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Invited Paper

Silicon Photonics: Optical modulators

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ABSTRACT

Silicon Photonics has the potential to revolutionise a whole raft of application areas. Currently, the main focus is on various forms of optical interconnects as this is a near term bottleneck for the computing industry, and hence a number of companies have also released products onto the market place. The adoption of silicon photonics for mass production will significantly benefit a range of other application areas. One of the key components that will enable silicon photonics to flourish in all of the potential application areas is a high performance optical modulator. 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 a worldwide state of the art showing the trend and technology available. 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, QCSE

1. INTRODUCTION

In the last few years processing power has increased tremendously and nowadays common desktop computer are able to achieve a few billions of floating points operation per second (FLOPs). Recently Intel demonstrated an 80 core processor capable of delivering more than 1 TFLOPs[1], perhaps describing what tomorrow's computing platforms could look like. Furthermore, storage media is moving towards solid state drives where transfer rates are steadily increasing, and also requires interconnects able to provide a sufficient data rate.

The computing market is setting 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 and possibly up to a Tb per second in the foreseeable future. In this regard silicon photonic circuits, may be the technology of choice, primarily because of the potential attraction of integration of photonic functionality with electronics 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 the very high data rates stated above, the need to achieve a very fast and efficient optical modulation function, using a CMOS compatible process on Silicon on insulator is of the utmost importance.

2. OPTICAL MODULATION RESEARCH AT SURREY

The University of Surrey has been active in the development of innovative carrier injection and more recently depletion based modulators since their inception. The preliminary work was done by Tang et al [2] in 1994, in support of an earlier simulation paper in 1993 [3], which showed that it was possible to obtain a 30% increase in the concentration of injected carriers into the waveguiding region of a phase modulator [2, 4] by changing the sidewall angle of the rib from vertical to 54.7 degrees (Figure). At the time when these devices were fabricated, the typical current densities were of the order of kA/cm^2 [5]. 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 of approximately an order of magnitude. Modulation bandwidths were in the range 5 – 20 MHz for different device variants.

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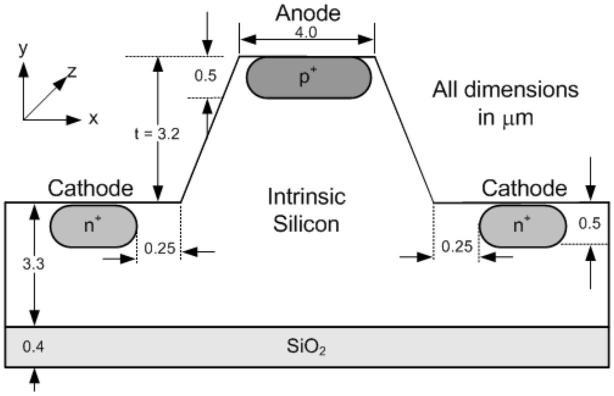


Figure 1: Three terminal phase modulator with angled rib walls [2, 4].

In 2000, Hewitt *et al*. [6] 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 optimisation is 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}, results in a drive current decrease from 63 to 8 mA while the transient rise time also decreases from 110 ns to 105 ns.

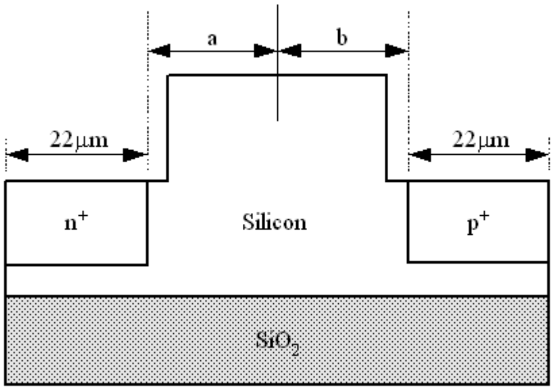


Figure 2: Varying the placement of the contact windows [6].

At the same time, the placement of the doping windows (Figure 2) was also found to improve/degrade device transient characteristics. Rise time was reduced from 184 ns when a = b = 7 μm (see figure 2), to 39 ns when a = b = 3 μm [6]. 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 [6, 7] it is clear that three terminal devices require 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 (3 terminal) is that additional optical attenuation may occur due to the doping contact at the rib top.

Png *et al*.[8], later improved upon the work of Ang *et al* [9]. by modelling devices of similar geometry (see figure 3), but with improved performance[10-12]. 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 optimised doping profile in the n^+ regions to optimise injection efficiency. In 2004 Png *et al.* [8] also reported the technique of pre-emphasis on critical device rise and fall times to increase device speed, improving a device based on Figure 3 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[13].

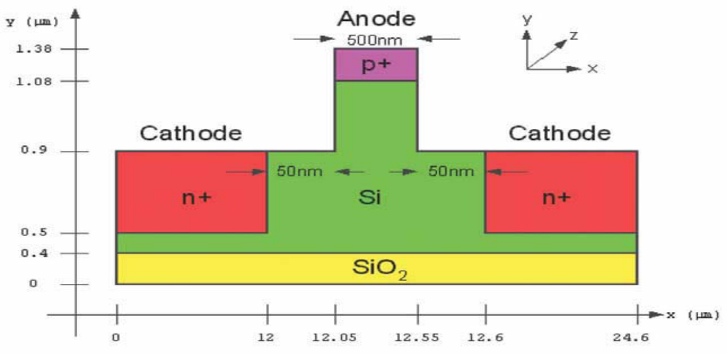


Figure 3: Proposed 3-terminal rib waveguide device based on SOI [8].

