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Delphine Marris-Morini[1], Gilles Rasigade[1], Laurent Vivien[1], David .J. Thomson[2], Frédéric Y. Gardes[2], Graham T. Reed[2], Jean-Marc Fédéli[3], Paul Crozat[1], Eric Cassan[1].

1: Institut d'Electronique Fondamentale, Université Paris Sud - CNRS, bât. 220, 91405 Orsay, France
2: Advanced Technology Institute, University of Surrey, Guildford, GU2 7XH, United Kingdom.
3: CEA, LETI, Minatec 17 rue des Martyrs, 38054 GRENOBLE cedex 9, France

ABSTRACT

Silicon optical modulators have generated an increasing interest in the recent years, as their performances are crucial to achieve high speed optical links. Among possibilities to achieve optical modulation in silicon-based materials, index variation by free carrier concentration variation has demonstrated good potentiality. High speed and low loss silicon modulators can be obtained by carrier depletion inside lateral PN or PIPIN diodes. When the diode is reverse biased, refractive index variations are obtained and then phase modulation of the guided wave is obtained. Mach-Zehnder interferometers are used to convert phase modulation into intensity modulation. Experimental results are presented for both PN and PIPIN diodes.

Keywords: Optical modulation, Silicon modulator, Carrier depletion, Integrated devices, Silicon photonics, Silicon On Insulator (SOI), rib waveguide.

1. INTRODUCTION

Silicon photonics has generated an increasing interest in the recent years, as it can profit from mature CMOS technology with high production volume [1] The integration of optics and electronics on the same chip would allow the enhancement of integrated circuit (IC) performances and optical telecommunications can benefit from the development of low cost and high performance solutions for high-speed optical links. In microelectronic chips, with the extreme miniaturization of transistors, performance limitations come more and more from electrical interconnects, which suffer from RC delay, signal distortion, and power consumption [2-4]. The replacement of global electrical wiring by optical interconnects can overcome some of theses limitations [4].

The use of silicon-on-insulator (SOI) substrates for silicon photonics presents several advantages. Due to the large refractive index difference between silicon and buried silicon oxide, light can be largely confined in submicron waveguides. Strip or rib waveguides on SOI wafers have been demonstrated by using standard optical lithography processes followed by full or partial etching of the silicon film [5-6]. To achieve high performances optical links, optoelectronic devices are required, and a high speed silicon optical modulator integrated in

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SOI waveguides is one of the fundamental building block, essential for the development of silicon microphotonics.

Silicon modulators are presented in the next section and experimental results on two structures based on carrier depletion in lateral PN and PIPIN diodes are presented in sections 3 and 4.

2. SILICON OPTICAL MODULATOR

A high performance optical modulator should present low insertion loss, large extinction ratio and high frequency operation. Classical electrorefraction effects cannot be used in silicon for high performances optical modulator. Indeed the Pockels effect is absent in pure silicon due to its symmetry, and the Kerr effect is low [7]. However the Pockels effect has been demonstrated in strained silicon, as the strain allows breaking of the crystal symmetry [8].

The most efficient way to achieve electrorefraction in silicon is to use refractive index variation by free carrier concentration variations which gives refractive index (Δn) and absorption coefficient ($\Delta\alpha$) variations, following these equations at 1.55 µm wavelength [7] :

$$\begin{aligned} \Delta n &= -8{,}8.10^{-22}\,\Delta N - 8{,}5.10^{-18}\,\Delta P^{0{,}8} \\ \Delta \alpha &= 8{,}5.10^{-18}\,\Delta N + 6{,}0.10^{-18}\,\Delta P \end{aligned} \qquad (1)$$

where ΔN and ΔP are respectively the electron and hole concentrations, expressed in cm^{-3}.

The free carrier concentration variation can be obtained by different ways: carrier accumulation in MOS capacitor, injection or depletion in PN or PIN diodes [9-16].

