Integrated Photonics and Nanophotonic Devices using Transparent Conductive Oxides

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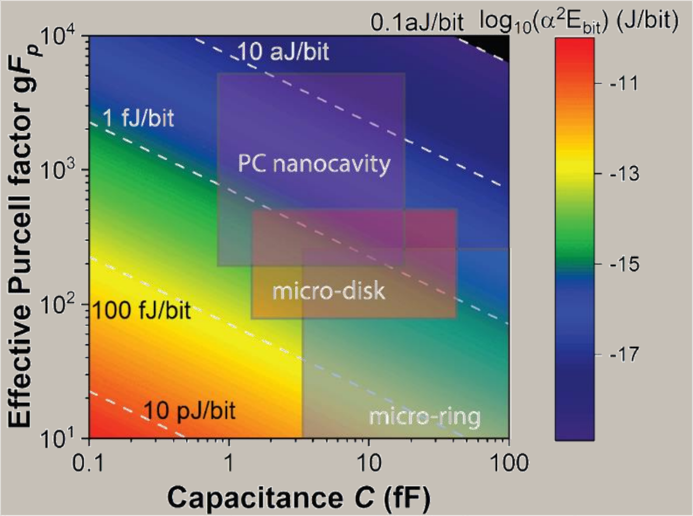
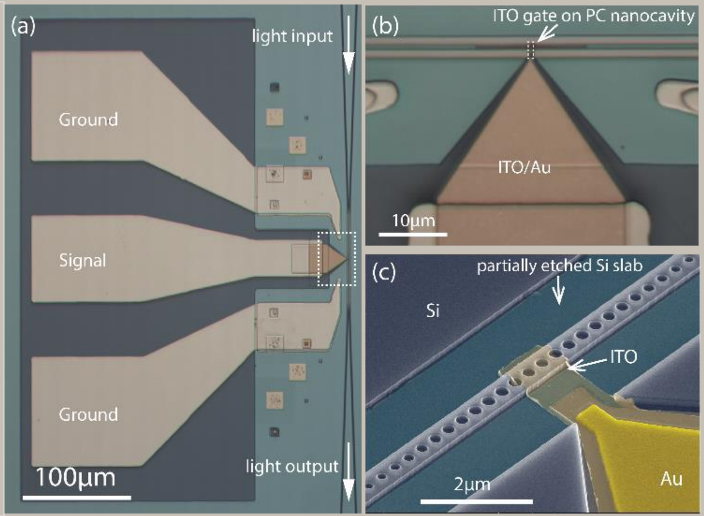
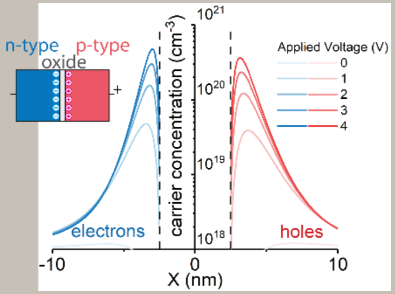
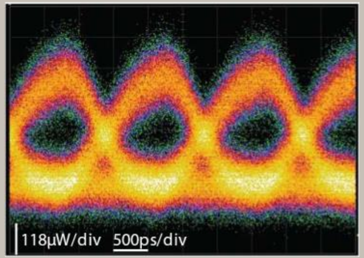




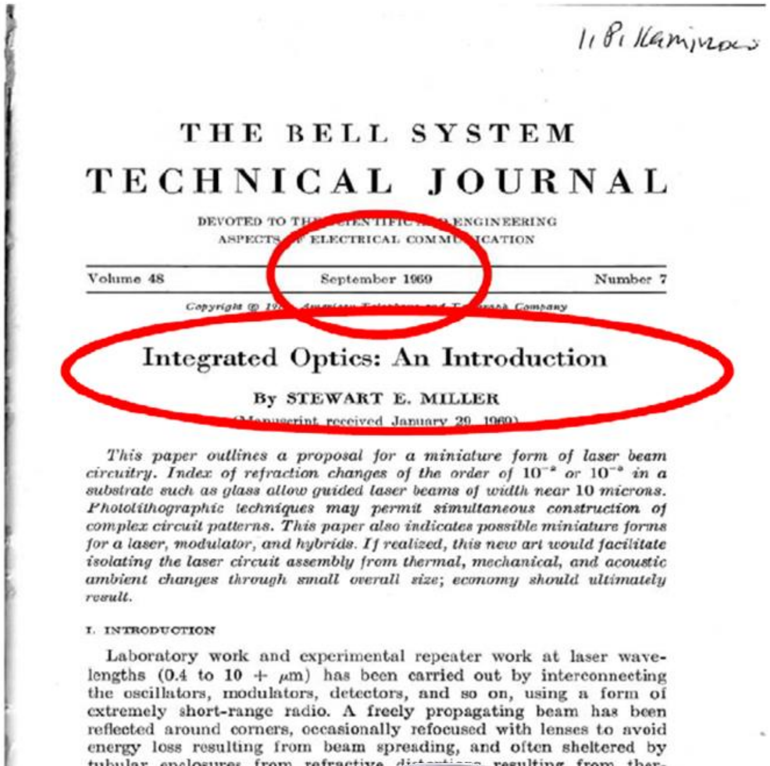




The NESC Academy Seminar, NASA, 09/21/2021

Birth of the Integrated Photonics Concept

> *"There is a conviction that the new miniaturized optical circuitry will prove useful… We must wait a while longer to find out how useful this new technology will become."*



I. P. Kaminow

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Volume 48 September 1969 Number 7

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Integrated Optics: An Introduction

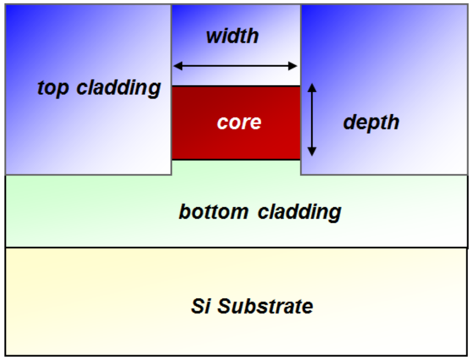
By STEWART E. MILLER

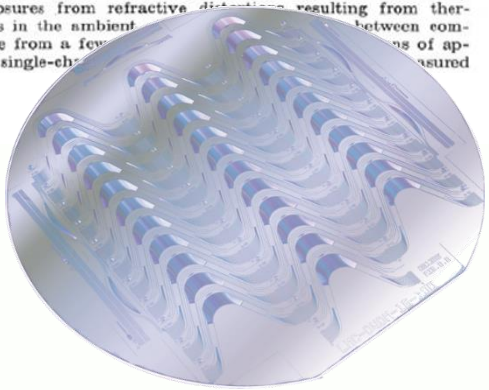
(Manuscript received January 29, 1969)

This paper outlines a proposal for a miniature form of laser beam circuitry. Index of refraction changes of the order of 10^{-2} or 10^{-3} in a substrate such as glass allow guided laser beams of width near 10 microns. Photolithographic techniques may permit simultaneous construction of complex circuit patterns. This paper also indicates possible miniature forms for a laser, modulator, and hybrids. If realized, this new art would facilitate isolating the laser circuit assembly from thermal, mechanical, and acoustic ambient changes through small overall size; economy should ultimately result.

I. INTRODUCTION

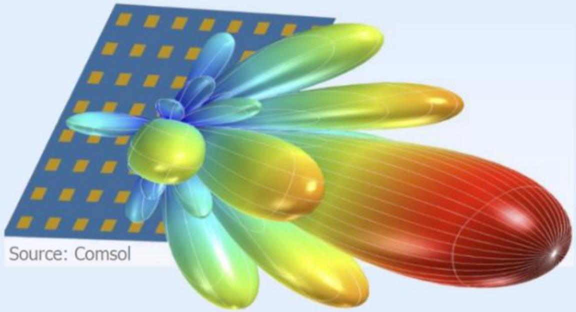
Laboratory work and experimental repeater work at laser wavelengths (0.4 to 10 + μm) has been carried out by interconnecting the oscillators, modulators, detectors, and so on, using a form of extremely short-range radio. A freely propagating beam has been reflected around corners, occasionally refocused with lenses to avoid energy loss resulting from beam spreading, and often sheltered by tubular enclosures from refractive [illegible] resulting from ther-[illegible] gradients in the ambient [illegible] between com-[illegible]ents range from a few [illegible] of ap-[illegible]atus in a single-ch[illegible] [illegible]asured





RF Phased Arrays – Radar & 5G

Improved Performance and System Scalability

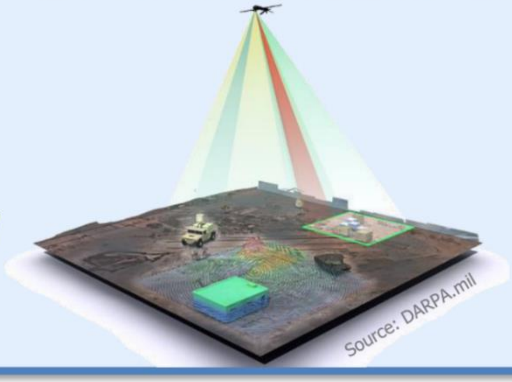


Source: Comsol

sensors,
edge,
DoD

Digital Sensors – Imaging

Scaling Pixel Array Size, Frame Rate, and Power



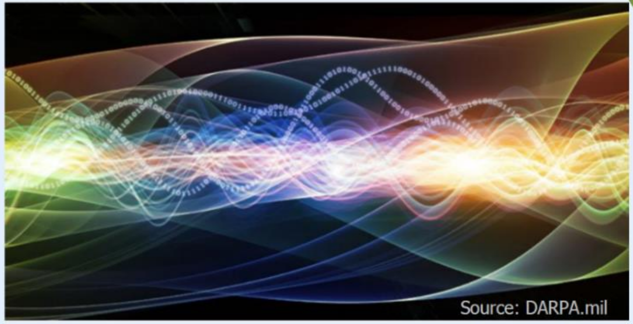
Source: DARPA.mil

PIPES Ecosystem

Establish sustained DoD access to domestic design, fabrication, and packaging capabilities

Machine Learning & Simulatio

Large-scale Modeling and Artificial Intelligence



Source: DARPA.mil

Computing & Data Analysis

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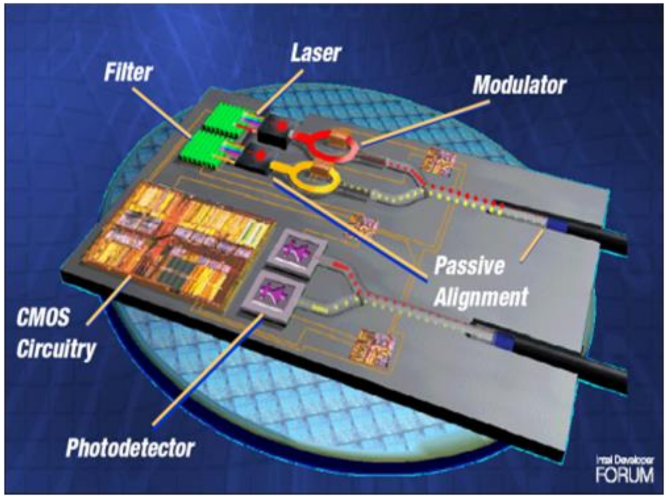
Silicon Photonics: the most Successful Integrated Photonics Platform

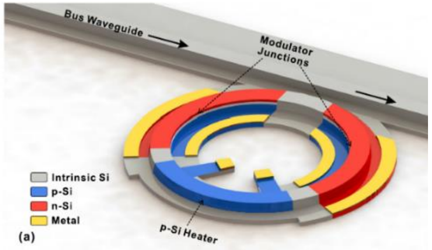


(Courtesy Intel)

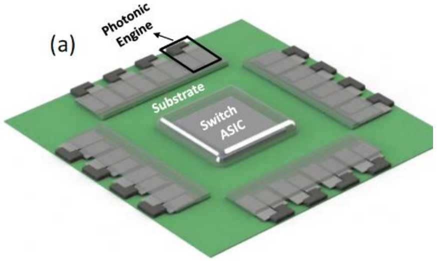
100G CWDM4 QSFP28 Optical Transceiver

400G QSFP-DD Optical Transceiver

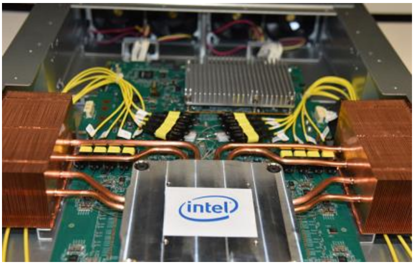
Intel Si microring modulator



Co-packaged photonic engine using Si MRM

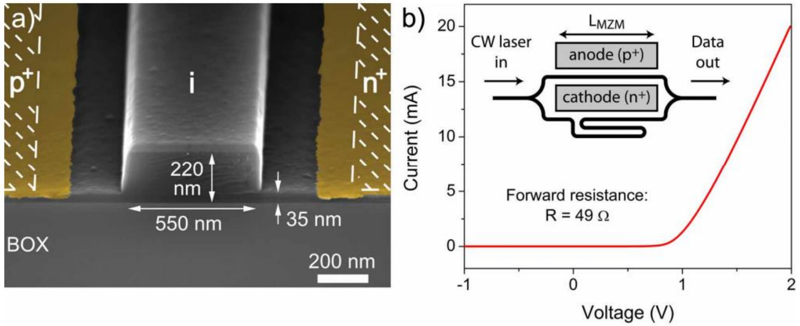


Industry first 1.6Tb/s switch with high density integrated optics



- Fathololoumi, S., Hui, D., Jadhav, S., Chen, J., Nguyen, K., Sakib, M.N., Li, Z., Mahalingam, H., Amiralizadeh, S., Tang, N.N. and Potluri, H., 2021. 1.6 Tbps silicon photonics integrated circuit and 800 Gbps photonic engine for switch co-packaging demonstration. *Journal of Lightwave Technology*, *39*(4), pp.1155-1161.