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*. [14] 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. Figure 4 shows a four terminal asymmetric 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.

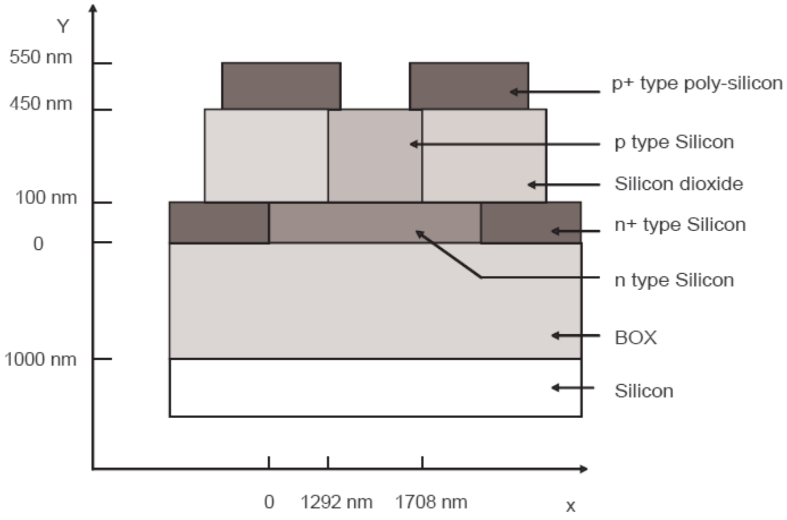
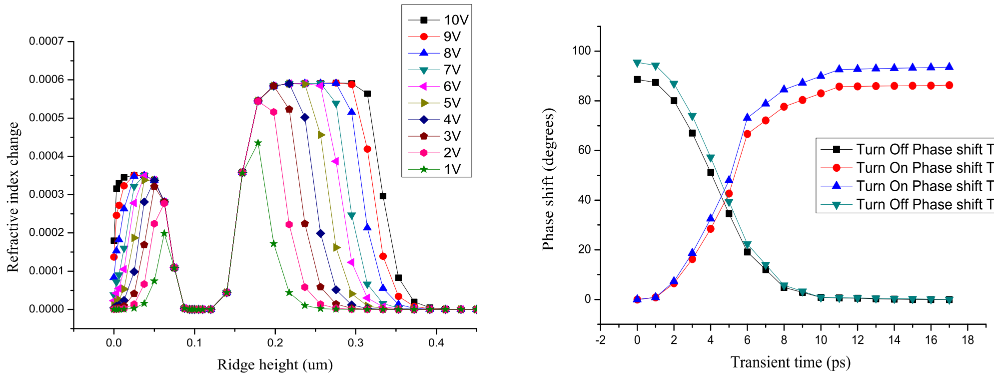


Figure 4: Schematic of a four terminal depletion type modulator [14]

The carrier concentration variation in this kind of device is not uniform, as can be seen in the predictions of the refractive index change in the waveguide shown in Figure 5, 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).



(a) (b)

Figure 5: (a)Variation of the refractive index in the waveguide; (b)Rise and fall time for TE and TM [14]

To improve further compactness and simplify fabrication a modulator based on a depletion of a vertical pn junction was demonstrated by Gardes et al. [15] . The proposed 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. As shown in Fig. 1, 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.

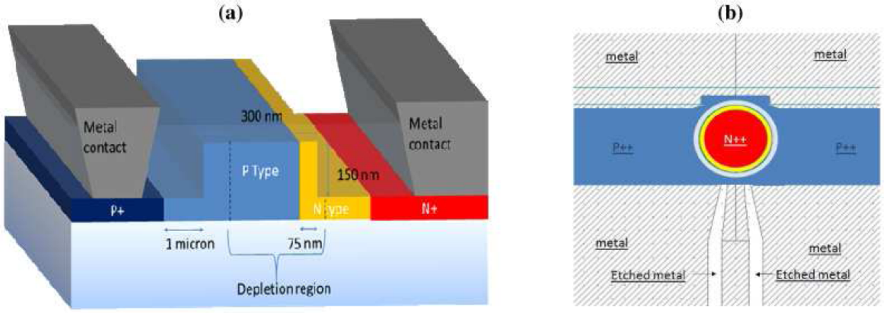


Figure 6: (a)Variation of the refractive index in the waveguide; (b) Right: Rise and fall time for TE and TM[15]

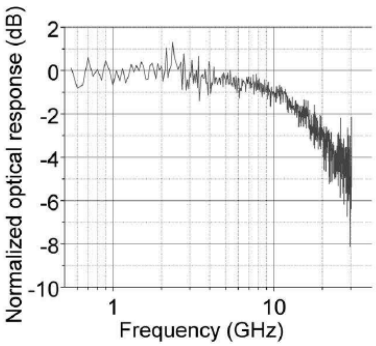


Figure 7: Normalized optical response as a function of frequency[15].

The modulator exhibited a DC on/off ratio of 5 dB at -10 V, and a 3 dB bandwidth of 19 GHz (figure 7). Despite the relatively high bandwidth result, the device is non-optimal, which can be attributed to misalignment of the junction and incomplete activation of the dopants used to form the pn junction.

