PDP15

A gigahertz silicon-on-insulator Mach-Zehnder modulator

Dean Samara-Rubio, Ling Liao, Ansheng Liu, Richard Jones, and Mario Paniccia
Intel Corporation, Mail Stop CHP3-109, 2200 Mission College Blvd, Santa Clara, CA 95054
dean.samararubio@intel.com

Oded Cohen and Doron Rubin
Intel Corporation, S. B. I. Park Har Hotzvim, Jerusalem, 91031, Israel

Abstract: We report a modulator in which a polysilicon-oxide-silicon capacitor forms a ridge waveguide to achieve unprecedented performance in silicon: 2.5GHz small-signal bandwidth and a driver-limited extinction ratio of 5dB at 1 gigabit per second.

©2004 Optical Society of America

OCIS codes: (060.4080) Modulation; (250.7360) Waveguide modulators

1. Introduction

The device reported here is based on free-carrier plasma dispersion as in the conventional p-i-n diode devices (which utilize clouds of charges in the intrinsic region of the diodes to change the index of refraction of a waveguide) [1]. However, here we demonstrate that the thin layers of charges accumulated at the surfaces of the gate oxide achieve the required index change for modulation in a compact device. Furthermore, when the capacitor is biased into accumulation, the majority carriers of the silicon electrodes are transported into and out of the optical path and accumulated on the capacitor. Thus, the relatively slow carrier recombination processes, that limit the speed of p-i-n diode devices, do not significantly influence the dynamics of our device allowing us to demonstrate unprecedented bandwidth in a silicon-based modulator [3].

2. Modulator Design

Fig.1 shows a schematic of the cross sectional view of our silicon waveguide based MOS capacitor phase shifter. It comprises a ~1.4 μm n-type doped crystalline silicon slab (the silicon layer of the SOI wafer) and a p-type doped poly-silicon rib with a 12nm gate oxide sandwiched between them.

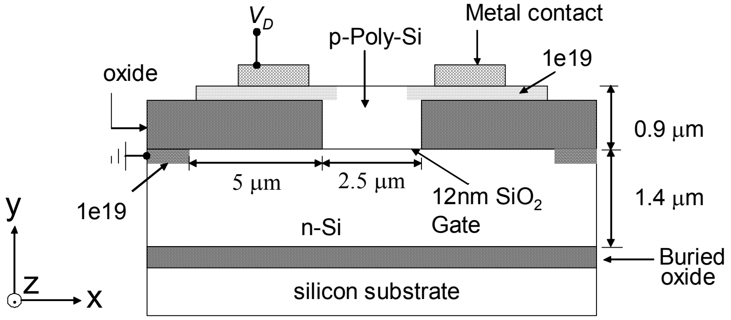

Fig. 1. Cross-sectional view of the MOS waveguide phase shifter. The optical mode propagates along the z direction.

In order to minimize the metal contact loss, we designed a wide (~10.5 μm) top poly-silicon layer on the top of the oxide layers on both sides of the poly-silicon rib. Aluminum contacts are deposited on top of this poly-silicon layer as shown in Fig.1. The oxide regions on either side of the rib maintain optical confinement and prevent optical field penetrating into the contact area. The poly-silicon rib and the gate oxide widths are both ~2.5 μm, and the total poly-silicon thickness at the centre of the waveguide is ~0.9 μm.

To convert the phase-shift to an amplitude modulation, one or more phase-shifter sections are placed within the arms of a passive Mach-Zehnder interferometer. The passive sections in this process retain the MOS structure but the contacts and most of the dopant implantation are omitted to minimize optical loss. Fig. 2 gives a schematic diagram of the two Mach-Zehnder interferometers utilized for this paper. In both cases, MZI has an optical path length difference of ~16.7 μm between the two arms. A Y junction is used to split and combine the optical beam in the MZI. The overall length of both MZI's is 1.5cm. The device in Fig. 2(a) is used to investigate the intrinsic bandwidth of the phase-shifter and has a 2.5mm phase shifter in one arm. The device in Fig. 2(b) is intended for large-signal modulation and 1cm phase shifters in both arms.

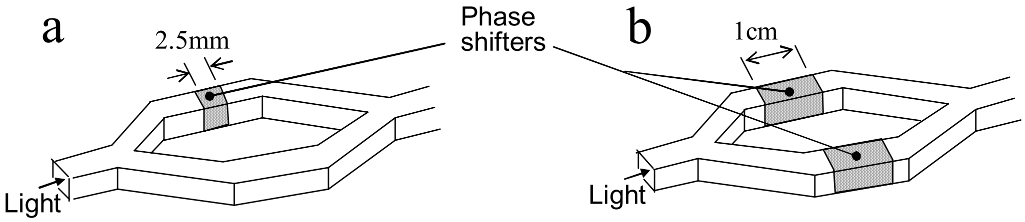

Fig. 2. Schematic diagram showing the two Mach-Zehnder interferometer (MZI) designs utilized for this paper.