Conventional silicon modulator based on Mach-Zehnder interferometer (MZI)



(Green, W.M. et al., 2007. *Opt. express*, *15*(25), pp.17106-17113.)

Pros:

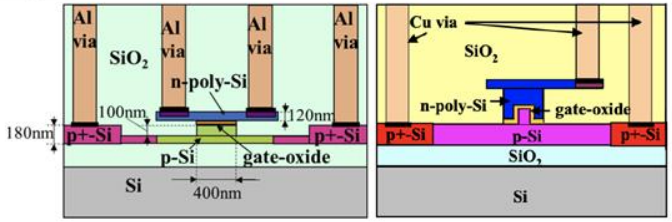
- Mature technique
- Fast speed (10~50GHz)
- Linear response
- Broadband operation

Cons:

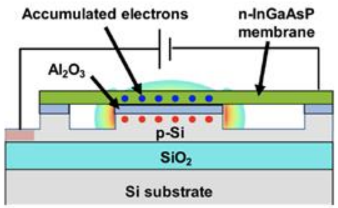
- Large size: hundreds of μm~mm
- Low electro-optic efficiency
- Large energy consumption: ~pJ/bit
- Not suitable for on-chip interconnects

Heterogeneous Integration with Silicon Photonics

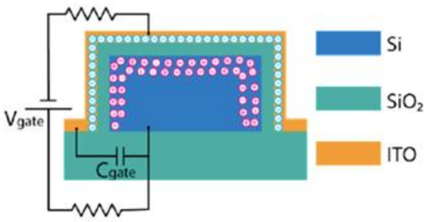
Poly-Si



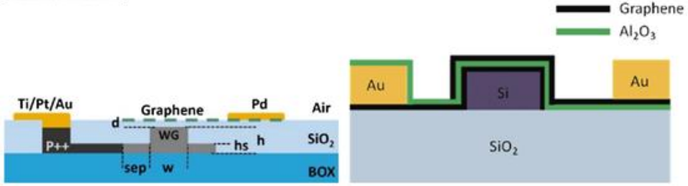
III-V



TCO



Graphene



Outline

- ☐ Introduction to Transparent Conductive Oxides (TCOs)
- ☐ Heterogeneous Integration of TCOs with Silicon Photonics:
    - ➢ Ultra-compact and energy-efficient Si-TCO nanocavity modulators
    - ➢ Broadband Epsilon-Near-Zero Plasmonic Electro-Absorption Modulators
- ☐ Summary and Future Work

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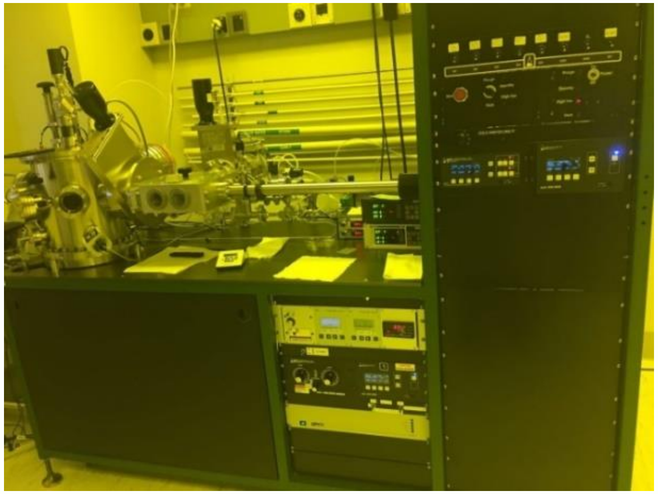
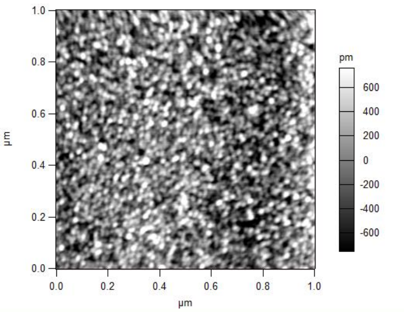
Transparent Conductive Oxides (TCOs)

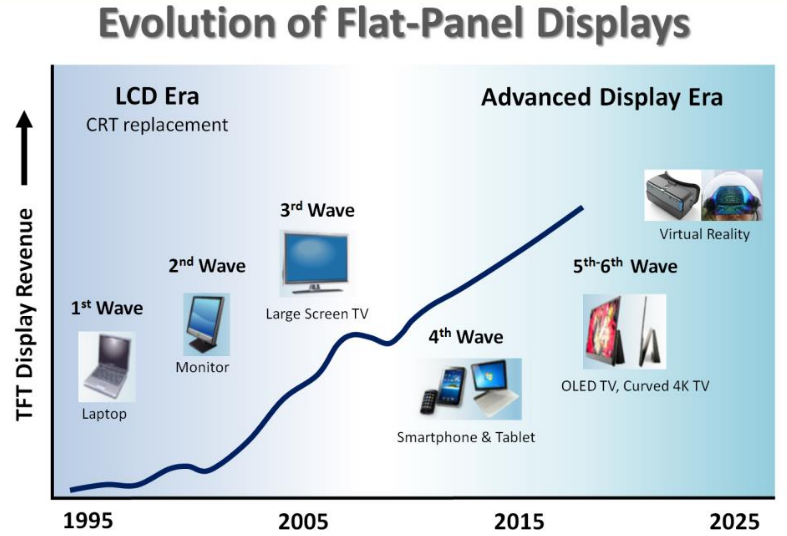
Typical TCO materials: highly conductive metal oxides such as indium tin-oxide (ITO), aluminum-doped zinc oxide (AZO) and gallium zinc oxide (GZO). The free carrier concentration can be dynamically controlled by an applied voltage

- Naik, G.V., Shalaev, V.M. and Boltasseva, A., 2013. Alternative plasmonic materials: beyond gold and silver. *Advanced Materials*, *25*(24), pp.3264-3294.

DC sputtering for TCO deposition



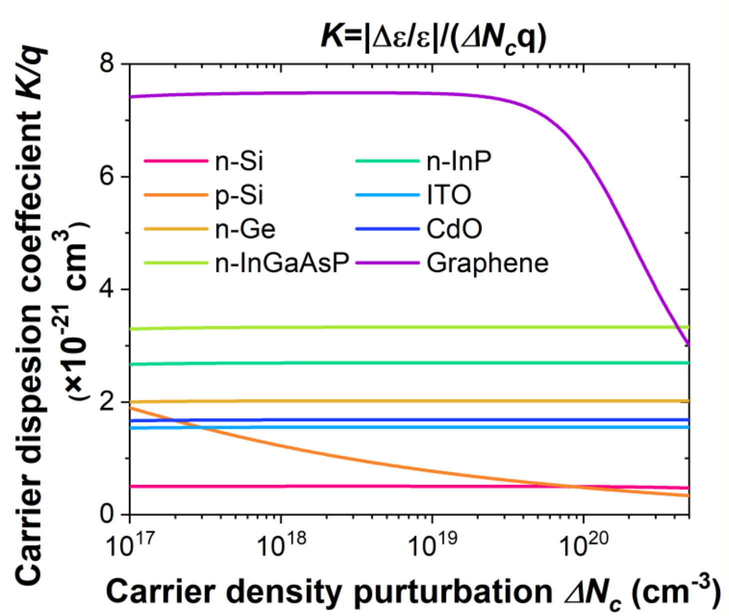




- Sputtering: compatible with silicon photonics processing, ultra-smooth surface
- 80nm ITO film on quartz
- Surface Roughness: 0.38 nm

➢ Unique Optoelectronic Features:

- Degenerately doped: 10^{19}~10^{21} cm^{-3}
- Highly conductive through oxygen vacancy doping, no ion-implantation is needed
- Strong plasma dispersion effect
- Ultra-large change of refractive index
- Epsilon-near-zero (ENZ) materials at telecom wavelength range



Drude Model

Relative permittivity: $\varepsilon_r = \varepsilon_\infty + \frac{\omega_p^2}{\omega(\omega + i\Gamma)}$

Plasma frequency: $\omega_p^2 = \frac{N_c q^2}{\varepsilon_0 m^*}$

Collision frequency: $\Gamma = \frac{q}{\mu m^*}$

High frequency permittivity: ε_∞

plasma collision frequency: Γ

Free carrier concentration: N_c

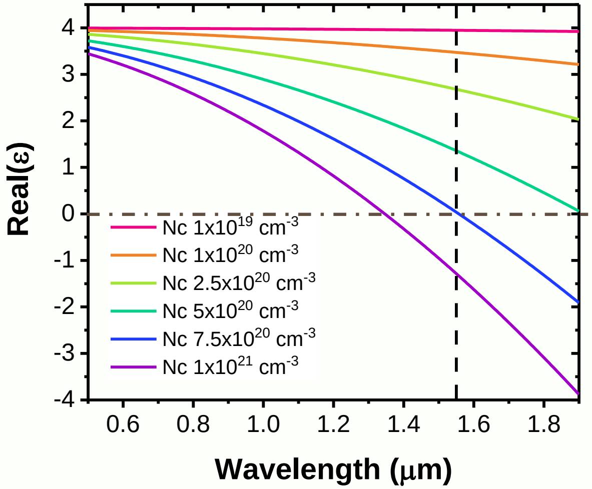
Effective mass: m^*

- **Free carrier dispersion coefficient:**

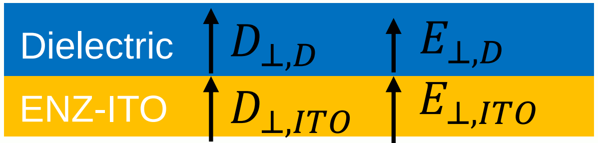
$$\boldsymbol{K} = -\frac{\boldsymbol{\partial\, \Delta\varepsilon/\varepsilon}}{\boldsymbol{\partial \Delta N_c}} = \frac{q}{\varepsilon_0 \varepsilon_r m^* \omega^2} = \frac{1}{q N_{ENZ}}$$

✓ TCO wins because of the combined advantages in plasma dispersion effect and process compatibility with silicon photonics: by sputtering deposition

