Silicon Photonic Crystal Modulation Device Based On Horizontally Activated MOS capacitor

Xiaonan Chen, Jiaqi Chen, Lanlan Gu, Wei Jiang, and Ray T. Chen[(a)]
Microelectronics Research Center, Department of Electrical and Computer Engineering,
The University of Texas at Austin, Austin, TX 78758
[(a)]Electronic mail: raychen@uts.cc.utexas.edu

Abstract

A MOS-capacitor-based silicon photonic crystal modulation device is proposed to achieve active transmission control with ultra-low gate capacitance and simplified fabrication processes. Optical and electrical simulation results confirm the enhanced modulation efficiency.

Introduction

Silicon photonics has recently attracted intense interest in light of potential as cost effective optoelectronic solutions for applications in the fields of optical interconnects, telecommunications, and optical sensors [1]. Any technological development in either silicon or associated microelectronics industry can provide an impetus in the advancement of silicon based integrated optics. As a good example, the rapid advances and breakthroughs in silicon-on-insulator (SOI) technology make it possible to build waveguide-based photonic microstructures on SOI substrate by conventional processing techniques compatible with silicon microelectronics manufacturing. The demonstrated silicon photonic devices include optical sources [2], modulators [3], and detectors [4], which are suggested to be the key building blocks for integrated silicon photonic chips. To date, all silicon-based high speed electro-optic (EO) modulators are based on the free carrier plasma dispersion effect [5] because the crystalline silicon exhibits no linear EO effects. According to Soref's conclusion [5], free carrier density change results in a change in the real refractive index and optical absorption coefficient of the waveguide material and therefore leads to a modulation effect. Three practical device configurations have been demonstrated to achieve the required free carrier distribution change. A regular one is the forward-biased p-i-n diode structure [6], which is based on excess carrier injection and recombination. A forward-biased diode device requires low driving voltage and thus provides high modulation efficiency. However, the response of the forward-biased p-i-n diode device is usually limited by the carrier lifetime. A similar structure is applied to build the reverse-biased pn junction device, which changes the width of the depletion region to induce the majority carrier density change. The high driving voltage is always a limitation of the reverse-biased pn junction devices since the width of the depletion region is proportional to the square root of the driving voltage. The implantation/diffusion process must be carefully designed for reverse-biased pn junction devices in order to target the pn junction at the waveguide region. In addition, both configurations require four-time implantation processes to form p-/n- doping regions with low optical propagation loss and p+/n+ doping regions to insure good Ohmic contact between silicon and metal contacts. Metal-oxide-semiconductor (MOS) capacitor structure based on carrier accumulation can also be employed to change the concentration of the majority carriers [7]. Both MOS capacitor structure and reverse-biased pn junction structure have been demonstrated with high modulation speed since the carrier concentration change is induced by electric field and the response is limited only by the RC constant. However, conventional waveguide-based silicon modulation devices always have a challenging limitation - the large size of the active region which depends on the optical response of materials to the external fields. Resonant light-confining structures [8] have been demonstrated with reduced active area, while there is an intrinsic trade-off for resonant structures between the modulation efficiency and the working wavelength range. Photonic crystals have been incorporated in modulation devices to enhance the interactions between the light wave and the wave-guiding materials with a reasonable working wavelength range and hence reduce the required interaction length. A silicon photonic crystal modulation device based on forward-biased p-i-n diode structure has been demonstrated with an ultra-compact active region [3]. In order to avoid the inherent carrier lifetime limitation and simplify the process flow, we design a MOS-capacitor-based silicon photonic crystal device structure with ultra-low gate capacitance and present detailed simulation results in this paper.

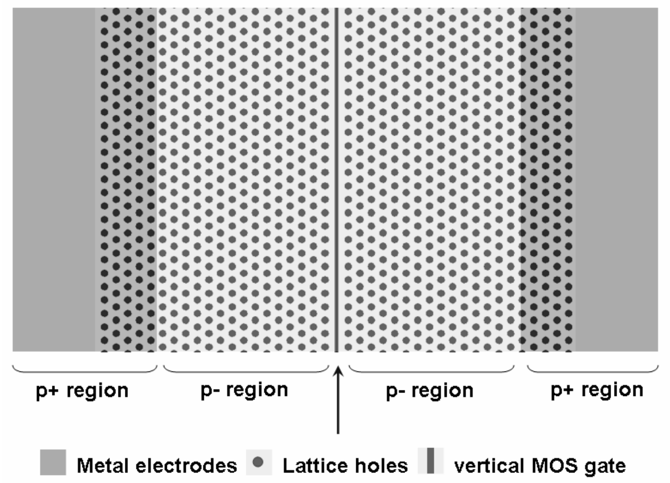


Fig. 1 Schematic top view of MOS-capacitor-based silicon photonic crystal waveguide

Results and discussion

A schematic top view of the MOS-capacitor-based silicon photonic crystal wave-guiding structure is depicted in Fig. 1. The device design is based on an SOI wafer with a 235 nm-thick top silicon layer and a 3 um-thick buried oxide layer. The lattice constant of the hexagonal photonic crystals is *a*=400 nm and the hole diameter is designed as *d*=0.5*a*. With a high index contrast in the vertical direction, such photonic crystal structures support an in-plane photonic band gap that lies below the light line. A single row of lattice holes is replaced with a narrow vertical gate oxide in order to introduce a line defect into the photonic band gap. It has been demonstrated that high-density plasma chemical vapor deposition (HDPCVD) techniques can be applied to fill in the narrow slot with aspect ratio higher than 2. We use the 3D fully vectorial plane-wave expansion (PWE) method to calculate the dispersion diagram of the slot PCW. The band structure plotted in Fig. 2 indicates that a quasi-TE mode appears near the

