40 Gb/s high speed silicon modulator for TE and TM polarisation

F. Y. Gardes, D. J. Thomson, G. T. Reed
Advanced Technology Institute, University of Surrey, Guildford, Surrey, UK

Abstract

The workhorse of future high speed short reach interconnect technology will be the optical modulator. These devices in silicon have experienced dramatic improvements over the last 6 years and the modulation bandwidth has increased from a few tens of MHz to over 30 GHz. However, the demands of optical interconnects are significant. Hence, the need for devices with compact real estate, broadband characteristics, operating at high speed and working for both polarisation is of outmost importance. Here we describe the approach taken at Surrey to meet these requirements from the early days to the more recent work where some initial data are introduced. The recent all-silicon optical modulator uses a CMOS compatible fabrication and demonstrates high data rate with large extinction ratio for TE and TM polarisations. This technology is not only compatible with conventional complementary MOS (CMOS) processing, but is also intended to facilitate a high yield, reliable fabrication process.

Keywords: microphotonics, waveguide, silicon-on-insulator, optical modulator, carrier depletion, integrated optics

Introduction

Silicon photonics research started in the 80’s with the aim to achieve the fabrication of optical transceivers on a silicon platform. The density and functionality of passive optical circuits has seen a gradual increase over the years, due to a better photolithography resolution and an SOI platform of higher quality. The key active component that has generated an enormous interest in the last five years, is the modulator. The research being undertaken on this specific component has been significant over the last 20 years. The devices have evolved from micrometer size waveguides using mostly the plasma dispersion effect in injection mode to sub-micrometer size waveguides where the plasma dispersion is in the majority of cases using majority carriers to obtain high speed modulation. We will describe below the research and the evolution of these modulators at Surrey from what was achieved in the early years to today’s state of the art devices.

The early years to nowadays

In order to keep the fabrication processes CMOS compatible, several different integration schemes using the plasma dispersion effect have been researched. The design rules are usually based around a rib waveguide where a diode is inserted. This design should take into consideration fabrication factors such as ease of fabrication and self aligned implants as well as device characteristics with a particular focus on single mode behaviour, polarisation dependence, efficiency (influencing the length of the device, the voltage swing and ultimately the power consumption) and the modulation bandwidth.

In the early days the designs were based upon silicon guiding layers fabricated on doped silicon substrates (to form the lower waveguide boundary), the latter having a reduced refractive index via the plasma dispersion effect. Later on Silicon-on-Insulator (SOI) wave guiding structures became more popular due to the possibility of much stronger optical confinement.

In the early 90's, work carried out at the University of Surrey by Tang *et al.* [1], in support of an earlier simulation paper [2] showed that it was possible to obtain a 30% increase in the concentration of carriers injected into the wave guiding region of a phase modulator ([1]) by changing the sidewall angle of the rib from vertical to 54.7 degrees. The separation distance of the n^+ injecting regions remained constant for both the vertical and angled rib waveguides. The device was designed at the University of Surrey and fabricated in a University of Surrey/University of Southampton collaboration.

By the mid 1990s, silicon modulator work was almost exclusively being carried out on SOI material. In 2000, Hewitt *et al.* [3] used computer simulations 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 optimisation was possible. For example, an increase in the doping concentrations of the p^+ and n^+ regions, from 10^{19} cm^{-3} to 10^{20} cm^{-3}, resulted in a drive current decrease from 63 to 8 mA while the transient rise time also decreased from 110 ns to 105 ns. At the same time, the placement of the doping windows was also found to improve/degrade device transient characteristics. The rise time was reduced from 184 ns when the resistive contact was 7 μm from the centre of the waveguide to 39 ns at a separation of 3 μm. From the work of Hewitt and others [3, 4], it was also clear that three terminal devices require less drive current (2.8 mA vs 8 mA) and were faster (29 ns vs 39 ns) than two terminal devices, for an equivalent injection concentration. For a silicon *p-i-n* phase modulator utilising free carrier injection, carrier confinement in the active region is also important. Trench isolation was proposed as a means of achieving carrier confinement, by Hewitt *et al.* [4], who predicted that employing lateral trench isolation on either side of the modulator improved both the direct-current (dc) and transient devices performances by up to 74% and 18% respectively. Following these principles and a trend of reduction in waveguide size, in 2002 Png *et al.* [5], modelled devices of similar geometry, but with improved performance [6-8]. In particular a series of devices were modelled with bandwidths ranging from 70 MHz to greater than 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 optimised doping profile in the n^+ regions to optimise the injection efficiency. Png *et al.*[9] also proposed the technique of pre-emphasis in 2004 on critical device rise and fall times to increase device speed, improving the bandwidth 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 [9].