We are currently carrying out preliminary work on two additional optical phase modulator designs as part of two different projects. The first is funded via the European Union Framework as part of a project known as HELIOS, and the second is part of a UK initiative entitled UK Silicon Photonics, funded by the Engineering and Physical Sciences Research Council (EPSRC). In both cases the aim is to demonstrate modulator variants with speeds of 10Gb/s and 40Gb/s.

3. RECENT DEVELOPMENT IN SILICON OPTICAL MODULATION

In 2007, Liu et al.[16] experimentally demonstrated a pn carrier depletion based silicon optical modulator with structure very similar to that proposed by Gardes et al. Figure 8 shows the schematic of the modulator as well as a SEM picture of the modulator cross section.

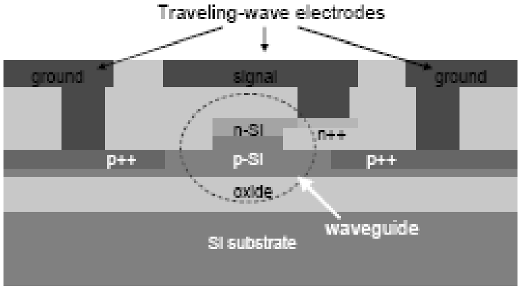
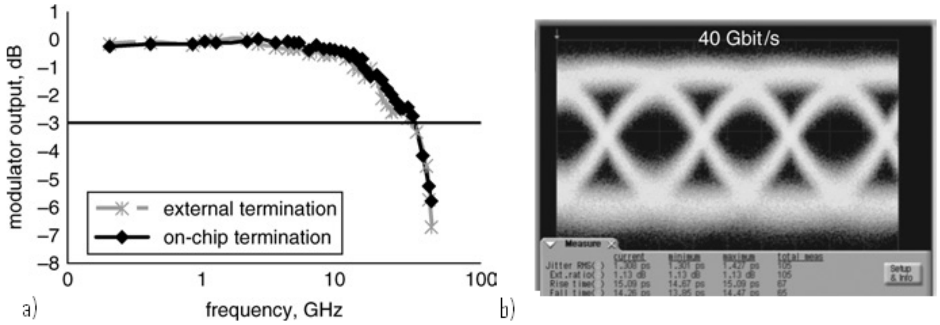


Figure 8: Cross sectional diagram of the modulator[16].

A modulation efficiency $V_\pi L_\pi$ (where V_π is the bias voltage required for π phase shift and L_π is the corresponding device length) of approximately 4 V.cm was reported.

Later in 2007 Liao et al. [17] presented further developments of the device, boasting an electro-optic bandwidth of 30 GHz and data transmission at 40 Gbit/s with an extinction ratio of about 1dB. The frequency response and eye diagram is shown in Figure 9. To date this is the fastest reported experimental optical modulator in silicon.



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              current     minimum     maximum     total meas
Jitter RMS( )  1.308 ps    1.301 ps    1.427 ps    105
 Ext.ratio( )  1.13 dB     1.13 dB     1.13 dB     105
 Rise time( )  15.09 ps    14.67 ps    15.09 ps    67
 Fall time( )  14.26 ps    13.85 ps    14.47 ps    65
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Figure 9: (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[17].

More recently, Park et al.[18] reported a carrier depletion MZI based modulator in 220nm overlayer SOI using high p and n doping concentrations to achieve a high efficiency. Figure 10 shows a cross sectional diagram, plan SEM image of the MZI structure and eye diagram at 12.5Gb/s. The structure is similar to one of the designs proposed by Gardes et al. A $V_{\pi}L_{\pi}$ efficiency of 2V.cm and a loss of approximately 4dB/mm were reported. A 3dB electro-optic bandwidth of 7.1GHz is reported and data transmission has been demonstrated at 12.5Gb/s and 4Gb/s with extinction ratios of approximately 3dB and 7dB respectively.

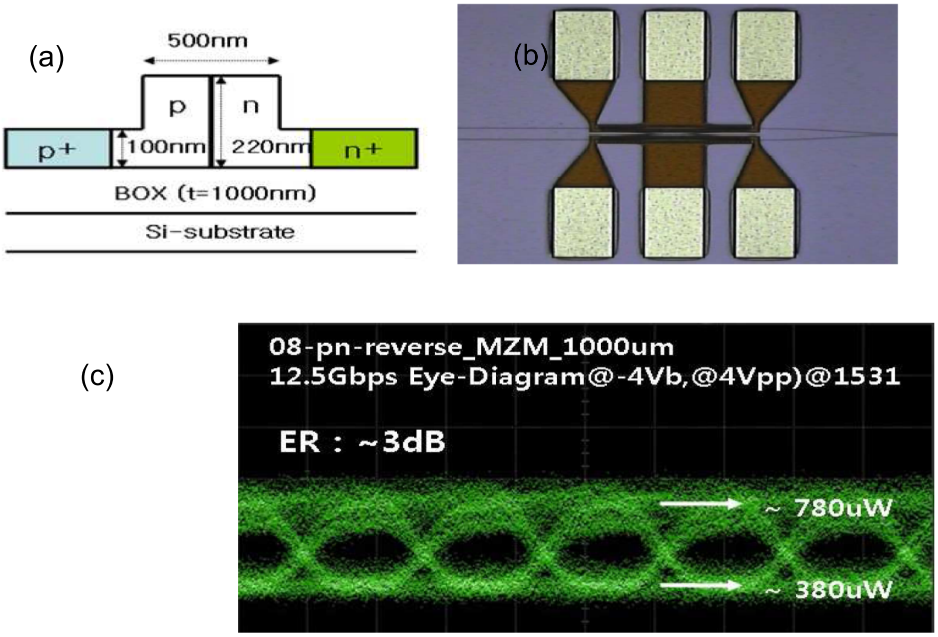
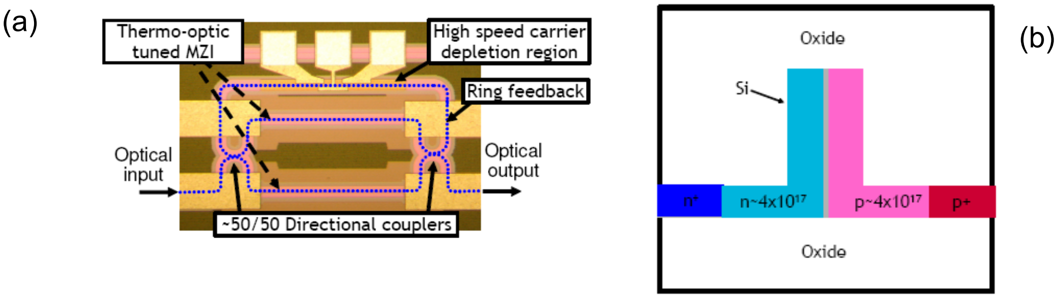


