Silicon-conductive oxide nano-cavity modulator with extremely small active volume

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Abstract: We design and experimentally demonstrated an ultra-compact modulator using transparent conductive oxide as the gate on 1-D silicon photonic crystal cavity. The device offers an ultra-small active volume (<0.06 μm^3) and 46 fJ/bit energy efficiency.

OCIS codes: (230.5298) Photonic crystals; (250.7360) Waveguide modulators; (140.3948) Microcavity devices

1. Introduction

The development of electro-optical (E-O) modulator with high bandwidth and extremely high energy efficiency to atto-joule/bit is critical to continue the exponential growth of computation and communication in the future. Silicon E-O modulators based on Mach-Zehnder interferometers (MZIs) and high-Q resonators have been reported to achieve high operational speed [1-4]. However, the weak plasma dispersion effect in silicon sets an intrinsic trade-off between the device footprint, energy efficiency, and optical bandwidth. To overcome this limit, various active materials have been integrated with silicon. Among those materials, transparent conductive oxides (TCOs), such as indium-tin oxide (ITO), have attracted wide attention due to their dramatic tunability of optical properties, which can be tuned from dielectric-like to metallic-like in the telecommunication wavelength range by manipulating the free carrier concentration. Especially, the epsilon-near-zero (ENZ) property offers additional optical confinement further enhancing the light-matter interaction. To date, several TCO-based E-O modulators have been reported, such as metal-insulator-metal (MIM) waveguide modulator [5], plasmonic metal-oxide-semiconductor (MOS) waveguide modulator [6], and plasMOStor [7]. However, these modulators are inevitably lossy because of the metallic plasmonic structures. In this paper, we design and experimentally demonstrated an ultra-compact and energy-efficient Si-TCO hybrid E-O modulator based on ITO-gated 1-D silicon photonic crystal nanocavity with 20nm SiO_2 gate oxide using commercial silicon-on-insulator (SOI) wafers.

2. Design, principle and fabrication

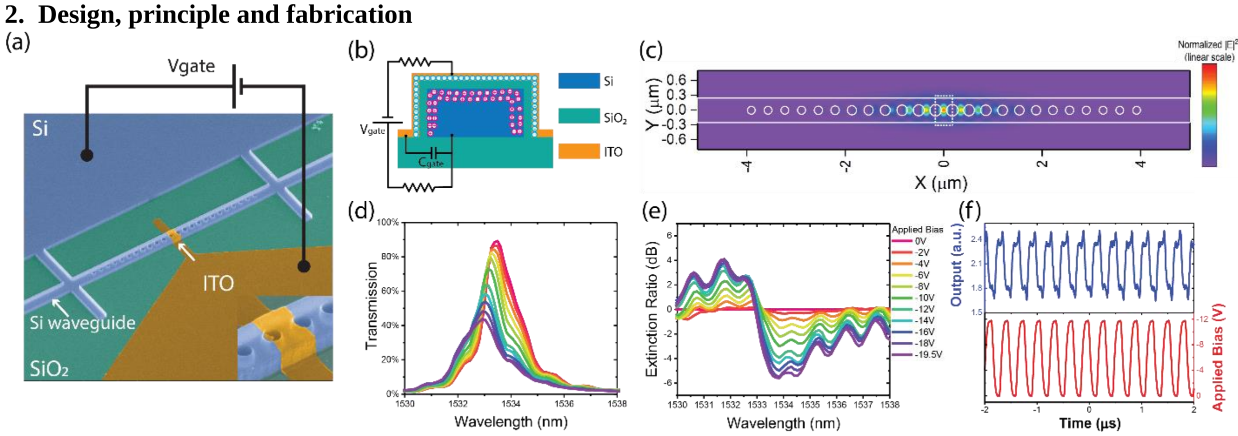

Fig. 1 (a) Colored scanning electron micrograph (SEM) of the silicon-TCO nanocavity modulator; (b) cross sectional schematic of the active region consisting of Si/SiO_2/ITO capacitor; (c) Optical mode profile of photonic crystal cavity simulated by 2D finite-difference time-domain (FDTD) method; (d) Transmission spectra and (e) extinction ratio of our device at different applied bias voltage. (f) AC optical modulation testing results at 1534.78nm with 12V sweep input bias voltage at 3.2MHz.