ENZ-Enhanced Electro-Absorption



ENZ-induced field enhancement

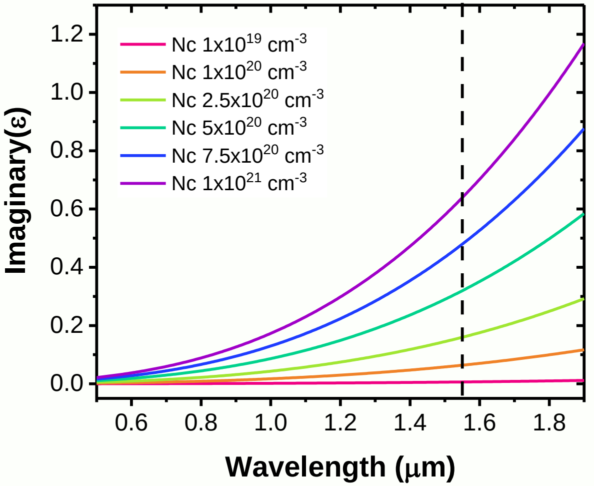


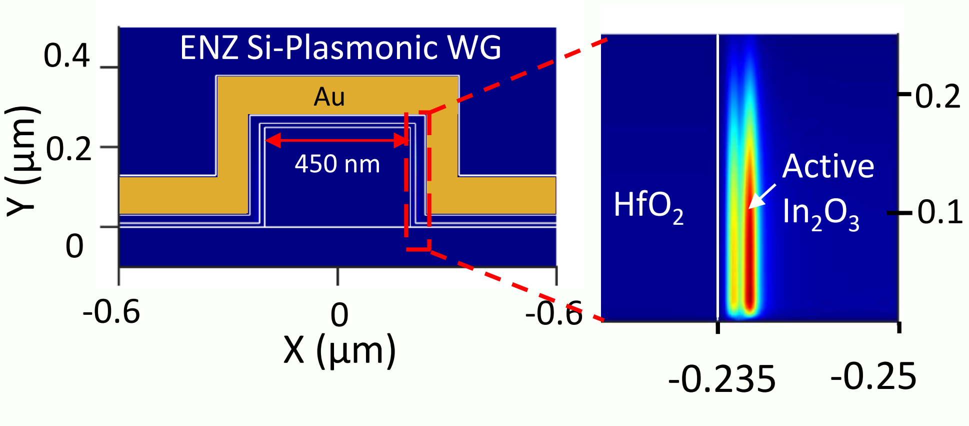
$$D_{\perp,ITO} = D_{\perp,D}$$

$$E_{\perp,ITO} = \frac{|\varepsilon_D|}{|\varepsilon_{ITO}|} E_{\perp,D}$$

$$\alpha = \frac{\mathrm{Im}(\varepsilon)}{|\varepsilon|^2}$$

α reaches the peak value at the ENZ wavelength





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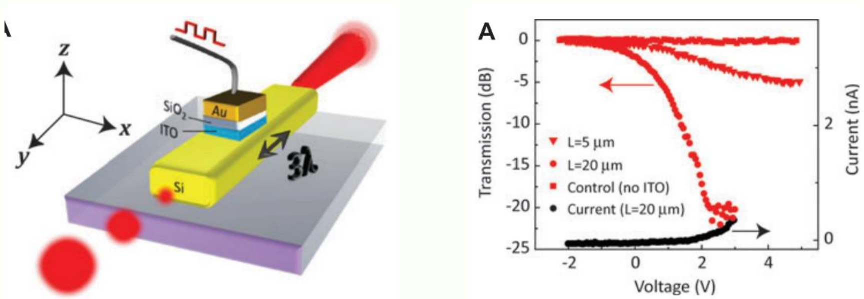
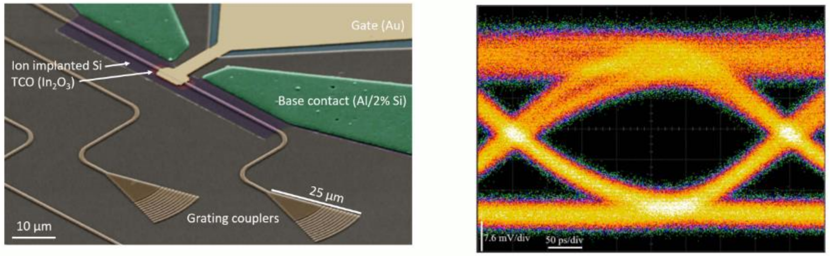
TCO-based ENZ Electro-absorption (EA) Modulators

Hybrid plasmonic-Si waveguide



(Sorger, Volker J., et al. Nanophotonics (2012))

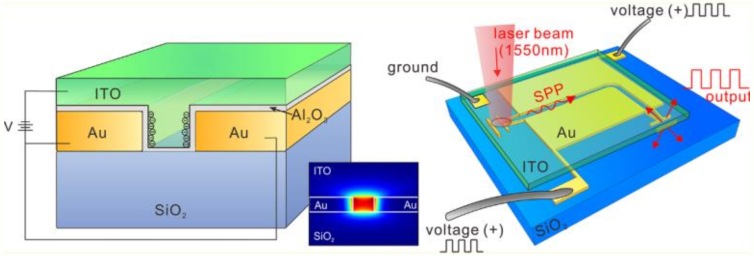
- Extinction Ratio (ER): 1dB/µm



(Wood, Michael G., et al. Optica (2018))

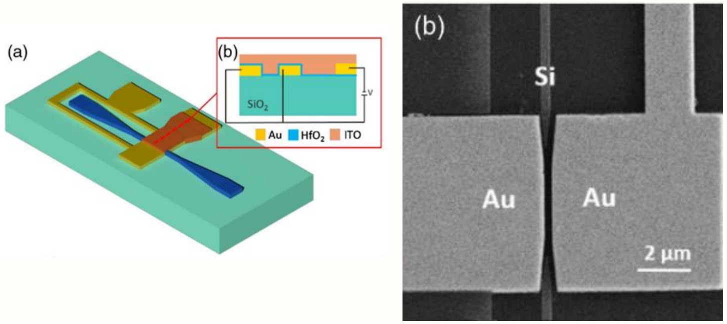
- Extinction Ratio (ER): 1.6~2.5dB/µm
- 2.5Gb/s data rate

Plasmonic slot waveguide



(Lee, Ho W., et al. Nano letters 14.11 (2014))

- Extinction Ratio (ER): 2.7dB/µm



(Gao, Qian, et al. Photonics Research 6.4 (2018))

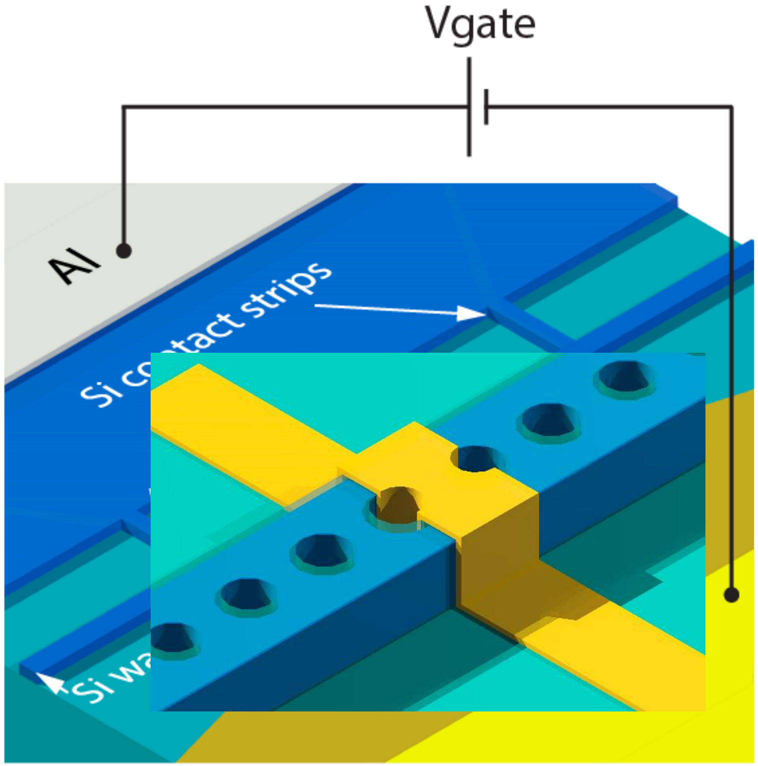
- Extinction Ratio (ER): 1.5dB/µm
- 40MHz

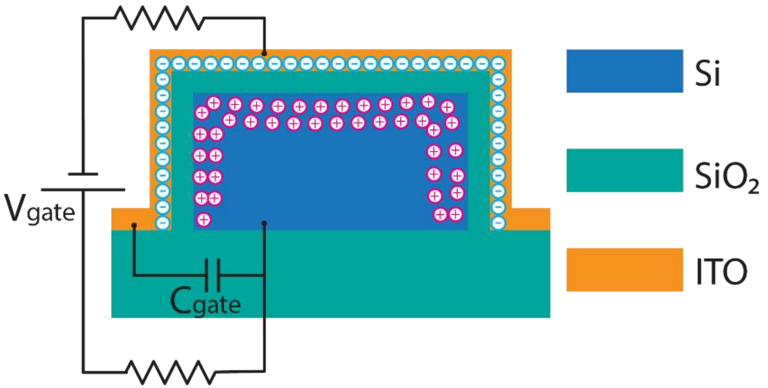
- 1~2.7dB/µm Extinction Ratio (ER) is achieved through epsilon-near-zero (ENZ)-enhanced absorption

Outline

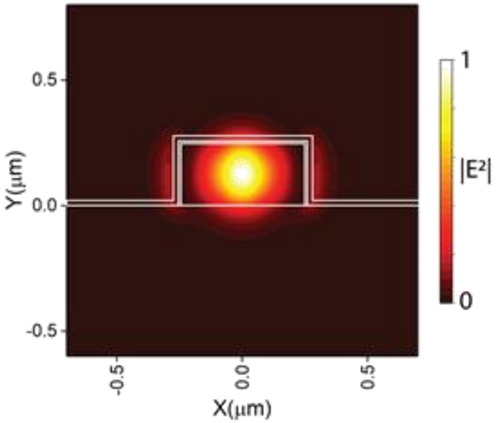
- ☐ **Introduction to Transparent Conductive Oxides (TCOs)**
- ☐ **Heterogeneous Integration of TCOs with Silicon Photonics:**
  - ➢ **Ultra-compact and energy-efficient Si-TCO nanocavity modulators**
  - ➢ **Broadband Epsilon-Near-Zero Plasmonic Electro-Absorption Modulators**
- ☐ **Summary and Future Work**

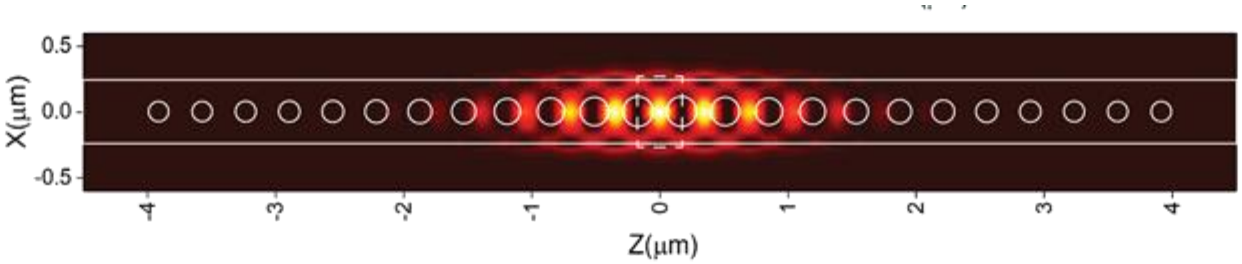
Hybrid Si-TCO photonic crystal nanocavity E-O modulator





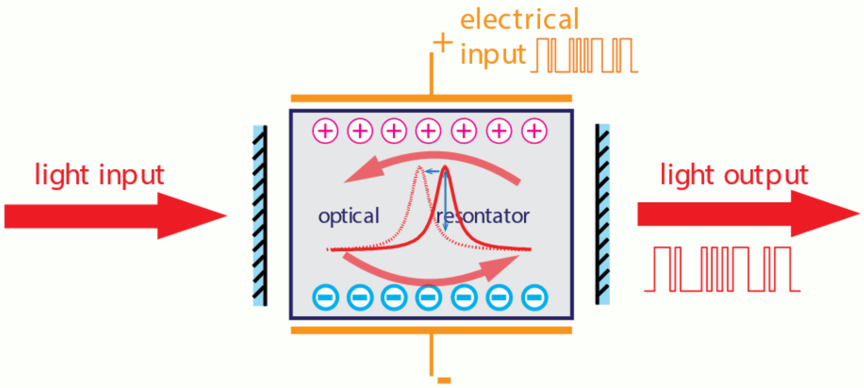
- TCO/Insulator/p-Si MOS capacitor
- Metal free structure: low loss
- High Q/V_{mode} (Purcell factor) resonator
- Footprint: 0.6 × 8 μm^2
- Active volume: width × height × length = 0.56μm × 0.28 μm × 0.375 μm = 0.06 μm^3 ($0.02\lambda^3$)

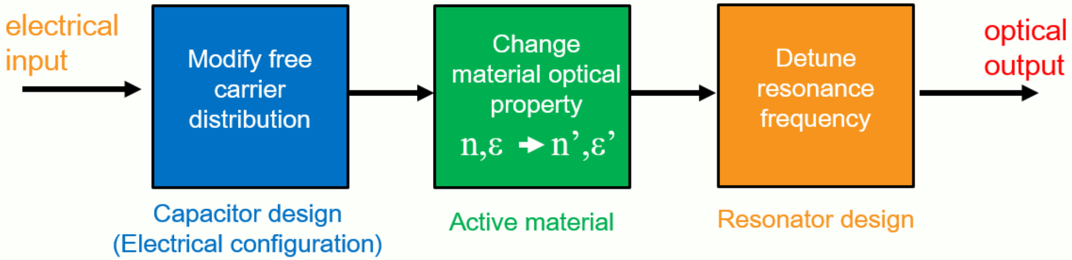




➢ Energy Efficiency of Silicon Resonator Modulators

General model of free-carrier-driven silicon micro-resonator modulators




electrical input

Modify free carrier distribution

Change material optical property

$n,\varepsilon \rightarrow n',\varepsilon'$

Detune resonance frequency

optical output

Capacitor design (Electrical configuration)

