Optical modulators in silicon

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Abstract—**Silicon Photonics is highly topical at present, having the potential to impact many application areas. Currently, the main focus is on various forms of optical interconnect as this is also the focus of a number of companies, some of whom have also released products into the market place. However, the implementation of silicon photonics for mass production will also benefit a range of other application areas. One of the key components that will enable silicon photonics to flourish is a high performance optical modulator. In this paper, an overview is given of the major Si photonics modulator research that has been pursued at the University of Surrey to date, as well as an overview of the state of the. We will show the trend taken toward integration of optical and electronic components with the difficulties that are inherent in such a technology**

Keywords- Silicon-On-Insulator (SOI), silicon photonics, Optical modulator, Depletion, Accumulation

I. Introduction

Recently, computer processing power has increased dramatically and nowadays common desktop computers are able to deliver a few billion floating points operation per second (FLOPs). Intel recently reported an 80 core processor capable of delivering more than 1 TFLOPs. Furthermore, storage media is moving towards solid state drives where transfer rates are steadily increasing, and requires correspondingly fast interconnects able to provide a sufficient data rate.

The computing market is leading the way with storage media and processing power for which interconnects will have to be able to deliver information in excess of 10Gb per second, up to a Tb per second in the near term. In this regard silicon photonic circuits, may be the technology of choice, primarily because of the attraction of integration of electronic and photonic functionality in a cost effective manner, and also because silicon on insulator substrates have proved successful for high volume processing of very low loss waveguides, of the order of 0.1 dB/cm. Almost every optical circuit can be replicated in silicon but in order to achieve a very high data rate, a fast and efficient optical modulation function is required, using a CMOS compatible process in Silicon on insulator.

II. Recent development in optical modulators in silicon

In 2007, Liu et al.[2] experimentally demonstrated a pn carrier depletion based silicon optical modulator with a structure very similar to that proposed by Gardes et al. [3] in 2005. The structure is a horizontal pn junction inserted in a rib waveguide where the top of the rib and the slab of the waveguide are connected to a highly doped area forming a resistive contact. This device was the first to demonstrate the possibility to achieve a bandwidth of 30 GHz and a data rate of 40 Gb/s

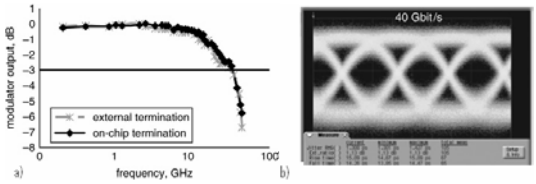

Figure 1: a) Represent the response of the modulator as a function of the RF frequency for a 1 mm active area. (b) Optical eye diagram of the modulator with a 1 mm long active area [2]

In 2008 Liu et al[4] reported a configuration of 8 MZIs based on the same modulator. The modulators were operated at 25Gb/s with an extinction ratio of 2dB. The amplified single-ended output of 3.2 V_{pp} (6.4 V_{pp} differential) was combined with 2 V_{dc} using a bias Tee to ensure reverse bias operation for the entire AC voltage swing. The DEMUX is shown Figure 2 and showed the possibility of transmitting data at an aggregate data rate of 200 Gb/s.

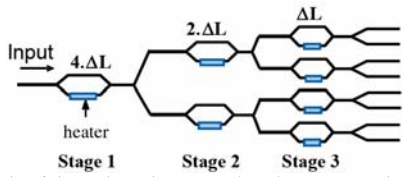

Figure 2: Schematic of the 8 channel DEMUX based on asymmetric MZIs; $4\cdot\Delta L$=97.2 um for $\Delta\lambda$=3.2 nm around 1550 nm, where $a.\Delta L$ and $\Delta\lambda$ are the length difference between two arms of the asymmetric MZIs and optical channel spacing, respectively.