Nevertheless if the driving signal is required to be kept as a standard square wave signal, the speed of such a modulator is limited by the recombination lifetime as well as the size of the waveguide, which requires the Ohmic contacts (highly doped regions) to be a few hundred nanometres away from each other to avoid further limiting the bandwidth which leads to higher optical losses.

In 2005, an alternative sub-micrometer modulator based on the depletion of a *p-n* junction was proposed by Gardes et al. which was the first of its kind at the time of publication [10]. 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 when a reverse bias is applied. The main advantage of using depletion to adjust the index of refraction in the waveguide is the fast response time, simulated in this work to be 7 ps. Figure 1 shows the cross-section schematic of a four terminal asymmetric *p-n* structure, where the concentration of *n*-type doping is much higher than the concentration of *p*-type doping. The reason for this structure is firstly to minimize the optical losses induced by the *n*-type doping and secondly to enhance the overlap between the optical mode and the *p*-type depletion region which provides a better phase shift to length ratio.

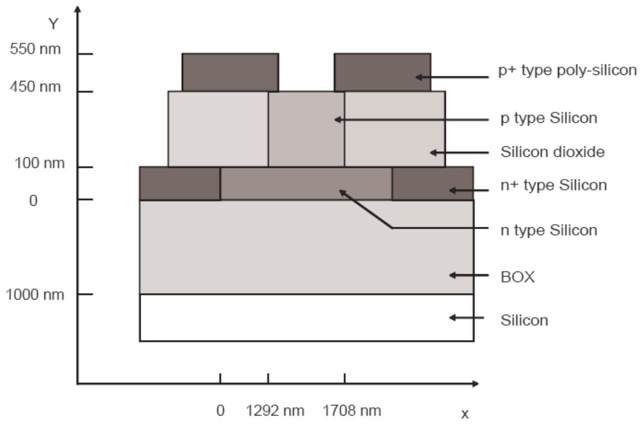


Figure 1. Schematic of a four terminal depletion type modulator [10].

The carrier concentration variation in this device is not uniform, however the predicted refractive index change across the vertical axis of the waveguide arises on both sides of the junction over a width of around 200 nm. It is believed that the device could be better optimized by increasing the overlap between the optical mode and the *p*-type depleted region. Regardless of this less-than-optimal result, the proposed device was modelled to have an intrinsic bandwidth of approximately 50 GHz when a reverse bias swing of 5 volts was applied to both arms of a Mach Zehnder Interferometer (MZI) (2.5 mm long active area in each arm), in a push-pull configuration.

In 2007, Liu et al. [11, 12] experimentally demonstrated a *p-n* carrier depletion-based silicon optical modulator with a structure very similar to that proposed by Gardes et al. [10] in 2005.

The research trend of moving towards smaller waveguides to reduce power consumption and device real estate led to devices such as the one recently reported by Gardes et al. [13] in 2009. The proposed ring resonator modulator was based on a 300 nm wide, 150 nm etch depth and 200 nm high rib waveguide. This structure was capable of providing single mode propagation. As shown in Figure 2, the *p-n* junction was asymmetrical in size and in doping concentration in order to maximize the depletion area that overlaps with the optical mode. The *n*- and *p*-type regions were 75 nm and 225 nm wide respectively, 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*-type regions, respectively. The device was fabricated in a Europe-wide collaboration [13].

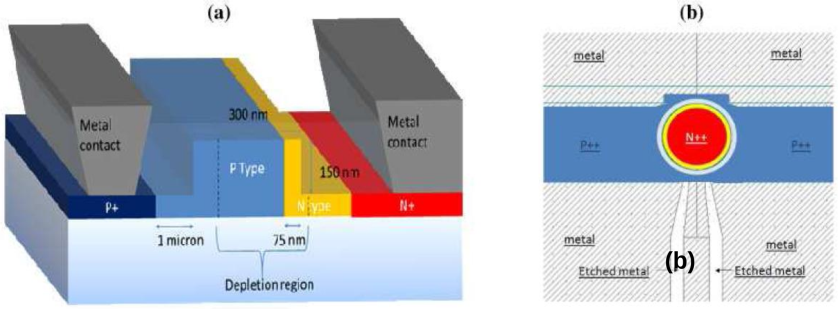


Figure 2. (a) Cross-section schematic of the rib waveguide modulator. (b) Plan-view schematic of the positioning of the doped area and electrodes around the ring [13].

