High-Speed Broadband Plasmonic-Silicon Modulator Integrated with Epsilon-near-zero Conductive Oxide

Bokun Zhou, Erwen Li, Yunfei Bo, 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 demonstrated a compact broadband plasmonic-silicon electro-absorption modulator driven by epsilon-near-zero conductive oxide, covering the entire C-band from 1515nm to 1580nm wavelength. It achieved 3.5 GHz modulation bandwidth and 4.5 Gb/s data rate.

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

1. Introduction

Transparent conductive oxides (TCOs) have attracted escalating attention for integrated photonics in the recent years, owing to their large plasma dispersion and epsilon-near-zero (ENZ) effect [1, 2]. The real part of permittivity of TCOs can be tuned crossing zero in the telecommunication wavelength by controlling free carrier concentration through electrical gating. When the TCO turns into ENZ state, light is strongly confined in the ENZ layer due to the continuity of electric displacement at the interface, which strongly enhance the free carrier absorption in the TCO material. Such property has been used to develop TCO-based electro-absorption (EA) modulators, such as plasMOStor [3] and plasmonic metal-oxide-semiconductor (MOS) waveguide modulator [4, 5], which have achieved both large optical bandwidth and small device footprint, showing great potential for large scale photonic integrated circuits. However, the modulation speed of most previous devices is limited to a few megahertz due to the large resistance-capacitance (RC) delay. Only ref [5] demonstrated a moderate data rate at 2.5 Gb/s. In this paper, we design and demonstrate a compact plasmonic-silicon modulator driven by ENZ indium-tin oxide (ITO). A clear absorption enhancement due to the ENZ effect is observed, which gives a 3.2 dB extinction ratio (ER) with only 2V voltage swing. We optimized electrical design and the MOS capacitance and RC delay are greatly reduced. The device achieved a high modulation bandwidth of 3.5 GHz, and digital modulation rate is measured up to 4.5 Gb/s. Moreover, analysis shows that the series resistance can be further reduced, which can increase the modulation speed to over 15GHz.

2. Design and Fabrication

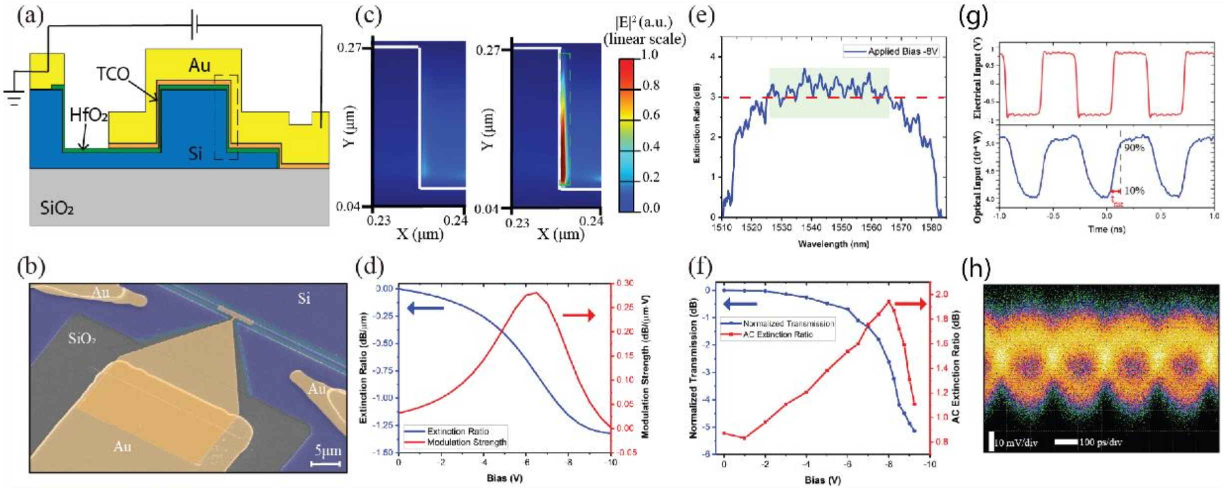

Fig. 1 (a) Cross sectional schematic of the hybrid plasmonic-silicon modulator at the active region. (b) Scanning electron micrograph (SEM) of the fabricated 8-μm-long EA modulator with false color. (c) Simulated mode profile at the TCO/HfO_2 interface, showing field confinement at 0V (left) and -8V (right) bias. (d) Simulated extinction ratio and modulation strength as a function of the applied bias. (e) Extinction ratio at -8V bias showing broadband response from 1515 nm to 1580 nm. (f) Experimental DC transmission and AC modulation strength at different bias. (g) 1.5 GHz AC modulation of the fabricated device. (h) Eye diagram of 4.5 Gb/s digital modulation.