Fig. 1a shows the scanning electron micrograph of the fabricated modulator. The 1D silicon photonic crystal nano-cavity is patterned on a SOI substrate with 250nm thick silicon layer by ebeam lithography (EBL) and reactive ion etching (RIE), operating in the TE mode. It consists of two back-to-back photonic crystal mirror segments. Each mirror segment has 12 air holes. The radius of air hole is linearly tapered from 112nm in the center to 74nm at the edge. The period between each hole p is 340nm and the waveguide width w is 500nm. Then, 20nm thick SiO_2 is formed through thermal oxidation. Next, metal contact is patterned using contact photolithography. Al is thermally evaporated onto Si and annealed at 475 ° C for 10min to form ohmic contacts. Au is chosen to form the contact with the ITO. Finally, a 375nm long ITO gate window is patterned by EBL in the center of the cavity, followed by RF sputtering 20 nm thick ITO and lift off process.

As a negative bias is applied to the ITO layer, electrons and holes accumulate at the ITO/SiO_2 and SiO_2/Si interface, respectively (Fig. 1b). The resonance peak has a blue shift due to the reduction of the real part of the refractive index caused by the plasma dispersion of both the ITO and Si. The resonance shift due to the plasma dispersion effect is proportional to the capacitance per unit active modulation volume [4]. Since we effectively created a 3-D MOS capacitor, carrier accumulates at all three interfaces surrounding the center cavity. Additionally, owning to the small mode volume of the photonic crystal nano-cavity (Fig 1c), we can achieve significant resonance shift from such small active modulation volume (0.06 μm^3 = 0.56 μm × 0.28 μm × 0.375 μm). Besides, the electrically induced absorption of ITO also decreases the resonance peak intensity, offering additional modulation depth.

3. Testing and discussion

To test the device, light is coupled into and out of the silicon waveguide by grating couplers using single-mode optical fibers with 10° tilted angle. A polarization-maintaining fiber is used as the input fiber in order to maintain the TE polarization. Fig 1d shows the transmission spectra of a fabricated E-O modulator at different bias voltages. The device loss at the resonance peak is only 0.5 dB due to the metal-free MOS structure, which is normalized to a straight SOI waveguide with the same dimension and length. The ITO bulk carrier concentration is controlled at 1×10^{20} cm^{-3}, which is still a dielectric material at telecom wavelengths. Therefore, the degradation of the Q-factor due to the presence of the thin ITO layer is minor. The measured Q-factor after ITO deposition is ~1,000, which is slightly smaller than the Q-factor (~1,200) before sputtering the ITO. Under the applied bias, the resonance peak shows a blue shift with resonance tuning efficiency of 30 pm/V. In the meanwhile, we observed a significant drop of the peak transmission by 45.34%, which is mainly due to the ITO absorption. Fig 1e shows the extinction ratio (ER) as a function of the applied bias. More than 1nm usable optical bandwidth is observed if we allow 1-dB variation of the ER. Maximum DC ER is observed at 1534.78nm, achieving 5.6dB ER with 19.5V applied bias. The MOS capacitor operation is verified by the low leakage current, which is measured to be less than 100fA even at -20V. Dynamic optical modulation is currently at 3.2 MHz as shown in Fig 1f, which is limited by our testing instruments. Higher speed E-O modulation is currently under testing.

The energy efficiency of the modulator is estimated by $E_{per\ bit} = CV^2/4$. The capacitance of the MOS structure is simulated to be 1.28 fF. Assuming a 12V voltage swing (3dB ER at the resonance peak), the energy consumption of the device is only 46fJ/bit. The performance of the hybrid silicon-ITO modulator can be further improved with high-k materials such as HfO_2. For example, if we replace the 20nm SiO_2 with 5nm thick HfO_2, the applied voltage will drop to 1V with the same electric flux density field in the gate oxide layer as current 12V bias. Then, the resonance tuning will increase to 360 pm/V and the energy consumption will drop to 6.2fJ/bit. Through improving the Q-factor, this design can potentially achieve energy efficiency below 1fJ/bit, which opens a new route for the development of next generation E-O modulator for future on-chip optical interconnects.

4. Conclusion

In summary, we report an ultra-compact silicon based E-O modulator occupying a footprint of 0.6×8 μm^2. The active modulation volume is only 0.06 μm^3 (~0.02λ^3), which is the smallest active volume that has ever been reported. We experimentally demonstrated a resonance tuning of ~30pm/V, which is measured with a moderate Q factor of 1,000. The energy consumption of the E-O modulator is estimated to be 46fJ/bit.

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