Silicon Microring Modulator Driven by Transparent Conductive Oxide Capacitor

Erwen Li, Bokun Zhou, Wei-Che Hsu and Alan X. Wang*

School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, 97331, USA

**Corresponding Author: wang@eecs.oregonstate.edu*

Abstract: We experimentally demonstrated a novel silicon microring modulator driven by transparent conductive oxide capacitor, achieving a large tuning efficiency of 95 pm/V. Analysis indicates that a potential high-speed operation above 44GHz can be reached.

OCIS codes: (250.4110) Modulators; (250.7360) Waveguide modulators

1. Introduction

Silicon microring modulators play pivotal roles in the silicon photonics platform due to their fast speed, compact size and low power consumption, which can meet the requirements for large-scale photonic integrated circuits (PIC)[1]. However, the performance of pure silicon based microring modulator is limited by the weak plasma dispersion of silicon. For example, a typical silicon microring modulator based on reversely biased PN junction usually has a tuning efficiency of less than 40pm/V [2]. Thus, it requires a large Q factor (~10^4) to reach enough extinction ratio (ER), which limits the modulation bandwidth due to the long photon life time. Heterogeneous integration with other functional materials on silicon photonic platform has shown great promise to overcome this intrinsic drawback. Transparent conductive oxides (TCOs), such as indium-tin oxide (ITO), are one kind of such emerging materials that attracting escalating attention in the recent years. TCOs are electrically conductive and optically transparent. It makes them perfect gate materials for heterogeneous integration with silicon. Through employing a hybrid TCO/oxide/silicon metal-oxide-semiconductor (MOS) capacitor, a modulator can be benefited from the large plasma dispersion of TCO [2] and the large capacitor density of MOS capacitor [3], which both improve the modulation efficiency. Recently, we have reported extremely large tuning efficiency of over 250 pm/V for both photonic crystal nanocavity modulator [4] and microring resonator filter [5] based on silicon-TCO hybrid MOS capacitor using high-k dielectric material, HfO_2, as gate oxide, showing great potential for low-voltage and ultra-energy-efficient PIC application. However, high speed hybrid TCO-silicon microring modulator has not been demonstrated yet. In this paper, we designed and experimentally demonstrated a high speed microring modulator based on ITO/15nm SiO_2/Si MOS capacitor. We achieved a large tuning efficiency of 95 pm/V and 3dB ER with $3V_{pp}$ voltage swing. AC modulation speed of 1GHz is measured. Because of the low Q factor of ~1,000, the operation speed is only limited by the resistance-capacitance (RC) delay. In the end, we perform analysis showing that a high-speed operation of 44 GHz can be expected through optimizing the electrode design. The corresponding experiment is still under progress.

2. Design and Fabrication

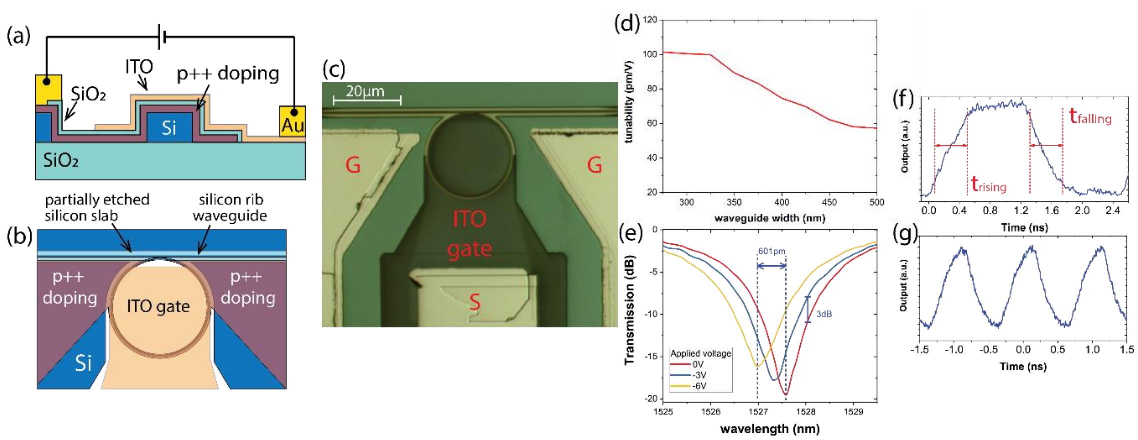

Fig.1 (a) Cross sectional schematic of the hybrid silicon-TCO microring modulator in the active region. (b) Partial layout of the mask used for the fabrication of the device. (c) Optical image of a fabricated hybrid silicon-TCO microring modulator. (d) Simulated tunablity as a function of the waveguide width. (e) Spectra of microring modulator under different negative bias voltage. (f) AC modulation output at 400MHz. (g) AC modulation signal at 1GHz.