Figure 10: Cross section of the phase shifter (a) SEM plan image of the MZI structure (b) and data transmission at 12.5Gbps (c) [18].

Modulation in a SOI based ring resonator structure has also been demonstrated with an electro-optic bandwidth in excess of 35GHz [19]. A plan and cross-sectional diagram of the modulator which is based in SOI with an overlayer of approximately 230nm are shown in figure 11 together which the electro-optic frequency response. The authors report an off-resonance loss of 0.5dB.



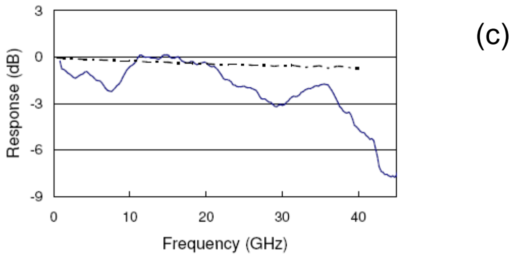
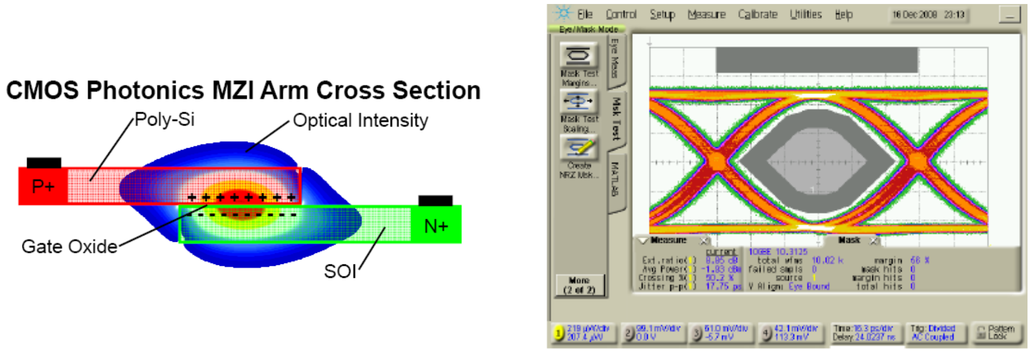


Figure 11: Plan view of the ring modulator (a), cross-sectional diagram of the phase shifter (b) and device electro-optic response (c)[19].

Whilst resonant structures are more compact than Mach-Zehnder Interferometers they are very sensitive to temperature changes which can be problematic when the modulator is to be integrated for example with electronics which tends to heat up during operation. As a result some DC tuning is normally required which complicates the design as well as increasing power consumption.

The state of the art for carrier accumulator based modulators has been reported recently by Lightwire Inc. [20]. The eye diagram displayed (figure 12) indicates data transmission at 10Gb/s with an extinction ratio of almost 9dB. Their device is very compact (800um x 15um) which is possible due to a high $V_{\pi}L_{\pi}$ efficiency of 2V.mm. One of the possible drawbacks of this device and all reported devices based upon carrier accumulation, is the complexity of the fabrication process required to produce the MOS capacitor like structure.



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              current   10GE 10.3125
Ext.ratio(1)  8.85 dB     total wfms   10.02 k        margin  56 %
Avg Power(1)  -1.83 dBm   failed smpls  0          mask hits  0
Crossing %(1) 50.2 %            source  1        margin hits  0
Jitter p-p(1) 17.75 ps    V Align: Eye Bound      total hits  0
```

