light' at the receiving end. More importantly, it discriminates between light and no light to reconstruct the patterns of the modulator on the transmitting end and convert this back into an electrical signal to be used by the receiving device as digital data.

The main components required for designing graphene photonics are optical fiber, light sources, light detectors and optical modulators. Bringing all this down to the scale of nanometers required some additional considerations. There are some areas to concentration to make graphene photonics a reality: Light source, Light guide, modulation, photo detection, low cost assembling, and intelligence to drive all these.

2.1 Graphene

Graphene is a one atom planar sheet of sp2-bonded carbon atoms that are densely packed in a honeycomb crystal lattice. Graphene is grown as a very thin sheets (one millimeter of pencil lead contains approximately 3 million layers of graphene). Optical absorption from graphene can become saturated when the input optical intensity is above a threshold value.

This nonlinear optical behavior is termed saturable absorption and the threshold value is called the saturation fluency. Graphene can be saturated readily under strong exciting over the visible to near and far infrared region, due to the universal optical absorption and zero bandgap. This has relevance for the mode locking of fiber lasers, where wideband tenability may be obtained using graphene as a saturable absorber. Due to this special property, graphene has wide application in ultrafast photonics.

2.2 Optical Properties Of Graphene

Graphene unique optical properties produce an unexpectedly high opacity for an atom in monolayer, with a startlingly simple value: it absorbs $\pi\alpha \approx 2.3\%$ of white light, where α is fine structure constant.

2.3 Optical Source

The use of a light source is the form of manipulation or modulation. To represent binary data, the light must represent two distinct levels. In optical communications, this is done by turning the light on and off. There are two common ways, called modulation techniques, by which this is done. The most obvious is to turn the light source on and off by applying or removing voltage to the source (called direct modulation). While this seems straight forward, it has problems. The two most impacting being the time required and a distortion in the signal called frequency chirp (Herve, Ovadia 2004). A second method, 'external modulation,' minimizes these problems. Here the light source is run in Continuous-Wave (CW) mode, meaning it is never shut down, while an external (to the light source) component determines when light is allowed to pass into the fiber or not.

Ultrafast lasers are widely used in science and technology, and there is an increase demand for compact, tunable laser source. This technology is so called mode locked lasers i.e., lasers that produce ultrashort pulses at a very high repetition rate is based on semiconductor saturating absorber mirrors (SESAM)

2.4 Graphene Mode Locker

The new ultrafast laser exploits graphene and grapheme layers as mode lockers. As graphene has no bandgap, it became a key requirement for mode locking in SESAMs.

Because of Pauli Exclusion Principle, when pumping of electronics in the excited state is quicker than the rate at which they relax, the absorption saturates. This is because no more electrons can be excited until there is space available for them in the excited state. Since the Dirac electrons in graphene linearly scatter, this means that it is the most wideband saturable light ever, far out-passing the bandwidth provided by any other known material. Hence graphene is the ideal wideband saturable absorber, able to operate from the UV to visible and far infrared wavelengths.

Materials with nonlinear optical and electro-optical properties are needed in most photonic applications. Laser sources producing nano to sub picoseconds pulses are a key component in the portfolio of leading laser manufacturing. Solid state lasers have so far been the short pulse source of choice, being deployed in applications ranging from the basic research. Regardless of wavelength, the majority of ultrafast laser systems use a mode locking technique, whereby a non linear optical element, called a saturable absorber, turns the continuous-wave output into train of ultrafast optical pulses. The key requirement of nonlinear materials are fast response time , strong nonlinearity , broad wavelength range, low optical loss, high power handling , low power consumption, low cost, and ease of integration into a optical system. Currently the dominant technology is based on semiconductor saturable absorber mirrors. However, these have a narrow tuning range and require complex fabrication and packaging. A simple alternative is to use single walled carbon nanotube (SWNT), in which the diameter controls the gap and thus the operating wavelength. Broadband tenability is possible using SWNTs with wide diameter distribution. However, when operating at a particular wavelength, SWNTs not in resonance are not used and contribute unwanted losses.

As discusses above, the non linear dispersion of the Dirac electrons in graphene offers an ideal solution: for any excitation there is always an electron-hole pair in resonance. The ultrafast carrier dynamics combined with large absorption and pauli blocking, make graphene an ideal ultra broadband, fast saturating absorber.