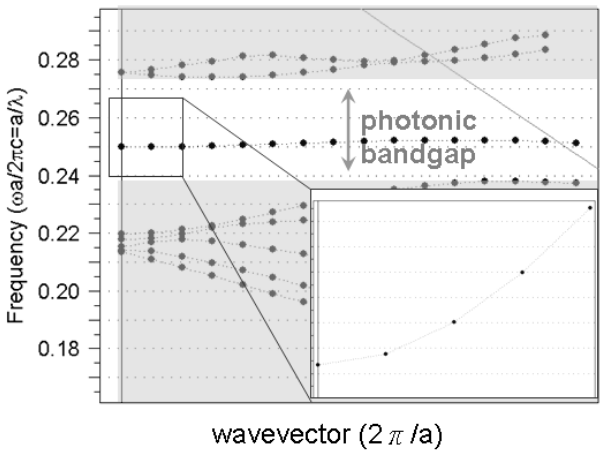
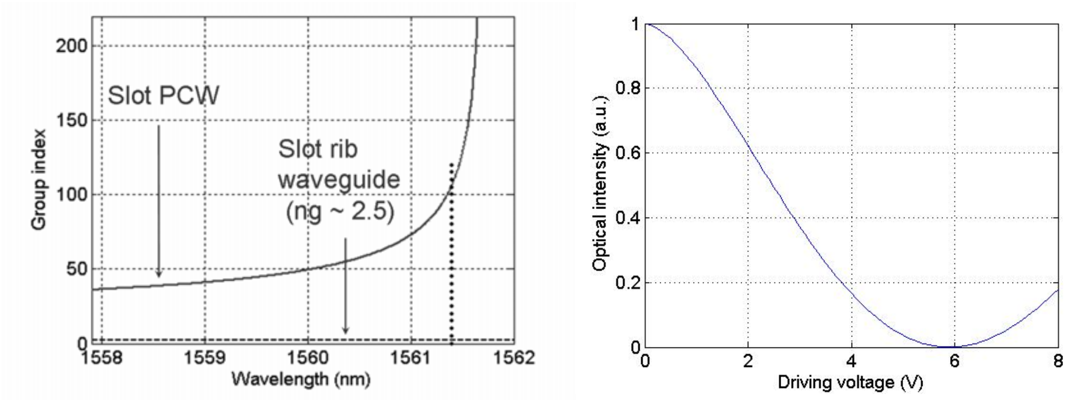


Fig. 2 Band diagram of the designed photonic crystal waveguide

mid-gap with slow light effect at the lower band edge. It has been suggested that the enhancement of modulation efficiency induced by slow light effect depends on the maximum group index of the guided mode provided by waveguide structures. We calculate the group indices at different wavelengths around 1560 nm as shown in Fig. 3 (a). A comparison between the designed photonic crystal waveguide with center gate oxide and slotted conventional rib waveguide exhibits a forty-fold increase of the group indices at the wavelength of 1561.4 nm. Further analysis indicates that a 300-um-long active region in accumulation mode can provide the required π phase shift to realize light switch in Mach-Zehnder interferometers (MZIs). The simulated DC modulation curve is depicted in Fig. 3(b). Calculation shows the gate capacitance of the compact active region is significantly reduced to 15 fF. The enhanced modulation efficiency benefits from the strong slow light effect generated by photonic crystals. More detailed experiments results will be presented at the conference.



(a) (b)

Fig. 3 (a) Group indices simulated at different wavelengths (b) DC modulation curve

References

[1] B. Jalali, M. Paniccia, G. Reed, "Silicon photonics," *IEEE, Microwave Magazine*, **7**, 58 (2006).

[2] O. Boyraz, B. Jalali, "Demonstration of a silicon Raman laser," *Opt. Express* 12, 5269 (2004).

[3] Y. Jiang, W. Jiang, L. Gu, X. Chen, R. T. Chen, "80-micron interaction length silicon nanophotonic crystal waveguide modulator," *Appl. Phys. Lett.* 87, 221105 (2005).

[4] S. J. Koester, G. Dehlinger, J. D. Schaub, J. O. Chu, Q. C. Ouyang, A. Grill, "Germanium-on-insulator photodetectors," *Technical Digest of 2005 2nd IEEE International Conference on Group IV Photonics*, 171 (2005).

[5] R. A. Soref and B.R Bennett, "Electrooptical effects in silicon," *IEEE J. Quantum Electron.* 23, 123 (1987).

[6] L. Gu, W. Jiang, X. Chen, L. Wang and R. T. Chen, "High speed silicon photonic crystal waveguide modulator for low voltage operation," *Appl. Phys. Lett.* 90, 071105 (2007).

[7] A. Liu, R. Jones, L. Liao, D. S. Rubio, D. Rubin, O. Cohen, R. Nicolaescu and M. Paniccia, "High-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor," *Nature (London)* 427, 615 (2004).

[8] Q. Xu, B. Shmidt, S. Pradhan and M. Lipson, "Micrometre-scale silicon electro-optic modulator," *Nature (London)* 435, 325 (2005).