```
1 219 µW/div 207.4 µW | 2 99.1 mV/div 0.0 V | 3 61.0 mV/div -5.7 mV | 4 42.1 mV/div 113.3 mV | Time:16.3 ps/div Delay:24.0237 ns | Trig: Divided AC Coupled
```

10GE ER Optical Eye with 56% MM

Figure 12: Cross-sectional Diagram of accumulation modulator (left) and 10Gb/s eye diagram (right)[20, 21].

Other effects are also being researched to achieve modulation through hybridisation of silicon with materials such as germanium. Strained layer silicon germanium epitaxy offers another optical modulation mechanism through the use of the Franz-Keldysh electro optic effect. In 2006 Jongthammanurak et al.[22] demonstrated electro-optic coefficients of 160pm/V and 280pm/V for bulk and strained Ge films respectively in the weakly absorbing regime. The authors claim that this enables the production of low loss modulators with large extinction ratios. In early 2007 Liu et al.[23] proposed the monolithic integration of this modulator with a photo detector of the same structure (figure 13). Using the same GeSi composition and structure for both modulator and detector allows for efficient monolithic process integration. The authors report that since the modulator is RC limited an electro-optic bandwidth in excess of 50GHz is expected together with an extinction ratio of 10dB. The photo detector proposed by Liu et al. has a predicted responsivity of >1 A/W and a 3 dB bandwidth of >35 GHz.

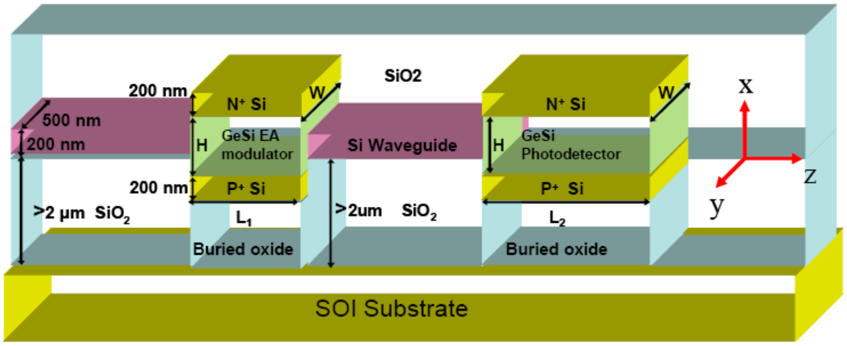

Figure 13: Structure of the proposed monolithically integrated GeSi electroabsorption modulators and photodetectors[23]

Both modulator and photo detector structures are based on a vertical Si/Ge$_{0.9925}$Si$_{0.0075}$/Si PIN diode with a doping density of 2×10^{19}cm^{-3} in n^+ and p^+ Si, and their height (H) and width (W) can be designed to obtain optimal device performance. The drawbacks of such a structure are the difficulty of obtaining efficient butt coupling to minimise losses due to the impedance mismatch between the strip waveguide and the modulator as well as the need to fabricate the vertical PIN diodes.

Another effect which uses a SiGe heterolayers is the quantum confined Stark effect (QCSE). The quantum-confined Stark effect (QCSE) describes a shift in the energy of the confined states of quantum wells (QWs) when an electric field is applied perpendicular to the plane of the QWs. For a rectangular QW, the energy of the ground state will be shifted closer to the band edge under an applied field [24]. Provided there is strong confinement, second order perturbation theory shows that the energy shift is parabolic, increasing with the square of the applied field. For Type-I quantum wells, both electron and hole confined states will be shifted towards the band edges, and we can expect a shift in the absorption edge to longer wavelengths.

There are two mechanisms by which we can exploit the QCSE for modulation of optical signals: electro-absorption (EA) and electro-refraction (ER). In an EA device the multiple quantum well (MQW) system is designed so that the absorption edge is close to the wavelength energy of the carrier. Under zero field, the absorption edge is at a shorter wavelength than the signal, and when a field is applied the absorption edge shifts to longer wavelengths so that the signal is absorbed. In an ER device, the MQW structure is designed so that the absorption edge always lies at a shorter wavelength than the signal (of the order of 50 nm), and the change in refractive index that is induced by the shift of the absorption edge is exploited by using a Mach-Zehnder interferometer (MZI) configuration.

Waveguide-integrated semiconductor EA devices employing the QCSE were reported in 1989 [25], where an InGaAlAs/InAlAs MQW structure was used to modulate a 1.55-µm signal at 20 GHz. MZI devices employing the QCSE were first reported in 1993, employing an InP/InGaAsP MQW heterostructure to modulate a 1.56-µm signal at 10 Gb/s [26]. Several MZI type devices based on InP have been demonstrated since, including travelling-wave devices operating at 40 Gb/s [27] and more compact lumped-element devices also operating at 40 Gb/s[28], as well EA modulators[29]. The QCSE is, in principle, an extremely fast process as no injection or depletion of carriers is required, and furthermore, for the same reasons it is expected that QCSE devices should result in improved power efficiency compared to carrier-depletion/accumulation devices. Modulation of the absorption coefficient of a Ge/SiGe MQW system, epitaxially grown on Si wafers using reduced pressure chemical-vapour deposition (RP-CVD) has been achieved. A contrast in the absorption coefficient of a factor of 4.69 was reported, and it was proposed that this structure could be employed in an electro-absorption device operating at ~ 1450 nm [30, 31].