So far, graphene polymer composites, CVD grown films, functionalized graphene and reduced graphene and reduce graphene oxide flakes have been used for ultrafast lasers. Graphene-polymer composites are scalable and more importantly, easily integrated into range of photonic system. Another route for graphene integration is by deterministic placement in a predefined position on subtract is choice.

III. OPTICAL MODULATOR

Integration optical modulation with high modulating speed and large optical bandwidth are posed to be enabling device for on-chip optical interconnections. By using semiconductor modulators heavy research has been done in past few years. However the devices footprints of silicon modulators is the order of millimeters, owing tom its week electro optical properties, germanium and other compound semiconductors on the other hand face the major challenge of integration with existing silicon electronics and photonics platform. Integrating silicon modulators with high quality factor optical resonators increases the modulation strength, but these devices suffer from intrinsic narrow bandwidth and required sophisticated optical design, they also have stringent fabrication requirements and limited temperature tolerance.

The latest researches demonstrates the way for the above problems .i.e., using monolayer grapheme having broadband, high speed, waveguide integrated electro absorption modulator. By tuning Fermi level of graphene sheet electrically, modulation of guided light can be obtained at frequency over 1GigaHetzes, together with broad operation spectrum that ranges from 1.35 to 1/6 micrometers under ambient conditions .High modulation efficiency of grapheme results in an active device are of merely 25 micrometers, which is among the smallest today. Graphene based modulator could overcome the space barrier of optical devices. It successfully shrunk a graphene based optical modulator down to a relatively tiny 25 square microns, a size roughly 400 times smaller than human hair. Even such small size, graphene packs a punch in bandwidth capability. It can observe a broad spectrum of light, ranging over 1000 of nanometers from ultraviolet to infrared wavelengths. This allows graphene to carry more data than current state of the art modulators, which operates bandwidth of up to 10 nanometers. They not only offer an increase in modulation speed, they can enable greater amount of data packets in each pulse.

To represent binary data, the light must represent two distinct levels. In optical communication this is done by turning the light on and off. This process in graphene is done easily i.e., the energy of the electrons, refers to as Fermi level, that can be easily altered depending upon the voltage applied to the material. The graphene's Fermi level in turn determines if the light is observed or not. When a sufficient negative voltage is applied, electrons are drawe out of the graphene and are no longer available to observe photons. The light is "switched on" because the graphene becomes totally transparent as the photons pass through. Graphene is also transparent at certain positive voltages, because in that situations, the electrons become packed so tightly that they cannot observe the photons. At the same time, when an enough voltage is applied so that electrons can prevent the photons from passing, effectively switching the light "off".

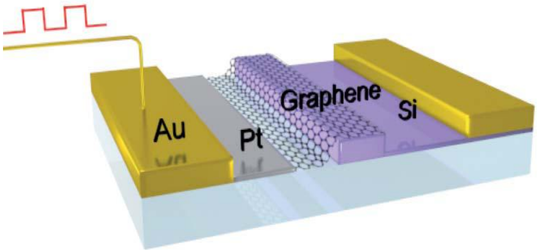
This graphene based optical modulator, have advantages of compact footprints, low operating voltage and ultrafast modulation speed across a broad range of wavelengths, can enable novel architecture on-chip optical communication.

However, one of the challenges involved in a direct graphene modulator is the limited absorption of a monolayer. This can be overcome by integrating graphene with an optical waveguide, which greatly increases the interaction lengthy through the coupling between the evanescent waves and graphene.

A graphene based waveguide integrated electroabsorption modulator has several distinctive advantages.