The first modulator achieving a 1 GHz bandwidth was demonstrated in 2004, and was based on carrier accumulation in a Metal-Oxide-Semiconductor capacitor [9]. With improvements in device design, material quality, and by using a custom driver to distribute the global capacitance in eleven smaller sections, 10 Gbit/s data transmission was obtained [10]. Carrier injection in a PIN diode has been for a long time thought to be limited to a few hundreds of Mbit/s, due to the carrier recombination lifetime in the intrinsic region. However, bit rates up to 18 Gbit/s have been obtained in ring resonators [12] and up to 10 Gbit/s using a Mach Zehnder interferometer (MZI) [13]. In both cases pre-emphasis of the electrical signal was used, to ensure rapid injection and then depletion of carriers by using pulses at rising and falling edges.

Carrier concentration variation can also be achieved by depletion, which is intrinsically high speed. Carrier depletion can be obtained in reverse biased diodes. A 10 GHz-bandwidth with low loss (3 dB) has been reported in a lateral PN diode [14], and depletion in a vertical PN diode has also been reported, showing a 30 GHz bandwidth [15]. Carrier depletion has also been demonstrated in a lateral PN diode using a ring as interferometric structure. A 19 GHz 3dB-optical bandwidth has been obtained [16].

Silicon modulators using carrier depletion in lateral PN and PIPIN diodes have been demonstrated and will be presented in the following sections. A lateral diode configuration has some advantages to achieve high frequency operation: lateral configuration usually ensures reduced capacitance and access resistances when compared to vertical ones. In the following, Mach Zhender interferometers are used to obtain intensity modulation. Despite the large active region length (few mms) required to obtain total modulation, which complicates getting high speed devices, these interferometers present some advantages in term of optical bandwidth and low wavelength sensitivity when compared with resonators.

3. CARRIER DEPLETION IN A PN DIODE

Carrier depletion can be obtained in a lateral PN diode, as represented in figure 1. The main advantage of this structure is its simple fabrication as no critical alignment of the implant windows is required. Indeed the pn junction position corresponds with waveguide edge as a result of a self aligned process. The concentrations of the n and p type regions were determined in order to ensure a large concentration variation in the waveguide with the applied voltage, while maintaining reduced optical loss.

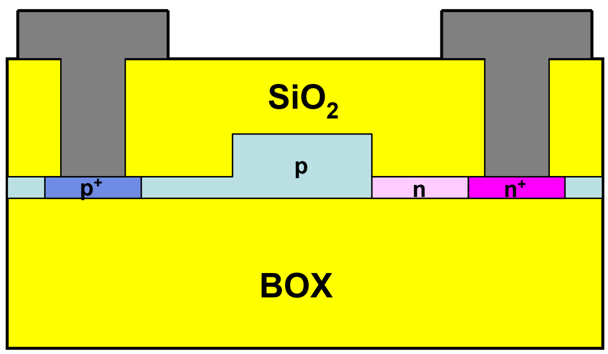

Figure 1: Optical modulator based on 220-nm thick PN diode.

The structure was integrated in a 220 nm-thick waveguide, and a 3.5-mm long phase shifter was inserted in both arms of an asymetric Mach-Zehnder however only one arm is biased to induce intensity modulation. Output spectra of the modulator are reported in figure 2 for 0 and 3 V. A static extinction ratio larger than 25dB is obtained.
The frequency response of the modulator was measured using an AC signal generated by an opto-RF vector network analyser (Agilent 86030A) coupled to the DC bias, using a bias tee. The RF signal was coupled to the coplanar electrodes from the optical input side and a 50 Ω termination load was added at the output side. The modulated optical signal was coupled back to the opto-RF vector network analyser. The normalized optical response as a function of the frequency is given in figure 3. A cut-off frequency of 8GHz is obtained.

