Integrated Photonics using Transparent Conductive Oxides

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Abstract: This paper reviews recent research progress of photonic integrated circuits using transparent conductive oxides. Especially, the heterogeneous integration of transparent conductive oxides with silicon photonics shows great potential for energy-efficient optical interconnects.

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1. Introduction

Photonic integrated circuits (PICs) hold the key to solve a myriad of grand challenges varying from data centers, high performance computing, 5G/6G network to machine learning and artificial intelligence, quantum computers and communication, and even autonomous driving. Unlike electronic integrated circuits that nearly exclusively rely on silicon, PICs have highly diverse requirement that can only be satisfied by heterogeneous integration of multiple optical and electronic materials. This abstract reviews transparent conductive oxides (TCOs) [1-3] as emerging materials for PICs that can offer extremely high electro-optic efficiency on silicon photonics. Ultra-compact photonic crystal nanocavity [4-5], plasmonic electro-absorption [6] modulators and microring resonators (MRRs) [7] were demonstrated with unprecedented energy efficiency at a few fJ/bit. In addition, an on-chip wavelength division multiplexing (WDM) PICs with large tunability is demonstrated.

2. High mobility TCO materials

High mobility TCO materials can greatly reduce the optical loss and improve the energy efficiency. Table I lists TCOs with different carrier mobility and the corresponding absolute value of the epsilon-near-zero (ENZ) permittivity. We simulated and compared the waveguide loss of the hybrid plasmonic-silicon structure with different TCOs. As the mobility of TCO increases, the waveguide loss is greatly reduced. In our recent experimental work, we use RF-sputtering to deposit $Ti:In_2O_3$ and a high mobility of 96 $cm^2V^{-1}s^{-1}$ is achieved. The mobility of $Ti:In_2O_3$ is strongly dependent on the oxygen flow, RF power, and background pressure.

TABLE I Permittivity $|\varepsilon|$ at ENZ for TCOs of different mobility

TCO Materials	Mobility ($cm^2V^{-1}s^{-1}$)	ENZ $\lvert\varepsilon\rvert$	Effective Mass	Waveguide loss (dB/μm)
ITO	15~30	0.96	0.33-0.35	1.66
In_2O_3	20~35	0.42	0.3-0.32	0.89
$Ti:In_2O_3$	70~100	0.15	0.27-0.31	0.64
CdO	280~300	0.05	0.22-0.24	0.46

3. Hybrid Silicon-TCO Photonic Devices

High-speed photonic crystal nanocavity modulator [8]: we fabricated a TCO-Si nanocavity modulator, which shows a wavelength tunability of 71 pm/V with a Q factor of ~5,600, achieving 3.45 dB ER with 2 Vpp applied bias. We demonstrated a 3dB modulation bandwidth of 1.94 GHz. E-O modulation was measured up to 3 Gb/s with 2 Vpp voltage swing, which corresponds to an energy efficiency of ~18.3 fJ/bit. In addition, we proposed that the series resistance can be further reduced by node-matched doping of Si and high-mobility TCO material, which can improve the 3dB bandwidth to over 23.5 GHz. Furthermore, based on the quantitative analysis of the overlapping factor, we predict that single-digit femto-joule per bit energy efficiency of 1.33 fJ/bit can be reached through optimizing the gate oxide thickness and fabrication processes. Further increasing the overlapping factor is possible through precisely covering the TCO-Si MOS capacitor at the subwavelength silicon bridge of PC nanocavity. With that, an extremely low energy consumption of 437 aJ/bit can be achieved.

High-speed plasmonic-silicon modulator driven by ENZ conductive oxide [9]: we reported an 8-μm-long plasmonic-TCO-silicon EA modulator with 3.5 GHz modulation bandwidth and broadband response from 1515 nm to 1580 nm. By biasing the device at the ENZ region, 3.2 dB ER with 2V voltage swing is observed. Eye diagram of 4.5 Gb/s digital modulation is measured. Furthermore, we demonstrated the dependence on TCO mobility for extinction ratio and energy consumption of EA modulator, based on enhanced ENZ effect. By adopting high mobility TCOs, a record-breaking device performance of energy consumption of 0.4 fJ/bits and high speed over 40 GHz is expected for a 3-μm-long EA modulator.

High Q-factor silicon microring resonator [10]: We demonstrate an electrically tunable silicon microring resonator driven by a titanium-doped indium oxide/hafnium oxide/silicon metal-oxide-semiconductor capacitor, achieving a high electro-optic tuning efficiency of 130 pm/V with a high quality-factor between 11,900 and 4,700. The high electro-optic tuning efficiency can be used to compensate for the drift of resonance wavelength induced by temperature fluctuation up to 12K with an extremely low-power consumption of 11 pW/nm, which is superior to the conventional thermal tuning.

4. On-chip WDM system using TCO-driven Si-MRRs

Fig. 1 shows the proposed on-chip WDM transmitter consisting of a silicon bus waveguide coupled to multiple dual-functional microring resonators driven by TCO gates. Four constant-wave (CW) lasers with wavelength of λ_1 to λ_N (N=4 in the figure) are coupled into the bus waveguide and each microring resonator can perform E-O modulation and wavelength multiplexing/de-multiplexing (MUX/DeMUX) independently. In the meanwhile, these microring resonators will dynamically compensate temperature fluctuation and fabrication variation with near-zero static power consumption, which eliminate power-hungry thermal heaters that have been widely used in silicon PICs.

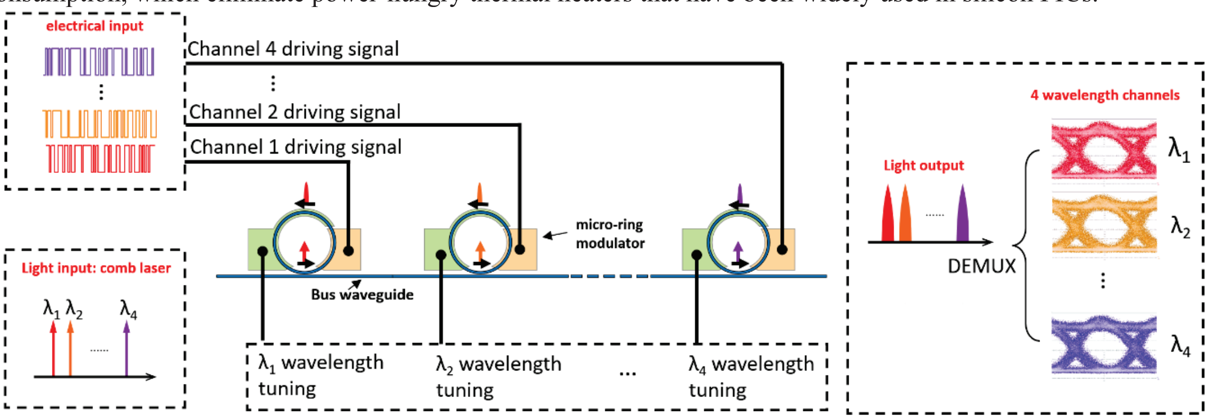

Fig.1 Schematic figure of 4-channle on-chip WDM transmitter that can perform E-O modulation and wavelength MUX/DeMUX independently using TCO-driven silicon microring resonators

5. Conclusion

In conclusion, we demonstrated silicon photonic devices and PICs driven by TCO materials. The heterogeneous integrated devices show significant advantages in terms of energy efficiency and E-O tunability.

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