3. Phase-shifter Performance

In accumulation, the n-type silicon in the MOS capacitor phase shifter is grounded and a positive drive voltage, V_{D}, is applied to the p-type poly-silicon causing a thin charge layer to accumulate on both sides of the gate oxide. With a change in free-carrier density (ΔN_e or ΔN_h), both refractive index (n) and absorption (α) of silicon are changed [4-6]. The change in index of the small amount of silicon containing the charge layers (less than 1% of the area of the TE fundamental mode) is manifest as a change in the effective refractive index for the mode (n_{eff}). Equation 1 shows this relationship between index and phase for a mode. As indicated in equation 1, the phase shift also depends on the wavelength of the light, λ, and the length of the phase shifter, L.

$$\Delta\phi = \frac{2\pi L}{\lambda}\Delta n_{eff} = \frac{2\pi L}{\lambda}\times\left[\frac{dn_{eff}}{dQ_{acc}}\right]\times C_{acc}\left[V_D - V_{FB}\right] \qquad (1)$$

In the second portion of equation 1, the change in the refractive index of the mode has been expressed in terms of its derivative with respect to the accumulated gate charge (Q_{acc}), and the external electrical parameters which determine the gate charge, namely the accumulation capacitance (C_{acc}) and applied voltage. The term dn_{eff}/dQ_{acc} is the charge-efficiency of the device and it is strongly affected by the position of the gate within the mode and waveguide dimensions. In addition, we have measured the waveguide loss by use of a cutback method and have found the loss to be 5.1dB/cm for the active phase shifter of which 4.1dB/cm is correlated to the dopants and 1dB/cm occurs in an undoped (passive) MOS waveguide [7].

To determine the intrinsic bandwidth, we have performed a small-signal measurement upon the MZI shown in Fig. 2(a). The input wavelength was chosen to bias the MZI at quadrature and the MOS capacitor was biased into accumulation with 3VDC. The applied AC voltage was monitored with a 6 GHz high-impedance oscilloscope probe landed on the phase shifter bond pad. The output light was collected into a 15 GHz high-frequency photo-receiver and measured on an electrical spectrum analyzer. Fig. 3(a) shows these measured values. The normalized response of the device (photo-receiver output / on-chip voltage) is presented in Fig 3(b) and shows that the phase shifter has an intrinsic bandwidth of ~2.5GHz (determined from the -3dB point).

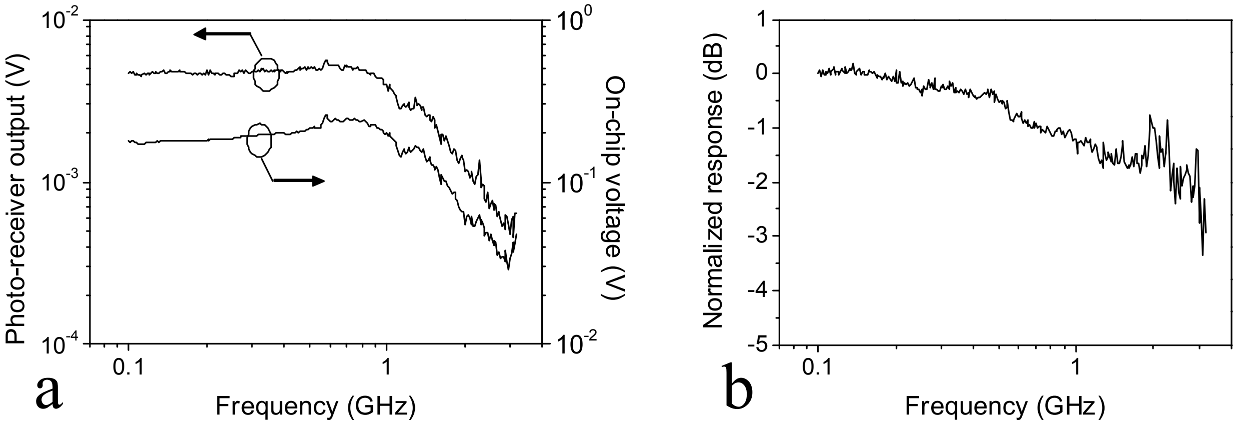

Fig. 3. (a) Input RMS voltage and photo-receiver output of an MZI containing a single 2.5 mm phase shifter. (b) Phase shifter normalized response (Photo-receiver output / On-chip voltage) of the showing an intrinsic bandwidth of 2.5GHz.