Of greatest commercial interest are the telecommunications ‘windows’ at wavelengths of 1310 nm and 1550 nm. The direct bandgap of bulk Ge is 800 meV, corresponding almost exactly to 1550 nm. A strain-symmetrised MQW stack of Ge QWs and SiGe barriers will result in compressive strain of the Ge wells, which will increase the bandgap [32, 33]. Choosing a high Si-fraction for the virtual substrate results in large amounts of compressive strain in the Ge QWs and will result in a shift of the absorption edge to shorter wavelengths. This strain engineering approach provides a method to design MQW structures for EA modulation at 1310 nm. If we consider that the confined electron and hole states will be displaced from the band edge, it is clear that EA modulation at 1550 nm will be more difficult to achieve, as the photon energy of the carrier will be considerably smaller than the absorption edge energy. It is therefore more suitable to design ER MQW structures to modulate 1550-nm light.

Two major milestones yet to be accomplished are waveguide-integration and process-integration. Waveguide-integration of RP-CVD-grown Ge detectors has been achieved using selective area epitaxy [34, 35]. In principle, we may expect that a similar approach would be suitable for the MQW structures used for QCSE devices. However, the requirements for such a device are much more demanding, since we require excellent control (sub-nanometer resolution) of the layer thicknesses in the MQW stack, and furthermore the layers must lie perpendicular to the applied field throughout the device. Current local-area epitaxy approaches will typically result in non-uniformities in the layer thicknesses across the device, and further development of local-area epitaxy is probably required. Additionally, even tighter thermal budget constraints are imposed by growing the MQW stack than is the case for Ge detectors, as heating the MQW stack will result in interdiffusion of the adjacent Ge and SiGe layers. Electro-optic modulation can also be achieved via the Pockels effect. The distinct advantage of this approach is that the speed of such a device is not limited by charge mobility or charge recombination times. Moreover, only an electric field is required and no current through the waveguide is needed. Modulators based on the Pockels effect have been widely demonstrated using materials with high Pockels coefficients, e.g. $LiNbO_3$. Silicon in nature has a centrosymmetric crystal structure and has no Pockels effect. However, engineering of the structure or alternative materials could be used to achieve electro-optical modulation in a silicon waveguide.

Strain on silicon waveguide could be a solution for the realisation of electro-optic modulation. Jacobsen et al. [36] demonstrated a significant linear electro-optic effect induced in silicon by breaking the crystal symmetry. The proposed structure used a deposited silicon nitride glass layer (Si_3N_4) as a straining layer, making the lattice structure of underneath waveguide asymmetric. The material nonlinearity of strained silicon measured in [36] is only 15 pmV^{-1},(compared to 360pmV^{-1} in Lithium Niobate) however, by using photonic crystal waveguides with enhanced group refractive index, n_g, the electro-optic effect induced by strain could substantially increase the nonlinearity of Si waveguides by more than one order of magnitude to a value of >800pmV^{-1}. The first attempt has been made to realise optical modulation on strained Si waveguide by [37]. A near breakdown voltage of 200V was applied on a strained Si ring resonator. However, the strain exerted on Si waveguide was only 1/20 of that reported in [36], and the optical modulation was not achieved by the linear electro-optic effect but by the effect of carrier concentration as a result of leakage current.

Enhancement of the electro-optic effect in silicon waveguides with the aid of polymers having large material nonlinearity was proposed [38, 39]and realised [40] in different waveguide structures. Polymers can have very high Pockels coefficients (> 300 pm/V) [39] and a purely electronic hyperpolarisability. The effect supports extremely broad bandwidth operation (>150GHz) [41] at low operating voltages**.** On the other hand, polymers themselves only offer moderate refractive indices ($n \approx 1.6$) and a less developed nano-structuring fabrication technology compared to silicon. It is possible to combine both material types to achieve high speed modulation in a silicon based waveguide. Recently, Baehr-Jones et al. used polymer as the cladding layer of a slotted silicon waveguide to achieve electro-optic modulation in a classical Mach-Zehnder geometry with a V_π of only 0.25V, while the geometry of the whole device was rather large (arm length of 2 cm) [40]. Brosi et al. [38] introduced electro-optic modulation based on a photonic crystal slotted waveguide with polymer inside the slot. A bandwidth of 78GHz, a drive voltage amplitude of 1V and a length of only 80μm was proposed. Wülbern et al. [39] designed a non-Mach-Zehnder type modulator using, a so called, heterostructure resonator in a polymer infiltrated silicon slotted photonic crystal waveguide. The electro-optical modulation was achieved by shifting the position of the resonance peak in the frequency spectrum via modulation of the refractive index of the NLO polymer through external electric field. A switching voltage of approximately 1 V at modulation speeds up to 100 GHz was envisaged.