Recently, Park et al.[5] reported a carrier depletion MZI based modulator in 220 nm overlayer SOI using high p and n doping concentrations positioned vertically in a 220 nm high, 500 nm wide rib waveguide to achieve a high efficiency. They showed an eye diagram demonstrating a data rate of 12.5 Gb/s. This structure is also similar to one of the designs proposed by Gardes et al [6]. A $V_\pi L_\pi$ efficiency of 2 V.cm and a loss of approximately 4dB/mm were reported. A 3dB electro-optic bandwidth of 7.1GHz was reported and data transmission was demonstrated at 12.5 Gb/s and 4Gb/s with extinction ratios of approximately 3dB and 7dB respectively.

Modulation in a SOI based ring resonator structure has also been demonstrated with an electro-optic bandwidth in excess of 35 GHz by Gill et al [7]. The modulator here is also based on SOI and the vertical pn junction is inserted in an overlayer of approximately 230 nm. The interesting feature of this device is the possibility to control the resonance of the ring by replacing the coupler by an MZI hence enabling a full control on the extinction ratio of the ring. Modulation is performed by switching the ring into and out of resonance.

Moving away from pn junction modulators, it is interesting to note that recently a modulator based on accumulation of carriers on both sides of an oxide region has been reported by Lightwire Inc[8, 9]. This device is based on the same principle used in [10] but reported a much higher efficiency, with a $V_\pi L_\pi$ of 2 V.mm which provides a compact device occupying (800um x 15um). The eye diagram indicates data transmission at 10 Gb/s with an extinction ratio of almost 9 dB. One of the possible drawbacks of this device and all reported devices based upon carrier accumulation, is the relative complexity of the fabrication process required to produce the MOS capacitor-like structure.

III. SURREY THE EARLY YEARS

The University of Surrey has been active in the development of innovative carrier injection devices since their inception, and more recently of depletion based modulators. Surrey experimental work on modulation was first reported by Tang et al [11] in 1994, in support of an earlier simulation paper in 1993 [12]. This showed that it was possible to obtain a net increase in the concentration of injected carriers into the waveguiding region of a phase modulator [11, 13] by changing the sidewall angle of the rib from vertical to 54.7 degrees. At the time when these devices were fabricated, the typical current densities were of the order of kA/cm^2 [14]. Therefore, with an experimental drive current of 7 mA, and current density of 175 A/cm^2, this device represented an improvement in the current density, and hence power consumption, of approximately an order of magnitude. Modulation bandwidths were in the range 5 – 20 MHz for different device variants.

In 2000, Hewitt et al. [15] used computer simulation to reconsider a simple two terminal p-i-n modulator based on a 5.5 μm SOI rib waveguide. It was predicted that even for a two terminal device, significant optimization is possible. For example, an increase in the doping concentrations of the p+ and n+ regions, from 1019 cm−3 to 1020 cm−3, results in a drive current decrease from 63 to 8 mA while the transient rise time also decreases from 110 ns to 105 ns.

At the same time, the placement of the doping windows forming the resistive contacts was also found to improve/degrade device transient characteristics. Rise time was reduced from 184 ns when the resistive contact was located 7 μm from the centre of the waveguide, to 39 ns when the distance was reduced to 3 μm [15]. Whilst the study was conducted for a specific device geometry, it was argued by the authors that the trends observed in the results, would have applicability in other device configurations.

From the work of Hewitt and others [15, 16] it is clear that three terminal devices required less drive current (2.8 mA vs 8 mA) and are faster than two terminal devices(29 ns vs 39 ns), for an equivalent injection concentration. This is because; three terminal devices offer more efficient carrier injection. The potential drawback of these devices is that additional optical attenuation may occur due to the doping contact at the rib top.

Png *et al*.[17],in 2003/4 improved upon the work of Ang *et al* [18]., by modelling devices with a three terminal geometry, but with improved performance[19-21]. In particular, a series of devices were modelled with intrinsic bandwidths ranging from 70 MHz to in excess of 1 GHz. The devices were based around a rib waveguide, approximately 1μm in height and between 0.5 μm and 0.75 μm wide. A feature of these devices was the optimized doping profile in the n^+ regions to optimize injection efficiency. In 2004 Png *et al.* [17] also reported the technique of pre-emphasis on critical device rise and fall times to increase device speed, improving the previously proposed device from 95 MHz to 5.8 GHz. Using such a scheme, a class of devices with nominal operating speeds of 1 GHz could theoretically be switched in excess of 40 GHz[22]. The pre-emphasis driving scheme is currently employed for high speed operation of silicon modulators up to 18 Gb/s [23, 24].