The plasmonic-silicon modulator consists of an Au/ITO/HfO_2/Si MOS capacitor in its active region, as is shown in Fig. 1a. The bottom electrode consists of a 250nm thick and 450nm wide p-type silicon rib waveguide and 50nm thick partially etched silicon slab providing electrical conduction path. The waveguide is covered by 16 nm thick HfO_2, working as the gate insulator. On top of that, 14nm thick ITO layer and 100nm thick gold film serve as the top gate electrode. Upon negative biasing the ITO gate, an electron accumulation layer is formed at the ITO/HfO_2 interface. The electron density determines the complex permittivity of ITO at the accumulation layer. Fig 1d plots the ER of the plasmonic-silicon waveguide as a function of the applied bias. At small bias, the ER increases almost linearly versus the applied bias, because the loss induced by free carrier absorption is proportional to the total free carriers. As the bias increases, the ITO accumulation layer is turned into ENZ state due to the increased electron density. The optical field gets confined in the ITO accumulation layer, as is compared in Fig 1c. Therefore, the ER dramatically increases, which is a typical characteristic of ENZ enhanced absorption. From the simulation, the maximum modulation strength happens on the onset of ENZ state around -6.5V bias, reaching 0.28 dB/(V·µm). The bandwidth of the hybrid plasmonic-silicon EA modulator is primarily limited by the RC delay, due to the accumulation mode operation. In our design, the total capacitance is reduced by minimizing the gate electrode overlapping with the bottom silicon layer; besides, to reduce the series resistance of the modulator, the top 50nm of silicon layer is highly doped to 1×10^{20} cm^{-3}.

The modulator is fabricated on a 250nm thick silicon-on-insulator (SOI) substrate. First, the waveguide and grating couplers are patterned by two steps of electron-beam lithography (EBL) and reactive ion etching (RIE). Then, the active region and contact region are highly doped by ion implantation with 5keV B+ ions at flux of 6×10^{14} cm^{-2}. After the ion implantation, the dopants are activated by rapid thermal annealing at 1000°C for 10 seconds. Next, 16nm thick HfO_2 layer is deposited using atomic layer deposition (ALD). After that ALD, an 8-µm-long ITO/Au gate is patterned by EBL. 14nm of ITO and 100nm of gold are RF sputtered and thermal evaporated, respectively, followed by liftoff process. The HfO_2 at silicon contact region is removed by Buffered HF. Finally, Ni/Au coplanar ground-signal-ground (GSG) electrode is patterned. Fig 1b shows the scanning electron micrograph of the fabricated device.

3. Results and Discussion

Fig 1e shows the ER spectrum of the fabricated modulator at -8V bias, exhibiting a relative uniform 3dB optical modulation bandwidth from 1515 nm to 1580 nm, which is majorly limited by our grating coupler. Fig. 1f shows the transmission and AC extinction ratio at different DC bias voltage. From -6.5V to -8.5V, the transmission dramatically decreases by ~3.2dB, clearly indicating that the ITO accumulation layer has reached the ENZ state. The maximum AC ER happens at the -8V bias, which is more than 2× larger than the ER at 0V bias. The over trend matches very well with the previous simulation. Next, the AC modulation is measured. Fig 1g plots the modulation wave form of the modulator at 1.5GHz. The "on" and "off" states can be clearly seen. The optical rise time (10%-90%) is ~0.1ns, from which we can estimate the modulation bandwidth to be ~3.5GHz. Fig 1f shows the eye diagram measured at 4.5Gb/s data rate. Through reducing the overlapping between the ITO/Au gate with silicon bottom electrode outside the active region, we reduce the capacitance of the modulator to around 100fF. Then, we can estimate energy efficiency by $CV_{pp}^2/4$ to be ~100fJ/bit. The series resistance is ~450Ω according to the S11 measurement, which majorly comes from the series resistance of the silicon conduction path. Through optimizing the silicon implantation, annealing condition, and moving the metal contact closer to the active region, the silicon resistance can be reduced to <100Ω [4], which will give us a modulation bandwidth over 15GHz.

4. Conclusion

To conclude, we reported an 8µm-long high-speed broadband plasmonic-silicon modulator. ENZ-enhanced absorption is clearly measured. The modulator achieves 3.2 dB ER with 2 V voltage swing and uniform modulation response from 1515 nm to 1580 nm wavelength range. The device exhibits a modulation bandwidth of 3.5 GHz. Eye diagram of 4.5 Gb/s digital modulation is measured. The speed of the modulator can be increased to over 15GHz by further optimizing the electrical design of the silicon conduction path.

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References

[1] Liu, K., Ye, C. R., Khan, S., and Sorger, V. J., "Review and perspective on ultrafast wavelength-size electro-optic modulators," Laser & Photonics Reviews, 9(2), 172-194 (2015).

[2] 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.

[3] J. A. Dionne, K. Diest, L. A. Sweatlock, and H. A. Atwater, "PlasMOStor: A metal-oxide-si field effect plasmonic modulator," Nano Lett., vol. 9, no. 2, pp. 897–902 (2009).

[4] Gao, Q., Li, E. and Wang, A.X., 2018. Ultra-compact and broadband electro-absorption modulator using an epsilon-near-zero conductive oxide. Photonics Research, 6(4), pp.277-281.

[5] Wood, M.G., Campione, S., Parameswaran, S., Luk, T.S., Wendt, J.R., Serkland, D.K. and Keeler, G.A., "Gigahertz speed operation of epsilon-near-zero silicon photonic modulators," Optica, 5(3), 233-236 (2018).