1. Strong light-graphene interaction.
In comparison to compound semiconductors, such as that exhibiting the quantum-well with quantum-confined stark effort (QCSE), a monolayer of graphene possesses a much stronger interband optical transition, which finds applications in novel optoelectronic devices such photodetectors.
2. Broadband operation:
As then high frequency dynamic conductivity for Dirac fermions is constant, the optical absorption of graphene is independent of wavelength, covering all telecommunications bandwidth and also the mid and far infrared.
3. High speed operation:
With carrier mobility exceeding 200000 cm square at room temperature, the Fermi level and hence the optical absorption of graphene can be rapidly modulated through the band filling effect. In addition speed limiting process in graphene operates on the time scale picoseconds which implies that graphene based electronics may have the potential to operate at 500 GHz depending on the carrier density and graphene quality.
4. Compatibility with CMOS processing:
The thermal optoelectronic properties of graphene and its CMOS compatible integration process as wafer scale make it promising candidate for post-CMOS electronics, particularly for high frequencies applications. With all this advantages monolithic integration of a graphene electroabsorption modulator could open new routes to integrated photonics using graphene.

The layer of graphene on top of silicon waveguide to fabricate optical modulators, therefore it enables to archive modulation speed of 1 GHz, but they noted that the speed could theoretically reach as high as 500 GHz for a single modulator.



Fig;1 Three dimensional schematic illustration of the device.

The structure of the electroabsorption modulator is schematically illustrated in fig: 1. A 50-nm thick silicon layer is used to connect the 250 nm thick silicon bus waveguide and one of the gold electrodes. Both the silicon layer and the waveguide were shallowly doped with boron to reduce the sheet resistance. A spacer of 7 nm thick Al2O2 is then uniformity deposited on the surface of the waveguide by atom layer deposition. A graphene sheet grown by chemical vapor deposition (CVD) is then mechanically transferred on to the silicon waveguide. To further reduce the access resistance of the device, the counter electrode is extended towards the silicon waveguide by depositing a platinum (100 nm) film on top of the graphene layer. The minimum distance between platinum and waveguide is controlled at 500nm, so that the optical modes of the waveguide remain undisturbed by platinum contact. The excess graphene is removed by oxygen plasma, leaving only the regions on top of the waveguide and the platinum electrode.

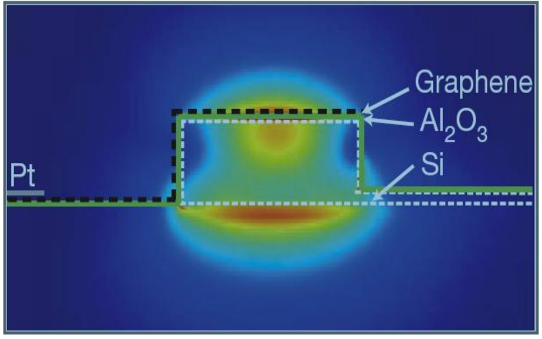


Fig 2: Cross section of device with a carrying a single optical mode.

The cross-sectional view of the device structure and the optical field distribution of the guided mode are shown in fig 1b. The thin silicon layer and platinum electrode adjacent to the waveguide have negligible effect on the mode profile. To further improve the electroabsorption modulation efficiency, the silicon waveguide is designed to have the electric field maximized at its top and bottom surface, so that the interband transition in graphene are also maximized.(fig 2). As graphene only interact with the tangential (in-plane) electric field of electromagnetic waves, the grapheme modulator is polarizationsensitive, as are conventional semiconductor-based electro-optical modulator.

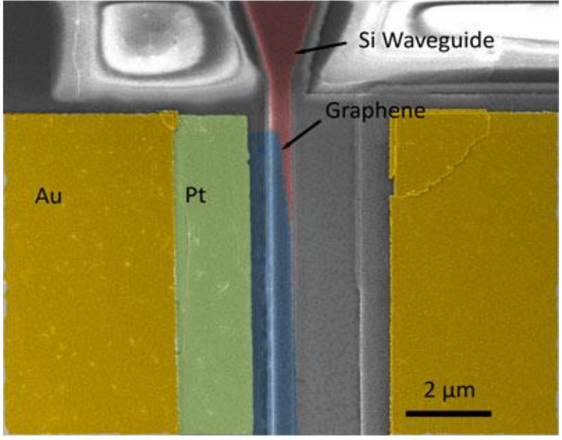


Fig 3: SEM image showing the detailed structure of the graphene modulator.

IV. OPTICAL PHOTODETECTOR

Photodetector plays a vital role in almost in all photonic applications. For example, in optical communication links, photodetectors convert information carrying optical bit streams to electrical signals. Therefore improving photodetector performance is essential for the advancement of photonics.