In order to increase the bandwidth further, a sub-micrometer modulator based on the depletion of a p-n junction was proposed in 2005 by Gardes *et al*. [3] In common with the MOS capacitor, the depletion type phase shifter is not limited by the minority carrier recombination lifetime and is based on the principle of removing carriers from the junction area when applying a reverse bias. The structure was 550 nm high 405 nm wide with a four terminal asymmetric horizontal pn structure, where the concentration of n-type doping is much higher than the concentration of p-type doping. The reason for such a structure is firstly to minimize the optical losses induced by the n-type doping and secondly to enhance the depletion overlap between the optical mode and the p-type region, in order to induce a better phase shift to length ratio. The carrier concentration variation in this kind of device is not uniform and arises on both sides of the junction over a width of around 200 nm. One way to optimize the device is by increasing the overlap between the optical mode and the p-type depleted region. The main advantage of using depletion is obviously the very fast response time, simulated to be 7 ps for this modulator. This corresponds to an intrinsic bandwidth of approximately 50 GHz. The device proposed by Gardes et al was 2.5 mm long and operated with a reverse bias swing of 5 Volts in a push-pull configuration as part of a Mach Zehnder interferometer (MZI). To further improve compactness and simplify fabrication, a modulator based on a depletion of a vertical pn junction was demonstrated by Gardes et al. [6]. The ring resonator modulator is based on a 300 nm wide, 150 nm etch depth and 200 nm high rib waveguide, which enables single mode transmission. The pn junction is asymmetrical in size and in doping concentration in order to maximize the area of hole depletion that overlaps with the optical mode. The n-type region is 75 nm wide and the p type 225 nm wide, and the net doping concentration of this particular junction varies between 6 x 10^{17}.cm^{-3} and 2 x 10^{17}.cm^{-3}, for n and p types, respectively. The junction was fabricated using ion implantation at CEA Leti in France, and the Ion Beam Centre at the University of Surrey. The modulator exhibited a DC on/off ratio of 5 dB at -10 V, and a 3 dB bandwidth of 19 GHz.

This showed the trend in miniaturization of the devices to obtain maximum performance in terms of mode confinement, frequency of operation and power consumption, where the ultimate goal is to integrate electronic drivers and optical building blocks on the same substrate, also referred to as “front end integration”.

IV. SILICON PHOTONICS IN EUROPE

Following the results obtained in the field of high speed modulation in silicon photonics two relatively large consortium based projects have been funded in Europe to demonstrate and establish the possibilities offered by silicon photonics. The first project is UK based “ UK silicon photonics” [25] and the second is a European based project called “Helios” [26] . The mission of the two projects is to demonstrate building blocks that will be use to achieve large scale integration. Innovative means are to be developed to combine a photonic layer with electronic circuitry, using microelectronics fabrication processes. One of the aims of the two projects is to develop optical modulation for 10 Gb/s and 40 Gb/s while improving figures of the state of the art in terms of efficiency and modulation extinction ratio. Furthermore, extensive research is applied to the fabrication of the components to enable reliable fabrication processing in order to obtain high yields

V. SUMMARY CONCLUSION

The state of the art in silicon photonics is varying at an enormous rate, with innovations being reported very frequently. Integration is one of the most topical subject areas and within the field of integration, optical modulators is a key component as it defines most of the chip parameters such as power consumption, size and speed of operation. This paper has discussed the state of the art, with emphasis on the work at the University of Surrey. Whilst significant progress continues to be made, device performance still needs to improve to be viable for high performance optical modulation, and particularly to move towards high scale integration of silicon photonic components with electronic functionality.

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