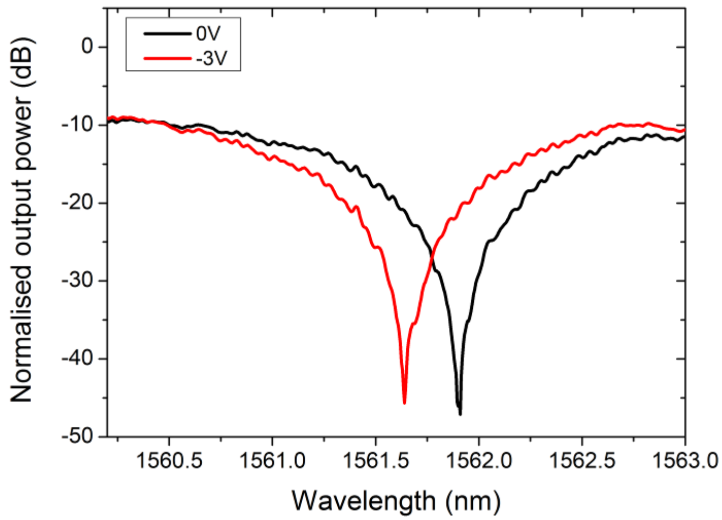

Figure 2: Experimental transmission of the PN modulator as a function of the wavelength,

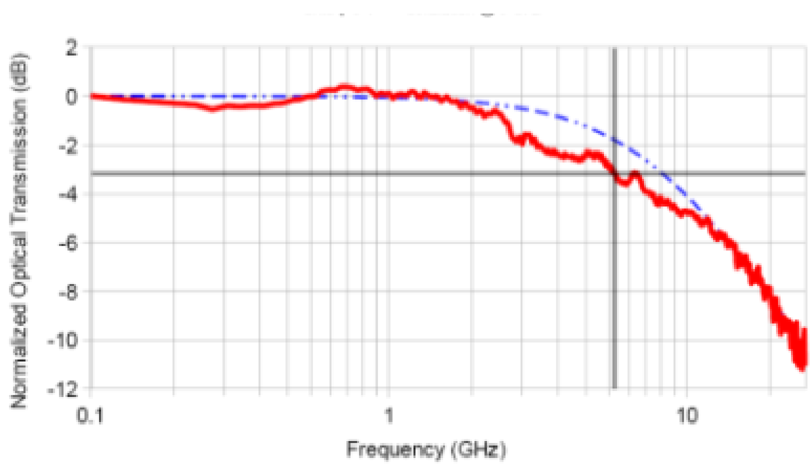

Figure 3: Experimental normalized optical response of the PN modulator as a function of the RF signal frequency

4. CARRIER DEPLETION USING A P-DOPED REGION IN THE MIDDLE OF A PIN DIODE (PIPIN DIODE)

Carrier depletion can also be obtained in a lateral PIPIN diode, as represented in figure 4. The P and N doped regions of the diode are on each side of the waveguide, and a p-doped slit is inserted in the middle of the waveguide, to bring holes at equilibrium in the center of the waveguide. The n-doped region slightly overlaps the guided mode, to ensure an efficient depletion of the thin p-doped slit. This structure appears very flexible to achieve given specifications [17]. Indeed, as a large part of the waveguide does not include any doped regions it is possible to increase doping levels of the doped regions without increasing optical loss.

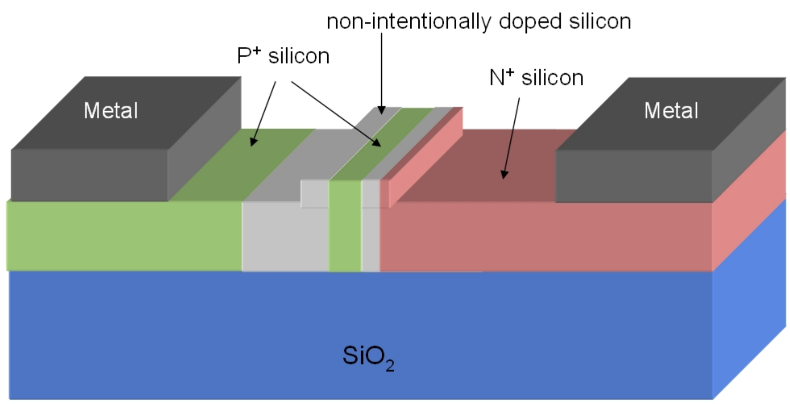

fig 4: Schematic view of the lateral PIPIN diode

When a reverse bias is applied on the diode, holes located in the doped slit are swept out of the waveguide.The index variation creates a phase shift of the guided mode. The phase shifter is inserted in both arms of a 4-mm long asymetric Mach-Zehnder interferometer. The structure is integrated in a 400 nm-thick waveguide.