Photodetectors are usually made from semiconductor materials with certain band gap. Only photons with higher energies than the bandgap of the photodetector materials can be observed and converted to electrical signals. Graphene a 2D carbon material assembled in a honey comb lattice can potentially be used to detect photons with any energy, because its bandgap is zero. In fact a single and few layer graphenes have recently attracted significant attention from engineers because of their unique band structures and extraordinary carrier mobility, which can be as high as 100,000 cm square per volt second at room temperature.

A single layer of graphene, nominally 0.34nm thick can observe 2.3% of incident photons regardless of their energy. In comparison 20nm of indium gallium arsenide is needed to observe 2.3% of incident light at a wavelength of 1.55µm. Moreover, the current saturation velocity in graphene can be as high as 5×10^7 cm/s, even under a very moderate electric field. Thus graphene photodetectors are also ideal for high speed applications.

Graphene- a sheet of carbon just one atom thick can accurately detect optical streams at speed of 10 Gbps, and it could be used to create new types of circuits that use both light and electrical current to process and transmit information. Photodetectors are devices that detect light by converting optical signals into electrical current. Modern light detectors are usually made using III-V semiconductors, such as gallium arsenide. When light strikes these materials, each absorbed photon creates an electron hole pair. These pair then separate and produce an electric current using internal electric field as shown in fig 4.

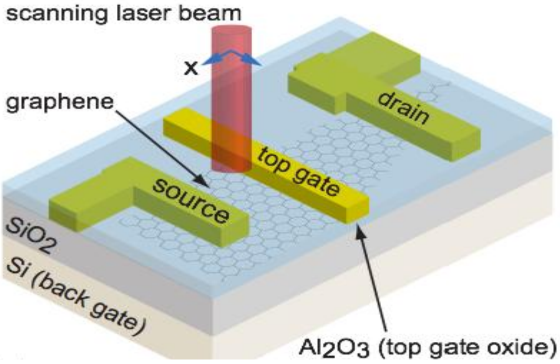


Fig 4: Schematic set-up

The internal field can be used to produce an ultrafast photocurrent response in graphene. Due to the high carrier transport voltage existing even under a moderate E-field, no direct bias voltage between source and drain needed to ensure ultrafast and efficient photocurrent generation. Such a zero-bias operation has been used in special unitravelling-carrier photodiodes with much higher built-in higher-bandwidth operation. However in most conventional photodiodes, large external bias directly applied to the photodetecting area and its complete deflection are essential for fast and efficient photodetection. Graphene photodetectors may find a wide range of photonic applications including high speed communications, interconnections, and terahertz detection.

Graphene has many unique physical and mechanical properties that make it suitable for detecting light. One of the main benefits is that electrons and holes move much faster through graphene than through other materials. Also, graphene is very good at absorbing light over a wide range of wavelength, ranging from the visible to the infrared. This is unlike III-V semiconductors, which do not work over such a wide range. At present optical photodetector can achieve the error free detection of optical data streams at rates of 10 Gbps, a figure that compares well to that of optical networks made of other materials, like III-V semiconductors.

The photoelectrical response of graphene has been widely investigated both experimentally and theoretically. Responses at wavelengths of 1.514, 0.633, 1.5 and 2.4 micrometers have been reported much border spectral detection is detection is expected because of graphene ultra wideband absorption.

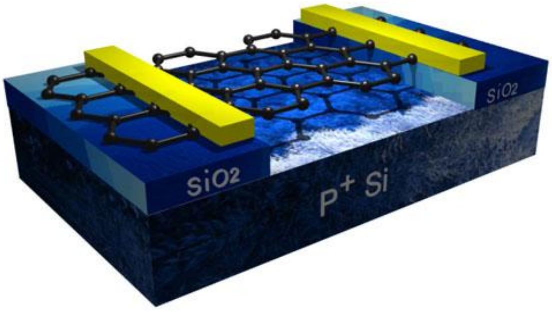


Fig 5: Graphic of a graphene layer attached to a metal sink and suspended across a trench In the silicon wafer The graphene has high heat conducting property. A sheet of densely arranged carbon that just a single atom thick can boasts strong heat conducting properties

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