Active material

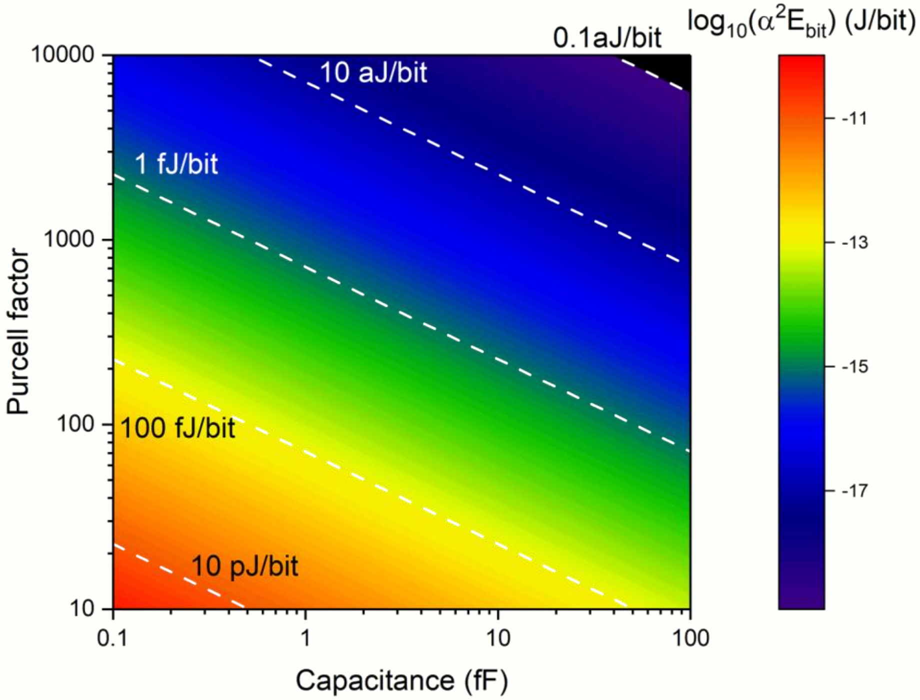
Resonator design

<u>Key design factors:</u>

- Active materials: Si, Ge, III-V, TCOs, graphene, etc
- Resonator design: micro-ring, micro-disk, photonic crystal nanocavity
- Electrical configuration: PIN injection, Reversed PN junction, and MOS capacitor

- Li, E. and Wang, A.X., 2019. Theoretical Analysis of Energy Efficiency and Bandwidth Limit of Silicon Photonic Modulators. *Journal of Lightwave Technology*, *37*(23), pp.5801-5813.

➢ Energy efficiency of resonator modulators



- Overlapping factor:

$$\alpha = \frac{\int \varepsilon \Delta N_c q |E|^2 dv}{Q_c \max(\varepsilon |E|^2)}$$

- Purcell factor:

$$F_p = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V_m}$$

- Energy per bit:

$$E_{bit} = \frac{1}{4} C V^2 = \frac{1}{4}\frac{(Q_{tot}/2)^2}{C}$$
$$= \frac{9}{64\pi^4}\left(\left(\frac{\lambda}{n}\right)^3 \frac{1}{F_p}\right)^2 \frac{(qN_{ENZ})^2}{\alpha^2 C}$$

- Purcell factor: a large Purcell factor increases the energy efficiency.
- Capacitance: a large capacitance induces more charges and will improve the energy efficiency.
- Electro-optic field overlap factor α: when α equals to 1, the modulator reaches the maximum efficiency. To maximize the energy efficiency, α should be as large as possible.

- Q: Q-factor
- V_m: mode volume
- Q_{tot}: total change of free carrier
- C: capacitance
- V: applied voltage

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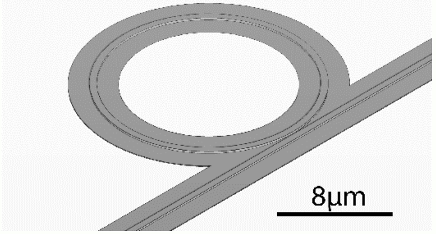
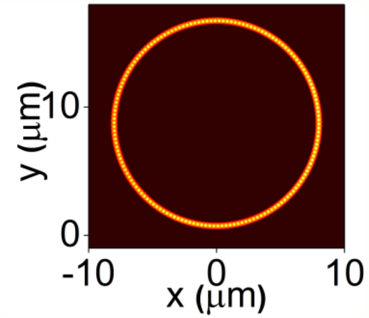
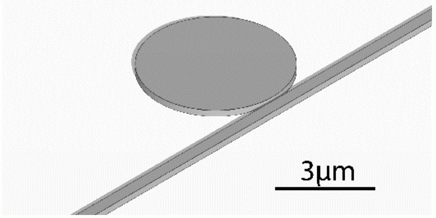
➢ Comparison of different resonators

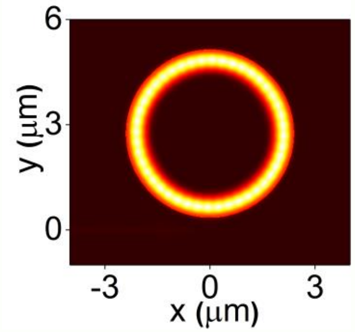
Micro-ring



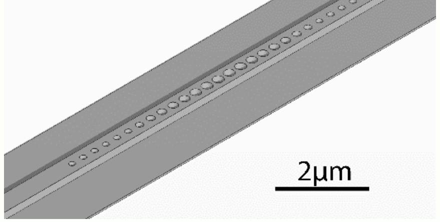


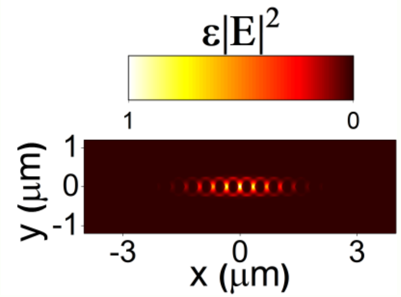
Micro-disk

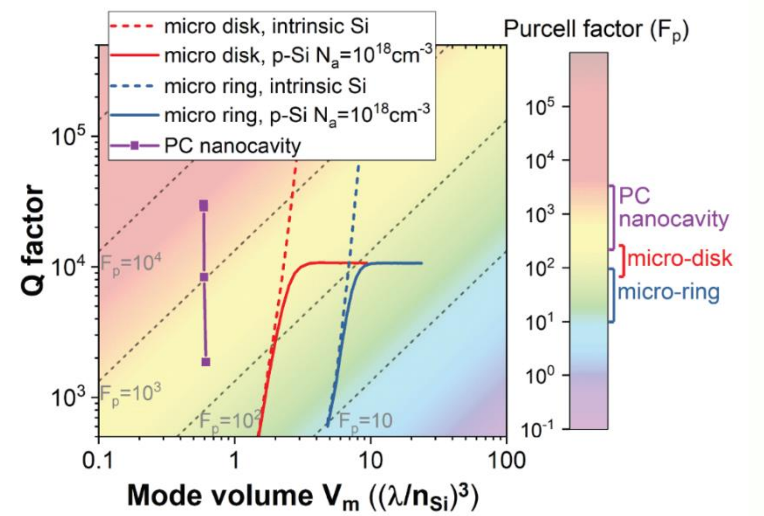


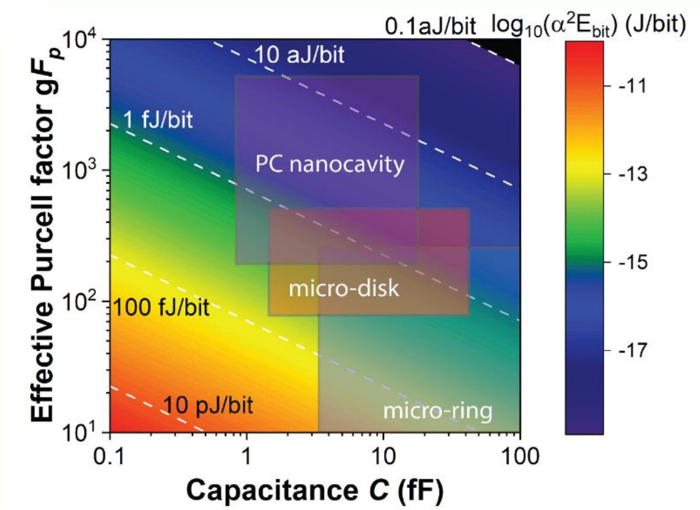


PC nanocavity



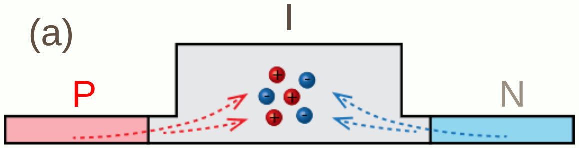




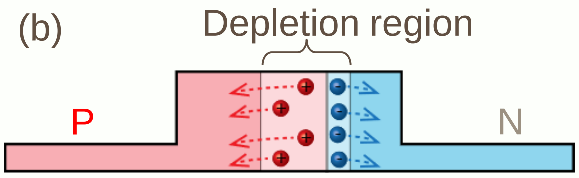


- Nanocavity offers the highest energy efficiency to ~10aJ/bit due to the ultra-large Purcell factor

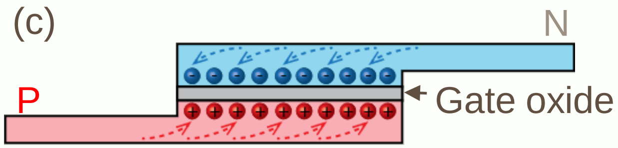
Bandwidth limit of silicon modulators



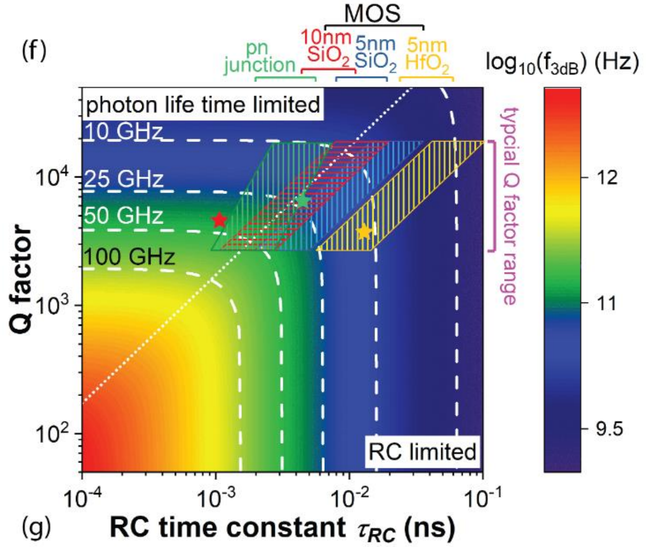
PIN Carrier Injection

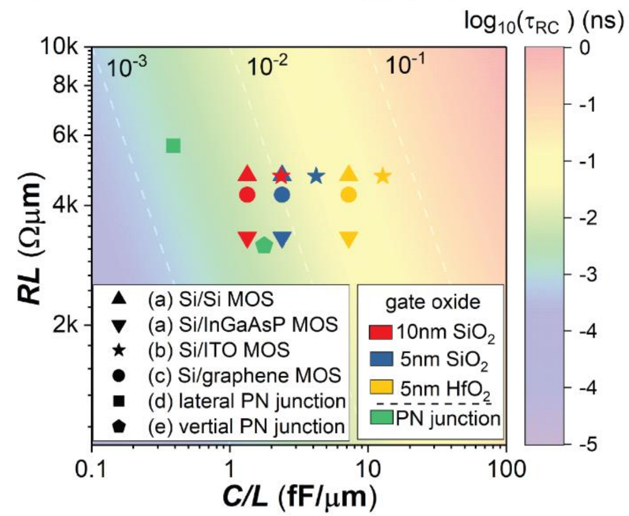


Reversed PN junction



MOS Capacitor Structure



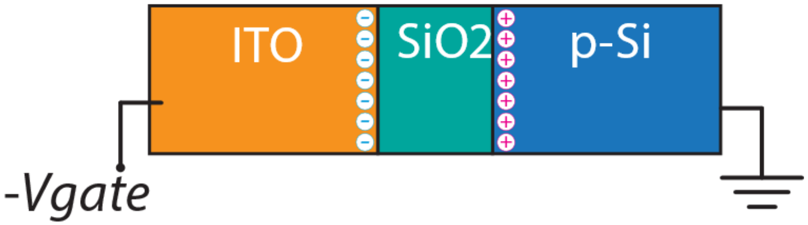


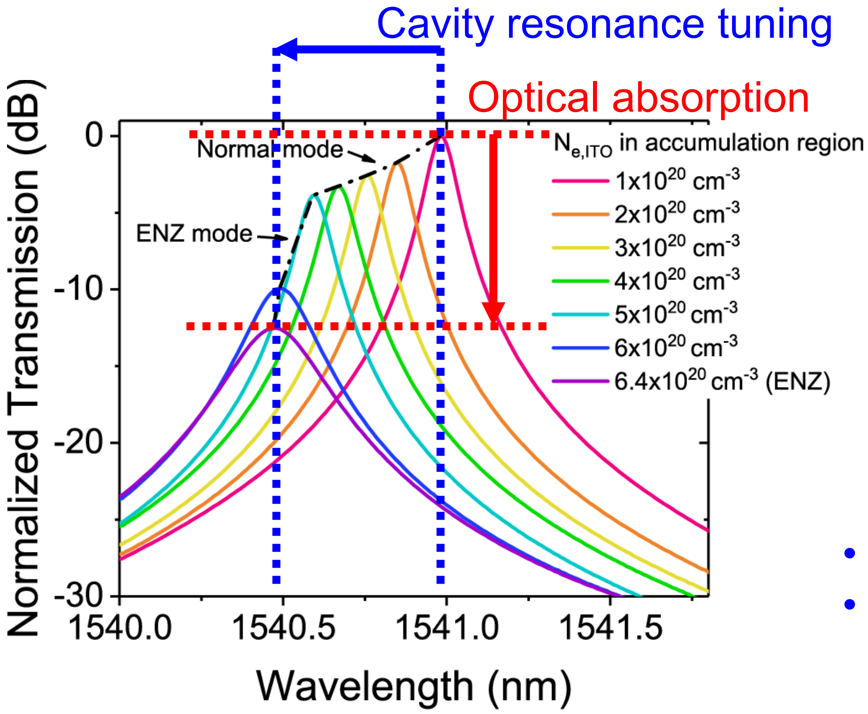
Intrinsic trade-off between bandwidth and energy efficiency:

- High Q-factor: more energy efficient, but longer photon lifetime
- Large capacitance: more energy efficient, but longer RC delay

Mechanism of ultra-high E-O modulation efficiency

- Electrons accumulate at TCO/Insulator interface
- Holes accumulate at Si/Insulator interface




Cavity resonance tuning

Optical absorption

Carrier induced permittivity variation:

$$\Delta\varepsilon_{ITO} = \Delta\varepsilon_{1\_ITO} + i\Delta\varepsilon_{2\_ITO}$$

$$\Delta\varepsilon_{Si} = \Delta\varepsilon_{1\_Si} + i\Delta\varepsilon_{2\_Si}$$

Real part of permittivity variation

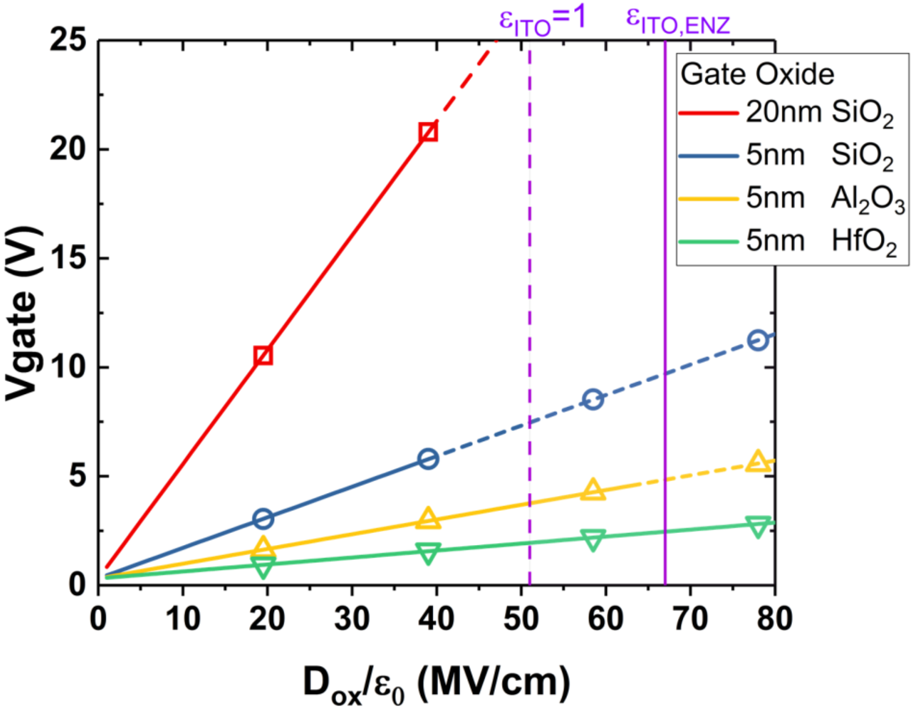
Imaginary part of permittivity variation

- Both materials contribute to E-O modulation;
- Both the real and imaginary parts of permittivity change contribute to E-O modulation

Effect of gate oxide

- Carrier accumulation is only determined by the **electric displacement field**: D_{ox}

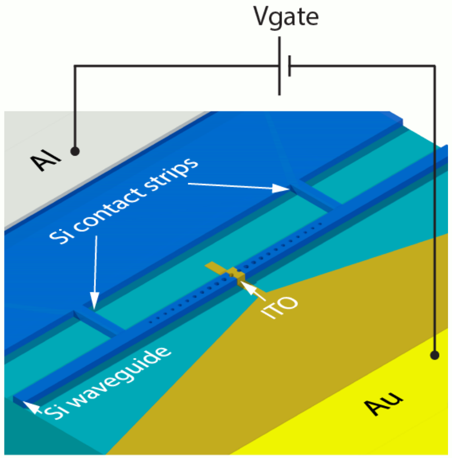
- We can scale down the operation voltage and energy consumption by:
  - Reducing the gate oxide thickness
  - Using high-k material as gate oxide



D_{ox}/ε_0 (MV/cm)	peak $N_{e,ITO}$ (cm^{-3})	total accumulated charge (cm^{-2})	V_{gate} (V) 20nm SiO_2 gate oxide	V_{gate} (V) 5nm SiO_2 gate oxide	V_{gate} (V) 5nm HfO_2 gate oxide
19.5	2.37×10^{20}	1.09×10^{13}	10.5	3.0	0.9
39.0	3.94×10^{20}	2.17×10^{13}	20.8	5.8	1.6
58.5	5.65×10^{20}	3.26×10^{13}	31.0 (breakdown)	8.5 (breakdown)	2.2
78.0	7.46×10^{20}	4.35×10^{13}	41.2 (breakdown)	11.2 (breakdown)	2.8

Summary of PC Nanocavity Modulator Design

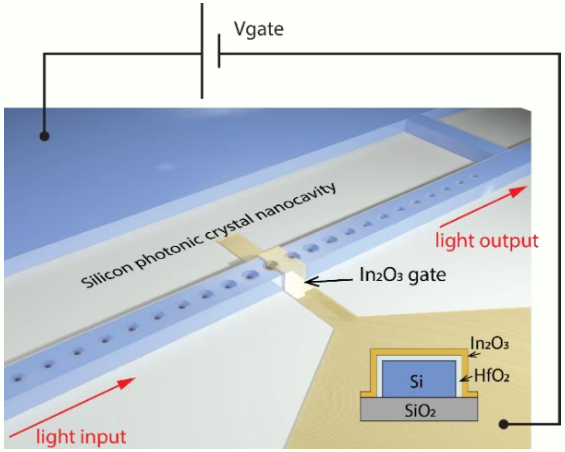
Proof of concept



- Si ridge waveguide
- Contact strips for ground electrode
- 20 nm SiO_2 gate oxide
- ITO gate

- 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.

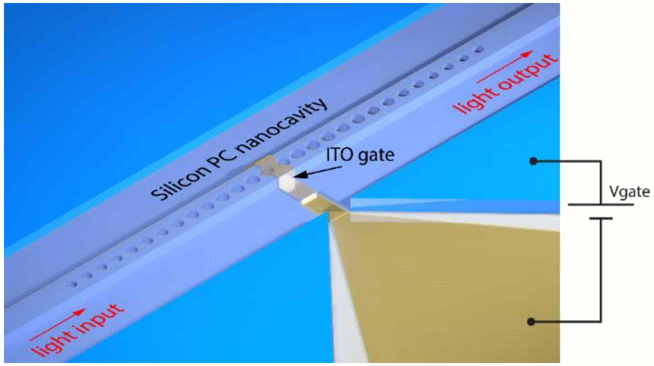
Low voltage, Low energy consumption



- Si ridge waveguide
- Contact strips for ground electrode
- 10 nm HfO_2 gate oxide
- In_2O_3 gate

- Li, E., Gao, Q., Liverman, S. and Wang, A.X., 2018. One-volt silicon photonic crystal nanocavity modulator with indium oxide gate. *Optics letters*, *43*(18), pp.4429-4432.

High speed design



- Si slab waveguide: partially etched Si slab for ground electrode with reduced series resistance
- 16 nm HfO_2 gate oxide
- ITO gate

- Li, E., Zhou, B., Bo, Y. and Wang, A.X., 2021. High-Speed Femto-Joule per Bit Silicon-Conductive Oxide Nanocavity Modulator. Journal of Lightwave Technology, 39(1), pp.178-185.

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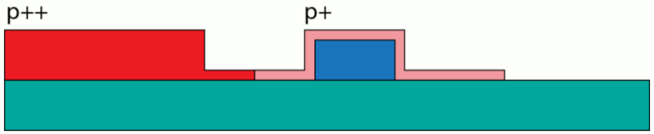
➢ Fabrication of TCO modulators

(a)

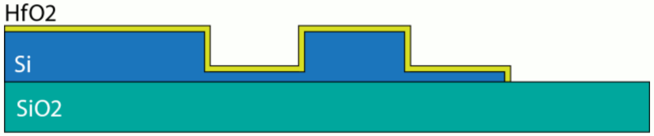
Silicon waveguide, nanocavity, and grating couplers are patterned by two steps of electron-beam lithography (EBL) on diluted ZEP520A resist, followed by reactive ion etching (RIE).

(b)



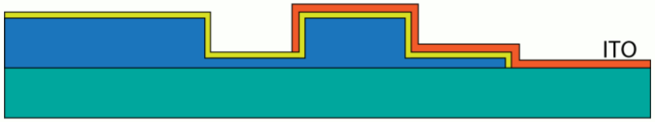
The active region and contact region are selectively implanted to equivalent dopant concentrations of 5e18 cm^{-3} and 1e20 cm^{-3} at top 50nm thick silicon layer. After the ion implantation, the dopant is activated by rapid thermal annealing at 1000° C for 10 seconds.

(c)



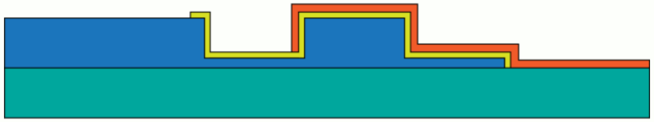
10 nm thick HfO_2 layer is deposited using atomic layer deposition (ALD)

(d)



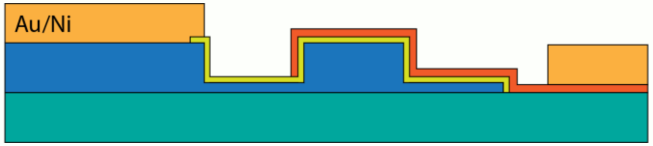
ITO gate layer is pattern by EBL on ZEP resist. 20nm of ITO is RF sputtered under O_2/Ar mix gas flow with 2% O_2, followed by liftoff process. Then the sample is treated with O_2 plasma for 5 minutes to increase the carrier concentration.

(e)



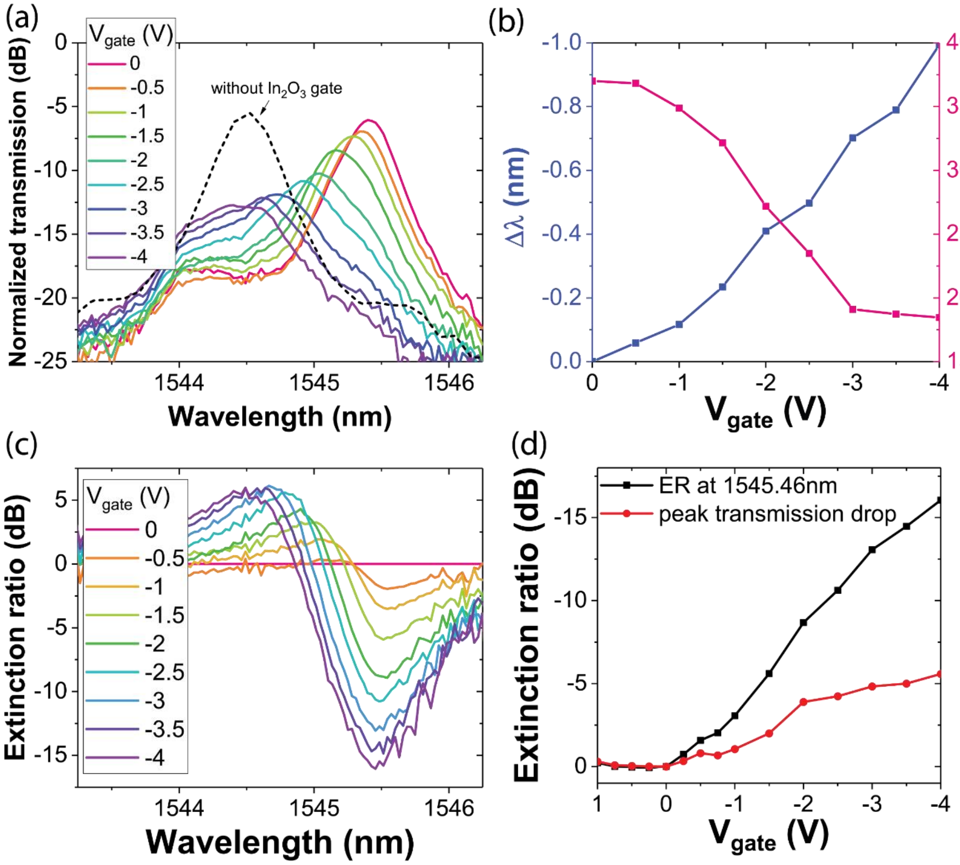
The HfO_2 at silicon contact region is removed by Buffered HF.