4. Large-signal Modulation

As seen in Fig. 4(a), the on-chip drive voltage drops to <50% of its low-frequency value at 1.5GHz despite the fact that the intrinsic bandwidth of the optical device is 2.5GHz. This effect is governed by the output impedance of the drive circuit used, the phase shifter capacitance, and the interconnect parasitics. To create a large-signal modulation, we consider the MZI of Fig. 2(b) which has two 1cm phase-shifters. Optical characterization of this device shows that it has an on-chip loss of 6.7dB and a DC extinction ratio in excess of 16dB [1]. From Table 1 we note that each phase shifter has capacitance of 70pF and will produce $\pi/2$ phase-shift if driven with a 3.85V amplitude signal. We have developed a drive circuit based on readily available silicon emitter coupled logic (ECL) buffers [8]. These buffers have a single-ended voltage swing of 1.6V (3.2V differential swing) which, based on calculation, should provide sufficient phase shift for an extinction ratio 5.8dB when the MZI of Fig. 2(b) is biased around quadrature. Fig. 4 shows the optical response of the modulator driven with a 2^{32}-1 pseudorandom bit sequence at 1Gbps. The measured high-frequency extinction ratio is 5dB and is close to the expected value.

Table 1. Figures of merit for the fundamental TE mode of the phase shifter in Fig. 1.

$[V_d - V_{fb}]L$ for π phase shift	dn_{eff}/dQ_{acc}	C_{acc}	Optical Loss	Intrinsic BW
7.7 V.cm	1.1×10^5 $(C/cm)^{-1}$	70 pF/cm	5.1 dB/cm	2.5 GHz

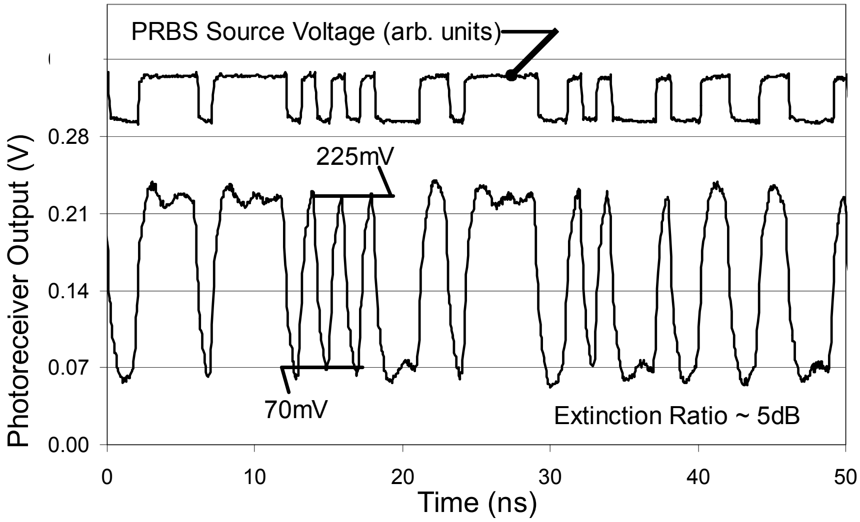

Fig. 4. Output signal of a Mach-Zehnder modulator driven with a 2^{32}-1 pseudorandom bit sequence (PRBS) at 1Gbps. The MZI has a pair of 1cm phase shifters as in Fig 2(b), and is driven differentially with total amplitude of 3.2V (1.6V single-ended). The RF extinction ratio is 5dB. The input wavelength was chosen to bias the MZI at quadrature.

5. Conclusions

We have shown a waveguide modulator based on an MOS capacitor with unprecedented performance in Silicon: 2.5GHz small-signal bandwidth and a driver-limited extinction ratio of 5dB at 1 gigabit per second. In addition, we have evaluated the charge-efficiency and optical loss of the phase shifter. Future efforts include scaling the optical waveguide to improve bandwidth and charge-efficiency, improving materials and processes to reduce optical loss, and engineering drive circuitry to achieve better RF extinction ratio.

6. References

1. P. Dainesi, *et al., "*CMOS compatible fully integrated Mach-Zehnder interferometer in SOI technology." IEEE Photon. Technol. Lett. **12,** 660–662 (2000).
2. C. K. Tang and G. T. Reed, "Highly efficient optical phase modulator in SOI waveguides," Electron. Lett. 31, 451-452 (1995).
3. A. Liu, *et al.,* "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor." Nature **427**, 615-618 (2004).
4. R.A. Soref & P.J. Lorenzo, "All-silicon active and passive guided-wave components for λ=1.3 & 1.6μm." IEEE J. Quantum Electron., **QE-22,** 873–879 (1986).
5. S.M. Sze, *Physics of Semiconductor Devices* 2nd edn (Wiley, New York, 1981).
6. For the measurements in this paper, the change in absorption, α, is present but not significant.
7. In preparation for publication.
8. The MZI is driven differentially by a set of four parallel-connected On-Semiconductor *MC10EP89* ECL buffers.