Fig 1a shows the cross sectional schematic of the hybrid silicon-TCO microring modulator. The active region consists of an ITO/SiO_2/Si MOS capacitor. The bottom electrode consists of a 250nm thick p-type silicon rib waveguide and

50nm thick silicon slab for electrical connection. The insulator oxide and gate layer consist of 15nm thick SiO_2 and 20nm thick ITO. The principle is similar to [5]. When a negative bias is applied on the ITO gate, the accumulated carriers at the interfaces blue shift the resonance of the microring. The E-O tuning efficiency of a carrier-driven resonator is proportional to the capacitance density per active volume[3]. The capacitance density of a silicon-TCO MOS capacitor can be controlled by the gate oxide thickness and dielectric constant. Here 15nm SiO_2 is chosen for the consideration of balance between tuning efficiency and RC delay. Besides, for given capacitance density, the E-O efficiency can also be increased by narrowing the waveguide width, as is shown in fig 1d, due to increase of the overlapping between the accumulated carriers with the optical mode. The tunability reaches 100 pm/V for 300nm wide waveguide. Furthermore, the top 50nm thick of the rib waveguide and partially etched silicon slab is doped to 1×10^{20} cm^{-3} to further reduce the series resistance. Fig 1b plots the mask layout we used for our device fabrication.

The microring modulator is fabricated on a 250nm thick silicon-on-insulator (SOI) wafer. First, the waveguide, microring are patterned by two steps of electron-beam lithography (EBL) and reactive ion etching (RIE). The microring has a radius of 12μm and a waveguide width of 300nm. Next, the active region and contact region are highly doped by implantation. Then, 15nm SiO_2 is formed by dry oxidation at 1000°C. After that, 20nm of ITO is RF sputtered, followed by the liftoff process. The oxide on silicon contact region is etched by Buffered HF. Then, Ni/Au electrode is thermally evaporated and patterned by photolithography to form Ohmic contact on both p-type silicon and ITO. Finally, the sample is annealed to reduce the resistivity.

3. Results and Discussion

The fabricated device is shown in Fig 1c. Fig. 1e shows the resonance detuning at different bias voltage around 1527nm. The resonance wavelength blue shifts by ~601pm with -6V bias. It corresponds to an average tuning efficiency of ~100pm/V which matches with the simulation result. At zero bias, a low Q-factor of ~1000 is measured. More than 3dB modulation can be achieved with $3V_{pp}$ voltage swing. Fig 1f shows the AC modulation output signal at 400MHz. We can clearly distinguish the "On" and "Off" states. Fig 1g shows the AC modulation signal at 1GHz. The modulation bandwidth can be estimated by the rise and fall time of 0.42ns to be 0.83GHz. The speed of our modulator is only limited by the RC delay, because of the low Q-factor which won't limit the bandwidth up to 190GHz. The total capacitance of modulator is ~120fF. Then, the total series resistance can be estimated to ~1500Ω, which is due to the non-optimized electrode configuration. The series resistance can be greatly reduced through optimizing the electrode design, such as concentric metal contact (fig. 2). The doped silicon and ITO both have low sheet resistance of ~1100Ω/□ and ~700Ω/□, respectively. Assuming the metal contact is 500nm away from the waveguide edge. It will give us series resistance less than 30Ω, which corresponds to a RC bandwidth of 44GHz.

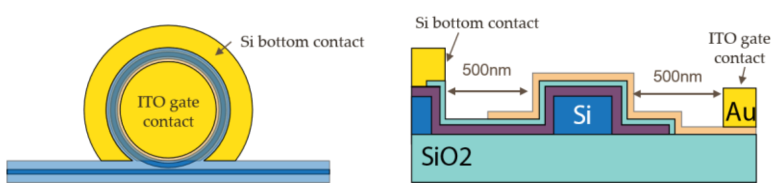

Fig.2 Schematic of concentric metal contact for the hybrid silicon-TCO microring modulator.

4. Conclusion

In conclusion, we have demonstrated a silicon microring modulator using TCO MOS capacitor. It achieved large tuning efficiency of 95pm/V with a low Q-factor of 1000. AC modulation is demonstrated up to 1GHz. Analysis shows that with optimized metal contact design, the modulation speed can be increased to 44 GHz.

Acknowledgement: This work is supported by the AFOSR MURI project FA9550-17-1-0071 and the NSF GOALI project 1927271.

References

[1] C. Sun *et al.*, "Single-chip microprocessor that communicates directly using light," *Nature*, 2015.
[2] E. Feigenbaum, K. Diest, and H. A. Atwater, "Unity-order index change in transparent conducting oxides at visible frequencies," *Nano Lett.*, vol. 10, no. 6, pp. 2111–2116, Jun. 2010.
[3] Li, E., Gao, Q., Chen, R.T. and Wang, A.X., 2018. Ultracompact silicon-conductive oxide nanocavity modulator with 0.02 lambda-cubic active volume. Nano letters, 18(2), pp.1075-1081.
[4] E. Li, Q. Gao, S. Liverman, and A. X. Wang, "One-volt silicon photonic crystal nanocavity modulator with indium oxide gate," *Opt. Lett.*, vol. 43, no. 18, p. 4429, Sep. 2018.
[5] E. Li, B. A. Nia, B. Zhou, and A. X. Wang, "Transparent conductive oxide-gated silicon microring with extreme resonance wavelength tunability," *Photonics Res.*, vol. 7, no. 4, p. 473, Apr. 2019.