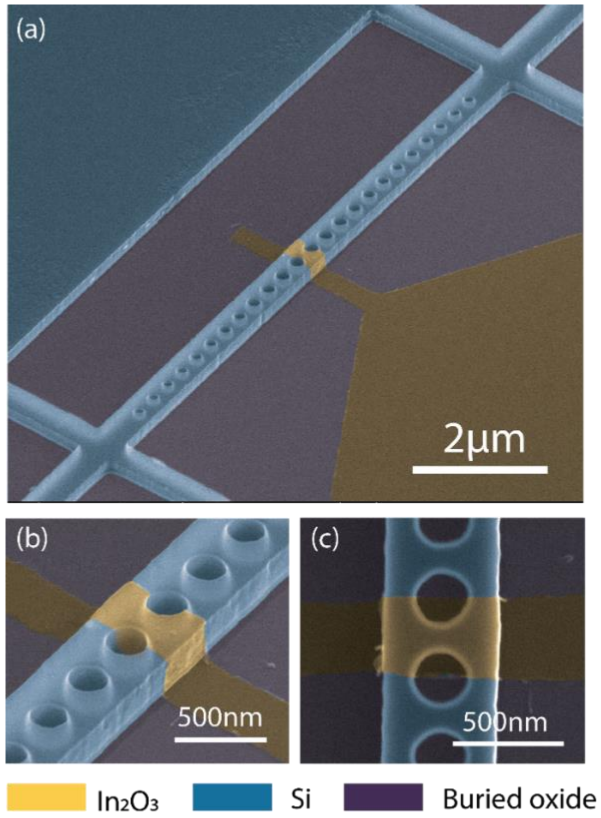
(f)



5nm Ni/ 200nm Au electrode is patterned to form ohmic contact on both p-silicon and ITO.

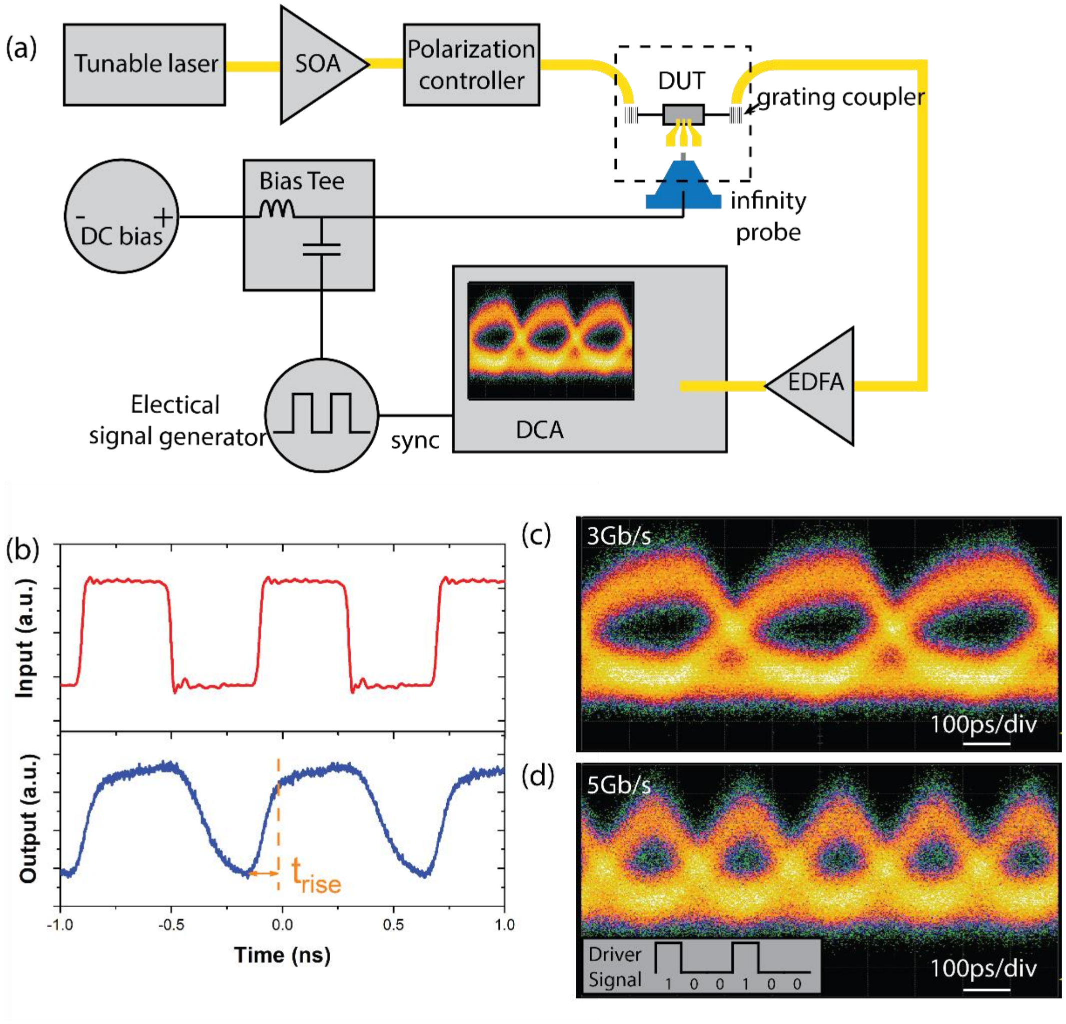
Energy-Efficient E-O Modulation: 20nm In_2O_3/10nm HfO_2/p-Si

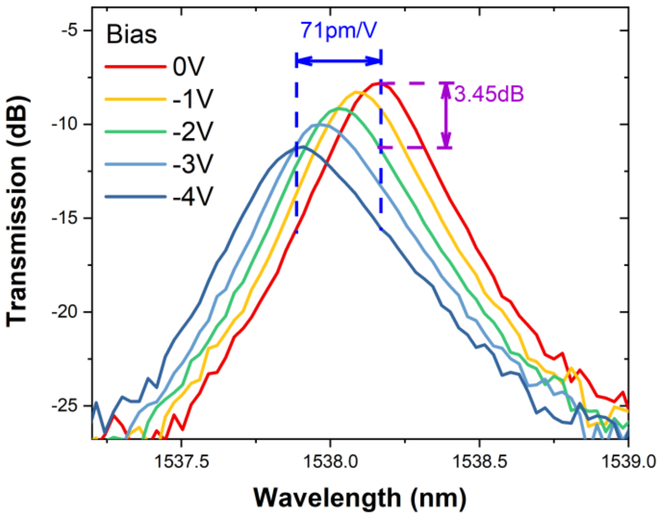




- E-O efficiency: **250pm/V**
- Modulated Q-factor: **3,700~1,800**
- Extinction ratio **@λ=1545.6nm: 16dB/4V**
- Energy efficiency: **3fJ/bit**

High-Speed E-O Modulation: 50nm slab waveguide design



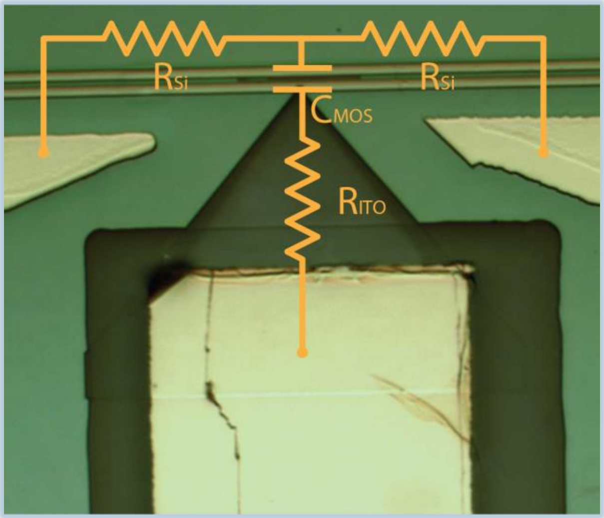


- Q factor: 5,200
- Tuning efficiency of 71pm/V
- 16fJ/bit energy efficiency

- 2.2 GHz 3-dB bandwidth
- 3Gb/s and 5Gb/s modulation rate

- Rise time (depletion): 0.135ns
- fall time (accumulation): 0.18ns

E-O Modulation Bandwidth Analysis



Current Device

- Measured speed: ~2.5 GHz
  - Rising time: 0.18 ns
- $R_{si}/2$:~1kΩ
- R_{ITO}: ~5.8 kΩ
  - ITO resistivity: $1.4 \times 10^{-3}\ \Omega\cdot\text{cm}$
- C_{MOS} (16nm HfO_2): 11.2fF

Optimization

- Increase node match p++ doping density

$R_{si}/2$: ~500 Ω

- Improve ITO conductivity
- Optimize electrical design (reduce ITO conduction path)

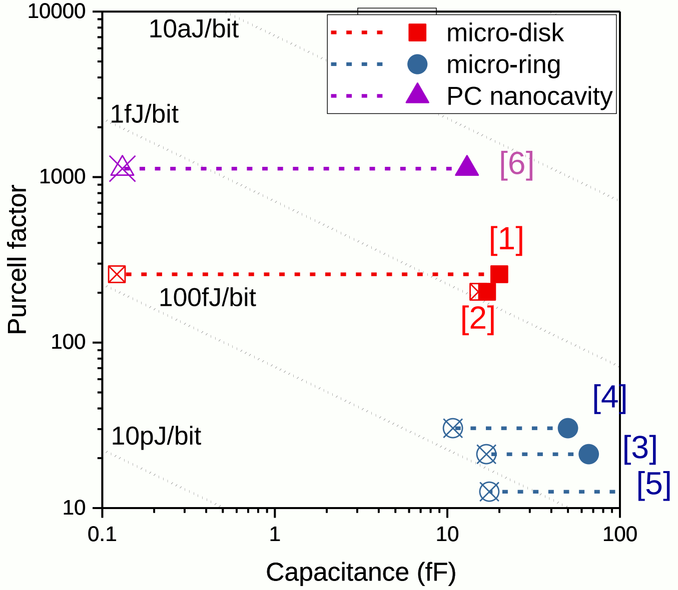
R_{ITO}: ~500 Ω

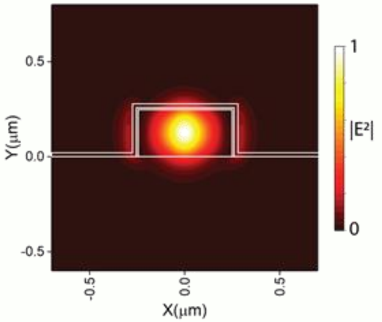
- 10nm HfO_2

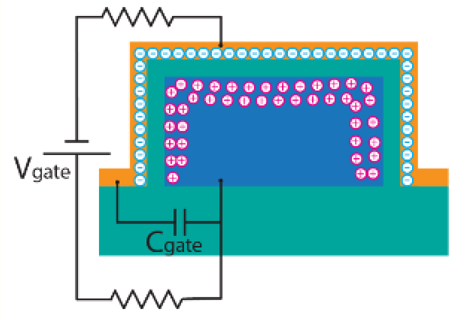
C_{MOS}: 15fF

Estimated speed: ~13 GHz

➢ How to further improve the energy efficiency to atto-joule/bit?