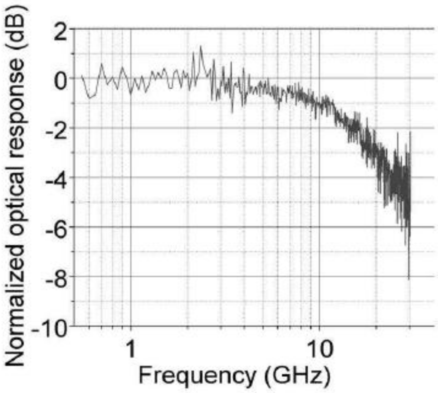


Figure 3. Normalized optical response as a function of frequency [13].

The modulator, based on a 40 micron radius ring resonator, exhibited a DC on/off ratio of 5 dB at -10 V, and a 3 dB bandwidth of 19 GHz (Figure 3). The principal issues regarding the fabrication of ring resonator modulators are the difficulties encountered in finding the right coupler configuration to obtain high resonance contrast for a wide range of wavelengths. These issues are exacerbated when the fabrication variations of the coupling area and the waveguide losses for a particular fabrication process are unknown. But the main issue on this device was the inaccuracy of the positioning of the junction due to processing tolerances.

This issue was solved by Thomson et al [14] with a new design of carrier depletion based silicon optical modulator for which a self aligned process (Figure 4) was used to form the pn junction. Experimental results obtained from an initial fabrication batch have demonstrated data transmission at 10Gbit/s with 6dB of modulation depth from a 3.5mm long phase shifter (Figure 5).

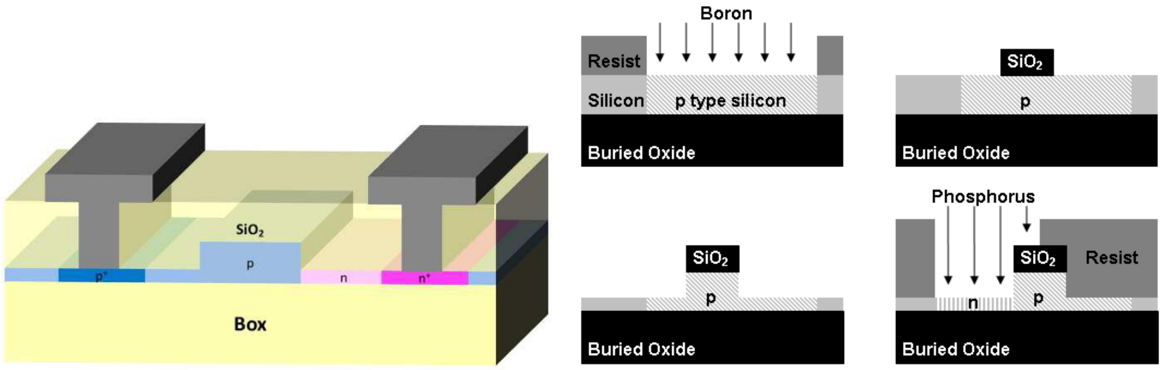
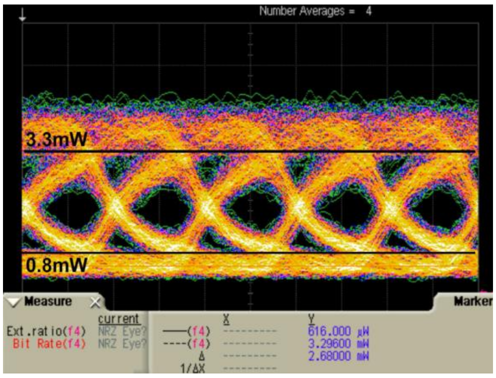


Figure 4. Cross section of the modulator and processing involved for the self aligned junction[14].



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              current              X            Y
Ext.ratio(f4) NRZ Eye?  ——(f4)  ---------   616.000 µW
 Bit Rate(f4) NRZ Eye?  ----(f4) ---------  3.29600 mW
                            Δ   ---------   2.68000 mW
                         1/ΔX   ---------
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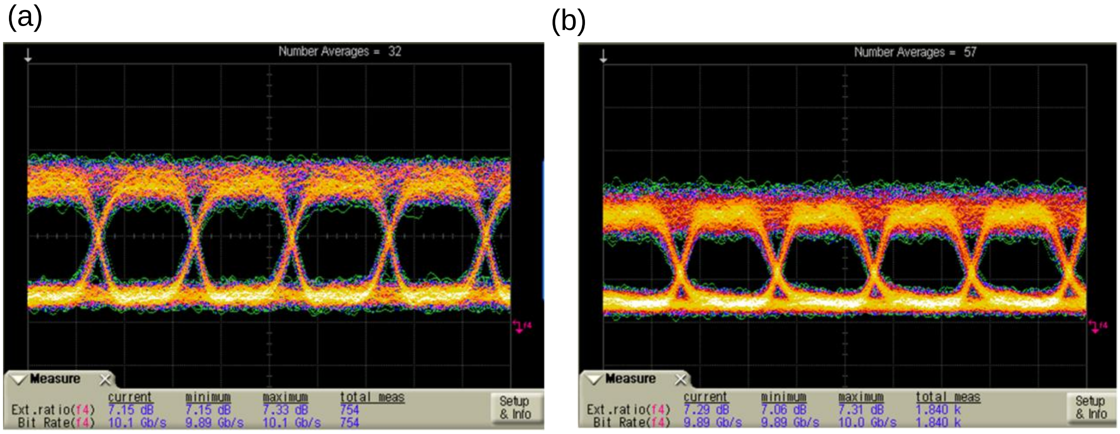
Figure 5. 10 Gb/s eye diagram for TE polarisation[14].