4. CONCLUSION

The optical modulator is a key component for a variety of applications. This paper has highlighted some of the most recent work in the field, and also some of the work of the Surrey group. It is clear that the field is very fast moving, and also that a variety of approaches are being adopted. Historically the most popular modulation mechanism has been the use of the plasma dispersion effect, but novel approaches to modulator design in recent years has explored a host of other effects, via hybrid integration of materials, or in some cases, purely modelling proposals. The buoyant nature of the field of silicon photonics means that the numbers of researchers in the field is growing consistently, and the investment in the technology means that it is likely that significant advances will be made in the near future. It is currently unclear which technology will ultimately win-out for the silicon based optical modulator, but perhaps the most likely outcome is a range of designs and structures for different applications. To date the fastest optical modulator in silicon has delivered a data rate of 40Gb/s, but only at a modulation depth of 1dB. This modulation depth must be improved for practical applications. Other issues are power dissipation, and footprint, both of which must be minimised for many applications. Similarly, integration is critical, both to combine silicon photonic devices (for example, multiple modulators), and to combine photonics and electronics, to really take advantage of the potential of the technology that is silicon photonics.

5. REFERENCES

[1] Intel, "Intel Research Advances 'Era Of Tera'," 2007.

[2] C. K. Tang and G. T. Reed, "Highly efficient optical phase modulator in SOI waveguides," *Electronics Letters,* vol. 31, pp. 451-452, 1995.

[3] C. K. Tang, G.T. Reed, A.J. Wilson, and A.G. Rickman, "Simulation of a low loss optical modulator for fabrication in SIMOX material," in *Silicon-Based Optoelectronic Materials Symposium, 12-14 April 1993*, San Francisco, CA, USA, 1993, pp. 247-52.

[4] C. K. Tang, G.T. Reed, A.J. Wilson, and A.G. Rickman, "Low-loss, single-mode, optical phase modulator in SIMOX material," *J. Lightwave Technol.,* vol. 12, pp. 1394-1400, October 1994.

[5] J. P. Lorenzo and R. A. Soref, "1.3 mm electro-optic silicon switch," *Appl. Phys. Lett.,* vol. 51, pp. 6-8, 1987/07/05 1987.

[6] P. D. Hewitt, and G.T. Reed, "Improving the response of optical phase modulators in SOI by computer simulation," *Journal of Lightwave Technology,* vol. 18, pp. 443-450, March 2000.

[7] P. D. Hewitt and G. T. Reed, "Multi micron dimension optical p-i-n modulators in silicon-on-insulator," San Jose, CA, USA, 1999, pp. 237-43.

[8] C. E. Png, S. P. Chan, S. T. Lim, and G. T. Reed, "Optical phase modulators for MHz and GHz modulation in silicon-on-insulator (SOI)," *Journal of Lightwave Technology,* vol. 22, pp. 1573-1582, 2004.

[9] T. W. Ang, G. T. Reed, A. Vonsovici, A. G. R. Evans, P. R. Routley, and M. R. Josey, "0.15 dB/cm loss in Unibond SOI waveguides," *Electronics Letters,* vol. 35, pp. 977-8, 1999/06/10 1999.

[10] R. M. H. Atta, G. J. Ensell, A. G. R. Evans, C. E. Png, and G. T. Reed, "Fabrication of a highly efficient optical modulator based on silicon-on-insulator," Maspalonas, Gran Canaria, Spain, 2003, pp. 495-501.

[11] C. E. Png, G. Masanovic, and G. T. Reed, "Coupling to 1 micron silicon modulators," San Jose, CA, USA, 2002, pp. 62-9.

[12] C. E. Png, G. T. Reed, R. M. H. Atta, G. Ensell, and A. G. R. Evans, "Development of small silicon modulators in Silicon-On-Insulator (SOI)," San Jose, CA, United States, 2003, pp. 190-197.

[13] C. E. Png, "Silicon-on-insulator phase modulators," *PhD thesis, University of Surrey,* 2004.

[14] F. Y. Gardes, G. T. Reed, N. G. Emerson, and C. E. Png, "A sub-micron depletion-type photonic modulator in silicon on insulator," *Optics Express,* vol. 13, 2005.

[15] F. Y. Gardes, A. Brimont, P. Sanchis, G. Rasigade, D. Marris-Morini, L. O'Faolain, F. Dong, J. M. Fedeli, P. Dumon, L. Vivien, T. F. Krauss, G. T. Reed, and J. Martí, "High-speed modulation of a compact silicon ring resonator based on a reverse-biased pn diode," *Opt. Express,* vol. 17, pp. 21986-21991, 2009.

[16] A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky, and M. Paniccia, "High-speed optical modulation based on carrier depletion in a silicon waveguide," *Optics Express,* vol. 15, pp. 660-668, 2007.

[17] L. Liao, A. Liu, D. Rubin, J. Basak, Y. Chetrit, H. Nguyen, R. Cohen, N. Izhaky, and M. Paniccia, "40 Gbit/s silicon optical modulator for highspeed applications," *Electronics Letters,* vol. 43, 2007.

[18] J. W. Park, J.-B. You, I. G. Kim, and G. Kim, "High-modulation efficiency silicon Mach-Zehnder optical modulator based on carrier depletion in a PN Diode," *Opt. Express,* vol. 17, pp. 15520-15524, 2009.