- Increase the overlap factor between the optical mode and the free carriers
- New cavity design with slot waveguide: 10% -> 50%
- Expected energy efficiency: 120 aJ/bit

Ref	Capacitor /resonator type	Q-factor	V_m $((\lambda/n_{Si})^3)$	F_p	C (fF)	E_{bit} (fJ/bit)	Overlapping factor α
[1]	vertical PN junction /micro-disk	15200	4.46	258.8	20	61	8%
[2]	vertical PN junction /micro-disk	18170	6.82	202.5	17	0.8	94%
[3]	lateral PN junction /micro-ring	14500	36.29	30.4	50	50	46%
[4]	Si/oxide/Si MOS /micro-ring	3500	21.20	12.5	320	180	23%
[5]	Interleaver PN junction /micro-ring	29400	105.74	21.1	66	66	51%
[6]	hybrid Si-ITO MOS /PC nanocavity	3700	0.59	476.5	13	3	**10%**

1. M. R. Watts, W. A. Zortman, D. C. Trotter, R. W. Young, and A. L. Lentine, “Vertical junction silicon microdisk modulators and switches,” *Opt. Express*, vol. 19, no. 22, p. 21989, Oct. 2011.
2. E. Timurdogan, C. M. Sorace-Agaskar, J. Sun, E. Shah Hosseini, A. Biberman, and M. R. Watts, “An ultralow power athermal silicon modulator,” *Nat. Commun.*, vol. 5, no. 1, p. 4008, Dec. 2014.
3. P. Dong *et al.*, “Low V_pp, ultralow-energy, compact, high-speed silicon electro-optic modulator,” *Opt. Express*, vol. 17, no. 25, p. 22484, Dec. 2009.
4. J. Van Campenhout *et al.*, “Low-Voltage, Low-Loss, Multi-Gb/s Silicon Micro-Ring Modulator based on a MOS Capacitor,” in *Optical Fiber Communication Conference*, 2012, p. OM2E.4.
5. X. Xiao *et al.*, “25 Gbit/s silicon microring modulator based on misalignment-tolerant interleaved PN junctions,” *Opt. Express*, vol. 20, no. 3, p. 2507, Jan. 2012.
6. 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.

Outline

- ☐ **Introduction to Transparent Conductive Oxides (TCOs)**
- ☐ **Heterogeneous Integration of TCOs with Silicon Photonics:**
  - ➢ **Ultra-compact and energy-efficient Si-TCO nanocavity modulators**
  - ➢ **Broadband Epsilon-Near-Zero Plasmonic Electro-Absorption Modulators**
- ☐ **Summary and Future Work**

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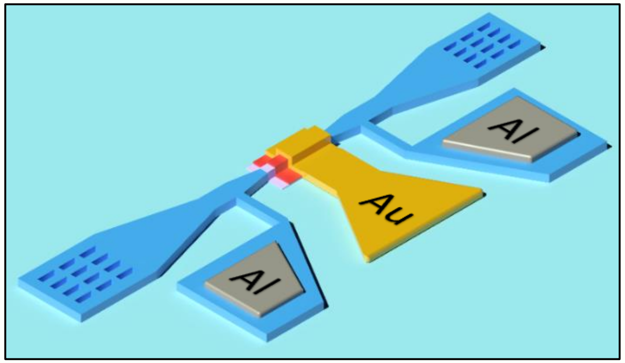
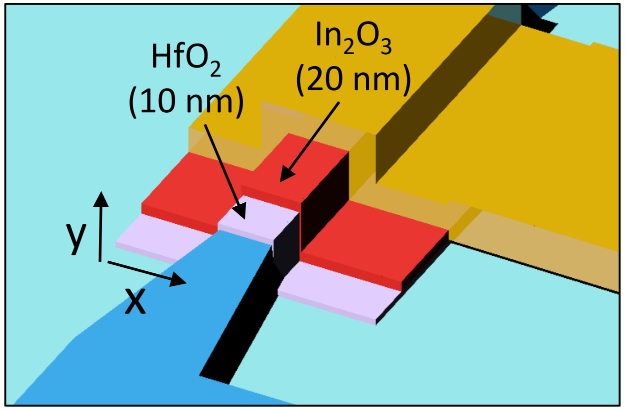
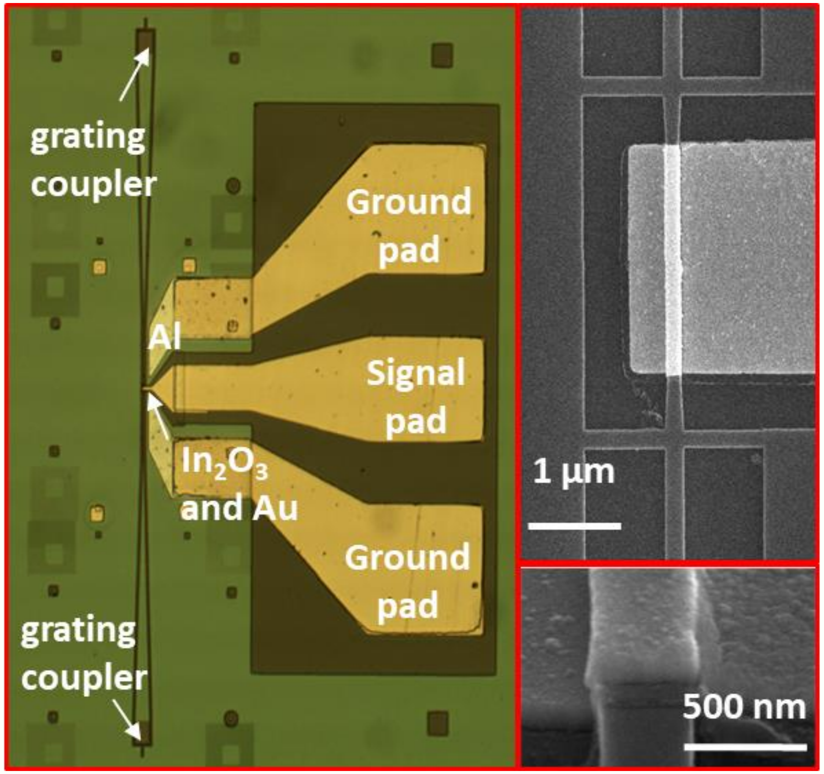
❑ Broadband Hybrid TCO-Si-Plasmonic EA Modulator

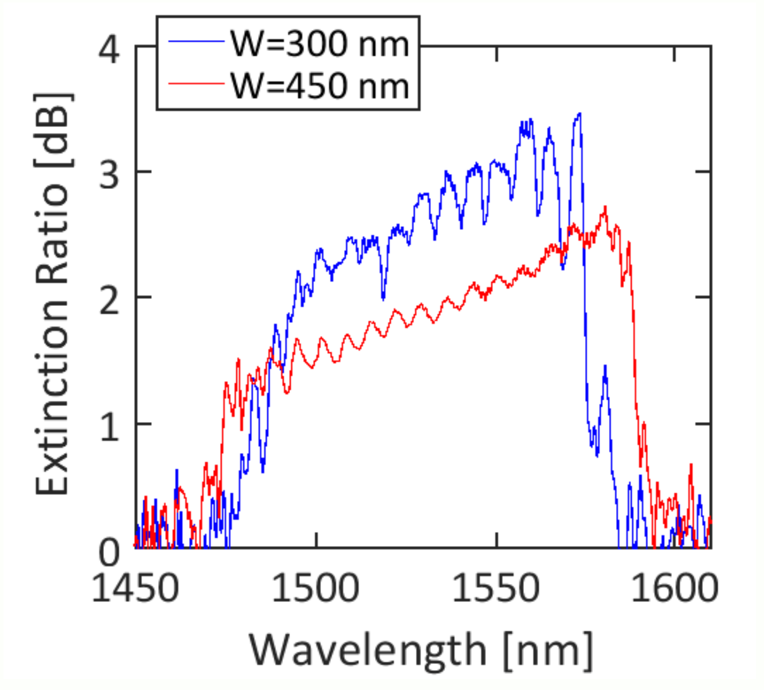




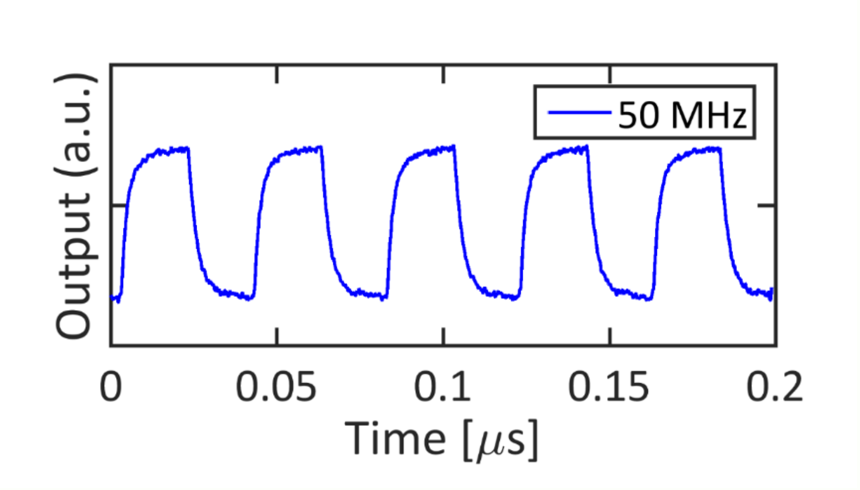


- Waveguide length = 5 µm
- TCO thickness = 20 nm
- Au thickness = 100 nm
- Waveguide width = 300 nm
  Waveguide width = 450 nm

Broadband EA absorption and AC modulation



- Uniform E-O modulation from 1470~1570nm wavelength
- Only limited by the bandwidth of the waveguide grating couplers



- Rise time (10% - 90%): 6.5 ns
- Bandwidth: 55 MHz
- Speed is limited by the large series resistance from the lightly doped silicon conduction strips
- capacitance: ~110 fF
- Estimated energy consumption ($CV^2/4$): 110fJ/bit ($2V_{pp}$)

- Gao, Q., Li, E., Zhou, B. and Wang, A.X., 2019. Hybrid silicon-conductive oxide-plasmonic electro-absorption modulator with 2-V swing voltage. Journal of Nanophotonics, 13(3), p.036005.

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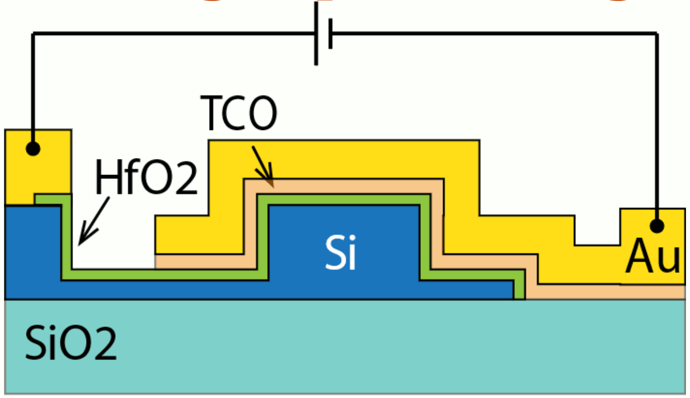
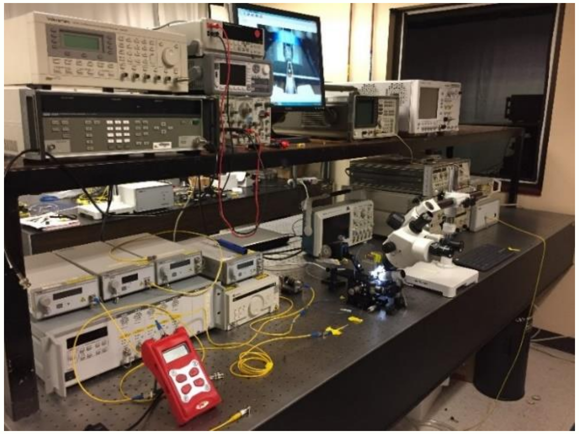
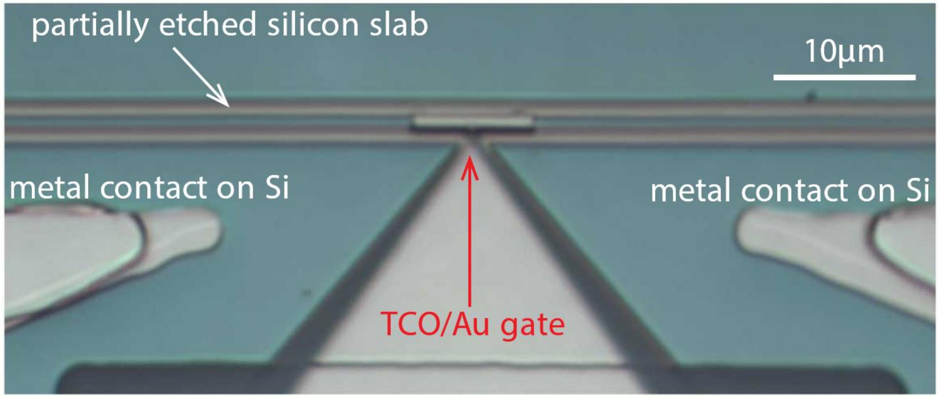
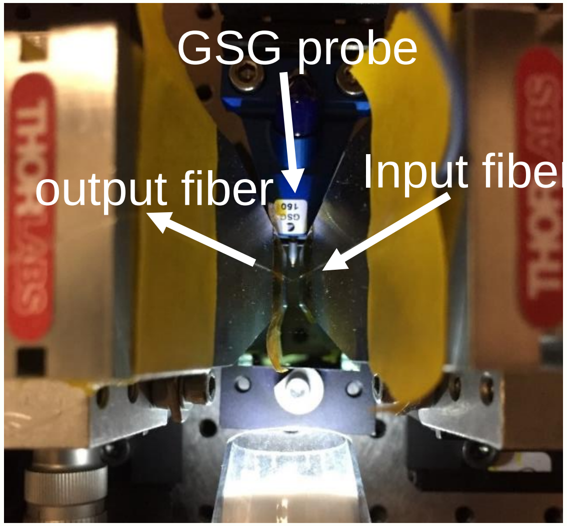
High Speed Design and Characterization