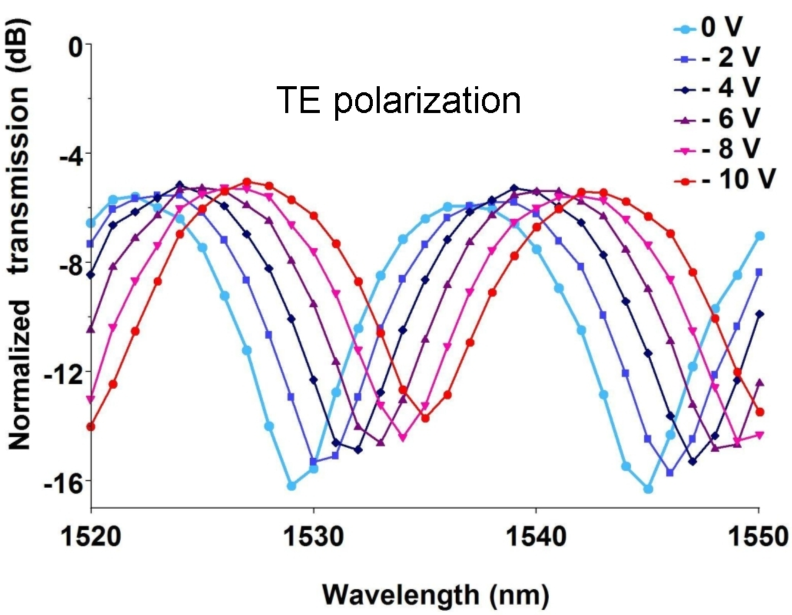

Figure 5: Experimental transmission of the PIPIN modulator as a function of the wavelength

Output spectra of the modulator are reported in figure 5 for different bias voltages from 0 to 10 volts. DC extinction ratio is around 14 dB from 0 to a reverse bias of 10 V, and optical loss is 5dB The frequency response of the modulator was measured using the same method as described previously, and the result is reported in figure 6. Two different designs are used for the Coplanar Waveguides Electrodes.15 GHz optical bandwidth is obtained.

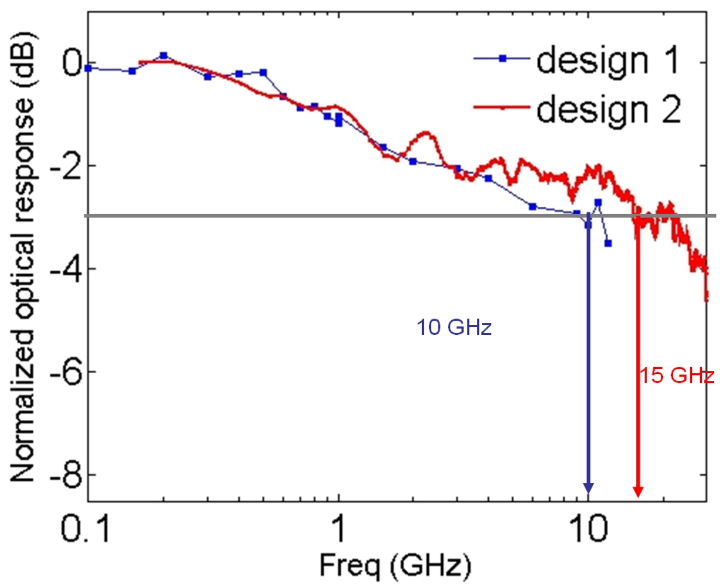

Figure 6: Experimental normalized optical response of the PIPIN modulator as a function of the RF signal frequency

CONCLUSION

Important progress in silicon-based modulators has been obtained in the last 5 years. Carrier depletion appears as one of the most efficient way to achieve high speed and high performance optical modulators. Two modulators based on lateral diodes integrated in asymmetric Mach Zehnder interferometers have been fabricated. Both devices present promising behaviour for the next generations of 10Gbit/s photonic circuits.

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