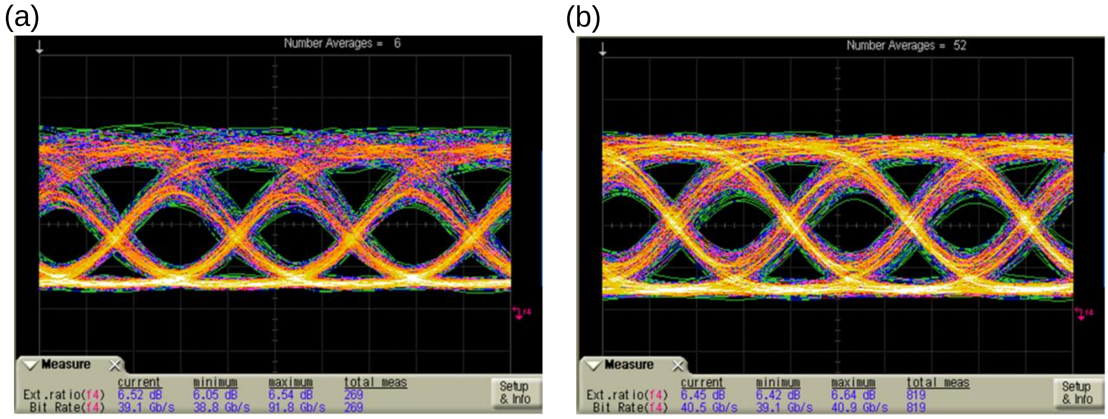
Due to the device size and structure the operation is mainly restricted to the TE mode. Gardes et al [15] demonstrated in 2010 a self aligned device also using carrier depletion. The device was demonstrated to operate at 40 Gb/s for a 1.3 mm long phase shifter. Of particular note was the fact that this device operates at this data rate for both TE and TM polarisation as shown in figures 6 and 7.



	current	minimum	maximum	total meas
Ext.ratio(f4)	7.15 dB	7.15 dB	7.33 dB	754
Bit Rate(f4)	10.1 Gb/s	9.89 Gb/s	10.1 Gb/s	754

	current	minimum	maximum	total meas
Ext.ratio(f4)	7.29 dB	7.06 dB	7.31 dB	1.840 k
Bit Rate(f4)	9.89 Gb/s	9.89 Gb/s	10.0 Gb/s	1.840 k

Figure 6: (a) Eye diagram for a 1350 micrometers long device measured at 10 Gb/s, and at a wavelength of ~1557 nm for TE polarisation.
b) Eye diagram for a 1350 micrometers long device measured at 10 Gb/s, and at a wavelength of ~1557 nm for TM polarisation.



	current	minimum	maximum	total meas
Ext.ratio(f4)	6.52 dB	6.05 dB	6.54 dB	269
Bit Rate(f4)	39.1 Gb/s	38.8 Gb/s	91.8 Gb/s	269

	current	minimum	maximum	total meas
Ext.ratio(f4)	6.45 dB	6.42 dB	6.64 dB	819
Bit Rate(f4)	40.5 Gb/s	39.1 Gb/s	40.9 Gb/s	819

Figure 7: (a) Eye diagram for a 1350 micrometers long device measured at 40 Gb/s, and at a wavelength of ~1557 nm for TE polarisation.
b) Eye diagram for a 1350 micrometers long device measured at 40 Gb/s, and at a wavelength of ~1557 nm for TM polarisation.

Conclusion

In conclusion we have presented the work on optical modulation at surrey from the early days where modulators had multi-micrometer size cross sections and were operating in the Megahertz range to a current device operating at 40 Gb/s for both TE and TM polarisation. The change in operating speed mainly occurred in the last 5 years when majority carrier devices were introduced.

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