[19] D. M. Gill, M. Rasras, T. Kun-Yii, C. Young-Kai, A. E. White, S. S. Patel, D. Carothers, A. Pomerene, R. Kamocsai, C. Hill, and J. Beattie, "Internal Bandwidth Equalization in a CMOS-Compatible Si-Ring Modulator," *Photonics Technology Letters, IEEE,* vol. 21, pp. 200-202, 2009.

[20] http://www.lightwire.com/, 2009.

[21] http://www.ofcnfoec.org/conference_program/2009/images/09-DAndrea.pdf, 2009.

[22] S. Jongthammanurak, J. F. Liu, K. Wada, D. Cannon, D. T. Danielson, D. Pan, J. Michel, and L. C. Kimerling, "Large Electro-Optic Effect in Tensile Strained Ge-on-Si Films," in *Group IV Photonics, 2006. 3rd IEEE International Conference on*, 2006, pp. 34-36.

[23] J. Liu, D. Pan, S. Jongthammanurak, K. Wada, L. C. Kimerling, and J. Michel, "Design of monolithically integrated GeSi electro-absorption modulators and photodetectors on a SOI platform " *Opt. Express,* vol. 15, pp. 623-628, 2007.

[24] D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, "Band-Edge Electroabsorption in Quantum Well Structures: The Quantum-Confined Stark Effect," *Phys. Rev. Lett.,* vol. 53, pp. 2173-2176, 1984.

[25] I. Kotaka, K. Wakita, O. Mitomi, H. Asai, and Y. Kawamura, "High-speed InGaAlAs/InAlAs multiple quantum well optical modulators with bandwidths in excess of 20 GHz at 1.55 mm," *Photonics Technology Letters, IEEE,* vol. 1, pp. 100-101, 1989.

[26] C. Rolland, R. S. Moore, F. Shepherd, and G. Hillier, "10 Gbit/s 1.56-mm multi-quantum-well InP/InGaAsP Mach-Zehnder optical modulator," *Electronics Letters,* vol. 1, 1993.

[27] K. Tsuzuki, T. Ishibashi, T. Ito, S. Oku, Y. Shibata, R. Iga, Y. Kondo, and Y. Tohmori, "40-Gbit/s n-i-n InP Mach-Zehnder modulator with a p voltage of 2.2 V," *Electronics Letters,* vol. 39, pp. 1464-1466, 2003.

[28] P. J. Winzer, S. Chandrasekhar, C. R. Doerr, A. D. T. Neilson, Adamiecki, and R. A. Griffin, "42.7-Gb/s modulation with a compact InP Mach-Zehnder transmitter," 2006.

[29] R. Lewen, S. Irmscher, U. Westergren, L. Thylen, and U. Eriksson, "Segmented Transmission-Line Electroabsorption Modulators," *Journal of Lightwave Technology,* vol. 22, pp. 172-179, 2004.

[30] Y.-H. Kuo, Y. K. Lee, Y. Ge, S. Ren, J. E. Roth, T. I. Kamins, D. A. B. Miller, and J. S. Harris, "Strong quantum-confined Stark effect in germanium quantum-well structures on silicon," *Nature,* vol. 437, pp. 1334-1336, 2005.

[31] Y.-H. Kuo, Y. K. Lee, Y. Ge, S. Ren, J. E. Roth, T. I. Kamins, D. A. B. Miller, and J. S. Harris, "Quantum-Confined Stark Effect in Ge/SiGe Quantum Wells on Si for Optical Modulators," *IEEE Journal of selected topipcs in quantum electronics,* vol. 12, pp. 1503-1513, 2006.

[32] Y. Ishikawa, K. Wada, J. Liu, D. D. Cannon, H.-C. Luan, J. Michel, and L. C. Kimerling, "Strain-induced enhancement of near-infrared absorption in Ge epitaxial layers grown on Si substrate," *Journal of Applied Physics,* vol. 98, 2005.

[33] D. J. Paul, "Si/SiGe heterostructures: from material and physics to devices and circuits," *Semiconductor Science and Technology,* vol. 19, 2004.

[34] T. Yin, R. Cohen, M. M. Morse, G. Sarid, Y. Chetrit, D. Rubin, and M. J. Paniccia, "31 GHz Ge n-i-p waveguide photodetectors on Silicon-on-Insulator substrate," *Opt. Express,* vol. 15, pp. 13965-13971, 2007.

[35] L. Vivien, J. Osmond, J.-M. Fédéli, D. Marris-Morini, P. Crozat, J.-F. Damlencourt, E. Cassan, Y. Lecunff, and S. Laval, "42 GHz p.i.n Germanium photodetector integrated in a silicon-on-insulator waveguide," *Opt. Express,* vol. 17, pp. 6252-6257, 2009.

[36] R. S. Jacobsen, K. N. Andersen, P. I. Borel, J. Fage-Pedersen, L. H. Frandsen, O. Hansen, M. Kristensen, A. V. Lavrinenko, G. Moulin, H. Ou, C. Peucheret, B. Zsigri, and A. Bjarklev, "Strained silicon as a new electro-optic material," *Nature,* vol. 441, pp. 199-202, 2006.

[37] Y. Amemiya, T. Tokunaga, Y. Tanushi, and S. Yokoyama, "Optical modulator using metal-oxide-semiconductor type Si ring resonator," *Optical Review,* vol. 16, pp. 247-251, 2009.

[38] J.-M. Brosi, C. Koos, L. C. Andreani, M. Waldow, J. Leuthold, and W. Freude, "High-speed low-voltage electro-optic modulator with a polymer-infiltrated silicon photonic crystal waveguide," *Opt. Express,* vol. 16, pp. 4177-4191, 2008.

[39] J. H. Wülbern, A. Petrov, and M. Eich, "Electro-optical modulator in a polymerinfiltrated silicon slotted photonic crystal waveguide heterostructure resonator," *Opt. Express,* vol. 17, pp. 304-313, 2009.

[40] T. Baehr-Jones, B. Penkov, J. Huang, P. Sullivan, J. Davies, J. Takayesu, J. Luo, T.-D. Kim, L. Dalton, A. Jen, M. Hochberg, and A. Scherer, "Nonlinear polymer-clad silicon slot waveguide modulator with a half wave voltage of 0.25 V," *Applied Physics Letters,* vol. 92, pp. 163303-3, 2008.

[41] M. Lee, H. E. Katz, C. Erben, D. M. Gill, P. Gopalan, J. D. Heber, and D. J. McGee, "Broadband Modulation of Light by Using an Electro-Optic Polymer," *Science,* vol. 298, pp. 1401-1403, November 15, 2002 2002.