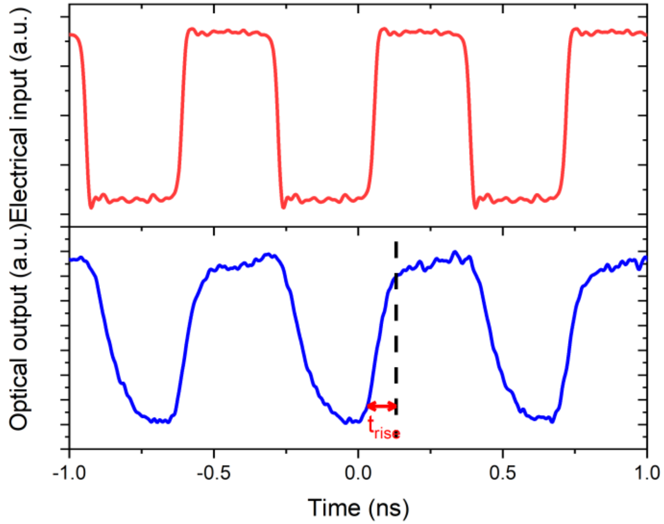


Improve the EO modulation bandwidth by the reduction of the Si WG series resistance:

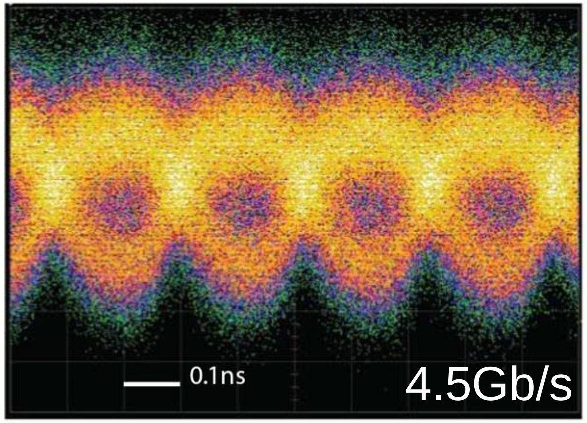
- Use partially etched Si slab instead of conduction strip
- Highly doped Si conduction path

- Zhou, B., Li, E., Bo, Y. and Wang, A., 2020. High-Speed Plasmonic-Silicon Modulator Driven by Epsilon-near-zero Conductive Oxide. *Journal of Lightwave Technology*.

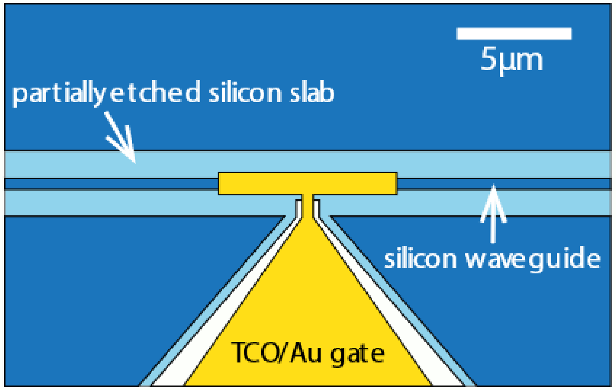
1.5GHz



- Rise time (10 % - 90 %): 0.1 ns
- Estimated bandwidth: 3.5GHz



Fabrication layout



- Capacitance: ~100fF
  - Increase EA efficiency
  - Reduce waveguide width
  - Reduce device length
- Capacitance: <50fF

- Series resistance: ~450Ω
  - Use high-µ TCO
  - Increase Si doping level
  - Move ground metal closer to the active region
- Series resistance: <100Ω

- Bandwidth: >30GHz

- Zhou, B., Li, E., Bo, Y. and Wang, A., 2020. High-Speed Plasmonic-Silicon Modulator Driven by Epsilon-near-zero Conductive Oxide. *Journal of Lightwave Technology*.

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- ❑ **Summary and Future Work**

❑ Summary

- Transparent conductive oxides have demonstrated tremendous potentials as next generation heterogeneously integrated materials on silicon photonics
- Research achievements in our group:
    - Applied quantum-moment model to analyze TCO-based MOS capacitor

  Gao, Qian, Erwen Li, and Alan X. Wang. "Comparative Analysis of Transparent Conductive Oxide Electro-Absorption Modulators", ***Optical Materials Express***, 8, no.9 (2018): 2850-2862

    - Demonstrated extremely compact ($0.02\lambda^3$) and energy-efficiency (3fJ/bit) Si-TCO nanocavity modulator
    - Implemented Si-TCO microring resonator with 270pm/V wavelength tunability with near-zero static power consumption

  Li, E., Nia, B.A., Zhou, B. and Wang, A.X., 2019. Transparent conductive oxide-gated silicon microring with extreme resonance wavelength tunability. ***Photonics Research***, 7(4), pp.473-477.

    - Demonstrated hybrid TCO-plasmonic EA modulator with 1.2 dB/µm ER and 110 fJ/bit energy efficiency covering the entire telecommunication window

  Gao, Q., Li, E., Zhou, B. and Wang, A.X., 2019. Hybrid silicon-conductive oxide-plasmonic electro-absorption modulator with 2-V swing voltage. ***Journal of Nanophotonics***, 13(3), p.036005.

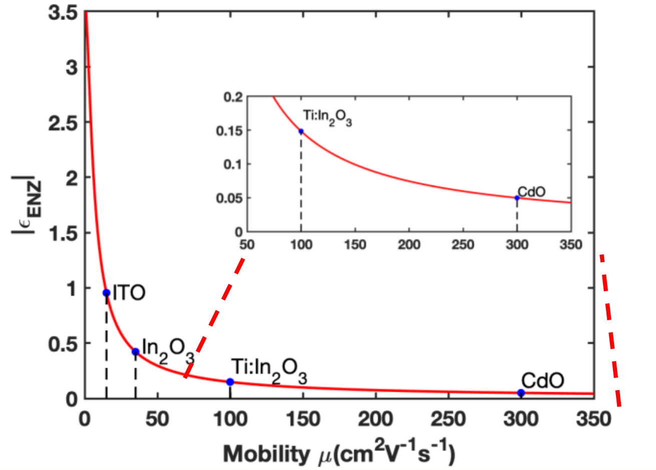
    - Demonstrated high speed TCO integrated photonic devices with 2.5GHz bandwidth and 5Gb/s modulation

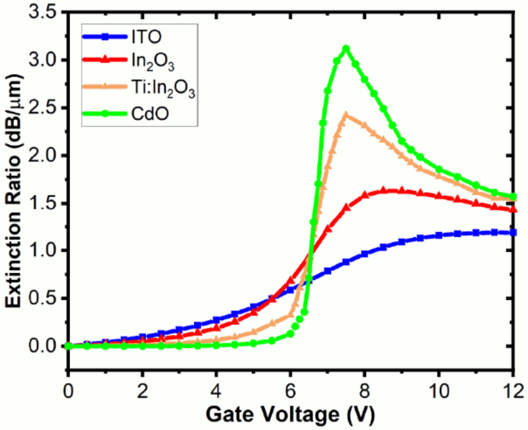
- Future Research Plan: High mobility transparent conductive oxides for silicon photonics and metasurfaces

Future Work: High Mobility TCO Materials for Integrated Photonics

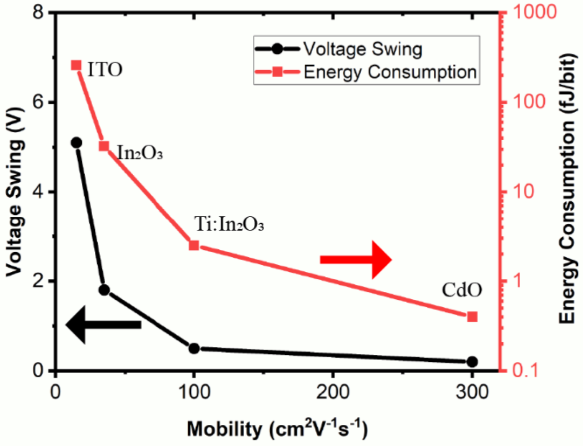
- Field enhancement: $E_{\perp,ITO} = \frac{|\varepsilon_D|}{|\varepsilon_{ITO}|} E_{\perp,D}$
- At ENZ condition, $|\varepsilon_{ENZ}| \approx \varepsilon_{2,ENZ}$
- Imaginary part of permittivity $\varepsilon_2 \propto 1/\mu$

TCO Materials	Mobility ($cm^2V^{-1}s^{-1}$)	ENZ |ε|	Effective Mass
ITO	15~30	0.96	0.33-0.35
In_2O_3	20~35	0.42	0.3-0.32
$Ti:In_2O_3$	70~100	0.15	0.27-0.31
CdO	280~300	0.05	0.22-0.24





(a)



(b)

Advantages of high-mobility TCO materials

- Reducing the driving voltage from 5V to 0.2V
- Improve the energy efficiency from 200fJ/bit to 0.5fJ/bit
- Reduce the series resistance and improve the RC-delay limited bandwidth
- Reduce the free-carrier absorption loss
- Improve the Q-factor of the optical resonators

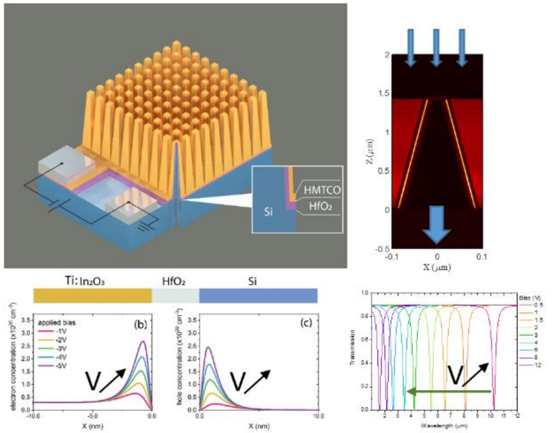
ESI: Electrically Tunable Quasioptical Filters Enabled by Inverse Design of Epsilon-Near-Zero Metasurfaces

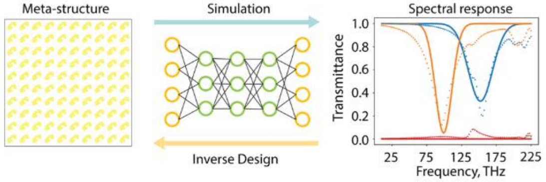
PI: Alan Wang,
Associate Prof., School of Electrical Engineering and Computer Science
Oregon State University

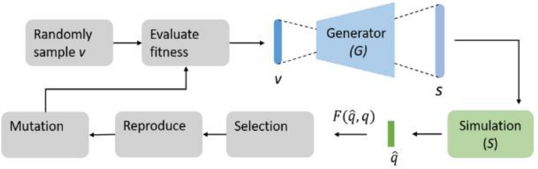
Co-PI: Wenshan Cai
Associate Prof., School of Electrical and Computer Engineering
Georgia Institute of Technology

Research Objectives

- Develop a prototype of electrically tunable, wideband (1.5~12µm wavelength), quasi-optical filters using epsilon-near-zero (ENZ) metasurfaces
- Innovation: 1) High mobility transparent conductive oxide (HMTCO) for enhanced ENZ effects; 2) Deep-learning-enabled inverse design for metasurface structures in response to customer-defined optical spectra
- Comparison to SOA: 1) Extremely large tunability from the electrically-induced ENZ effect; 2) Versatile on-demand spectral properties using artificial intelligence (AI)-based design scheme
- Projected TRL: TRL (1) to TRL (3)







Approach

- Develop deep-learning enabled frameworks for inversely designed metasurfaces
- Validate designs via fabrication and characterization of passive devices

- Sputtering deposition of high mobility Ti-doped Indium oxide ($Ti:In_2O_3$)
- Nano-fabrication of ITiO/HfO_2/p-Si (p-Ge) meta-surfaces by scalable semiconductor processes
- Spectral characterization and electric tuning of broadband spectral responses with FT-IR

Potential Impact

The proposed electrically tunable quasioptical filters will bring transformative impact to remote sensing applications:

- AI-based design to generate customer-defined spectral features for dichroics, bandpasses, notch filters, and polarizers
- Extremely large electrically tunable wavelength response in the mid-IR range from 1.5 to 12µm

- Scalable fabrication using standard silicon photonics foundry for large aperture, cost-effective filter array
- Game-changing devices for future applications such as hyperspectral imaging and infrared spectroscopy

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