Nonvolatile programmable silicon photonics based on phase-change materials

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We demonstrate nonvolatile electrically tunable silicon photonic switches based on PIN diode and graphene heater. Emerging PCMs Sb_2Se_3 and Sb_2S_3 are further explored for ultra low-loss operation from the visible to near IR.

Reconfigurable silicon photonics
- ✓ Thermo-optic / electro-optic effects
- ✓ Challenges: small tuning, volatile → large footprint, energy consumption

- Phase-change materials (**PCMs**)
  - ✓ High optical contrast ($\Delta n > 1$) between amorphous and crystalline states
  - ✓ Nonvolatile ~10 years
  - ✓ Fast (ns), low-energy (fJ/bit), reversible switching with high cyclability (10^{15}).
  - ✓ Excellent scalability

Highlights

> A low-loss, compact, nonvolatile, programmable Si photonic platform.

> high endurance with cyclability >1000

> Ultra low switching energy down to 8.7aJ/nm^3

> A low-loss phase shifter enabled by Sb_2Se_3

> Applications in microwave photonics, data centers, neural networks, quantum information processing ...

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Publication:
Zheng, J., Z. Fang, et al. *Adv. Mater.* (2020).
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Fang, Z., R. Chen, et al. *Under Review* (2021).
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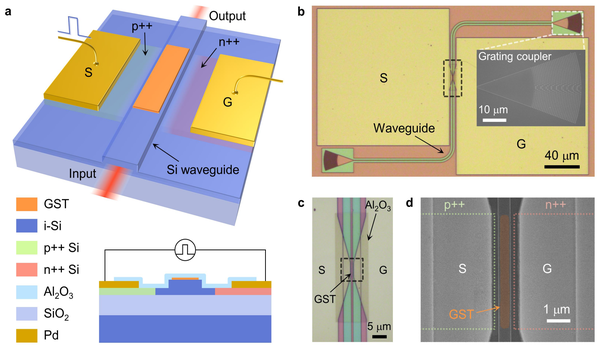
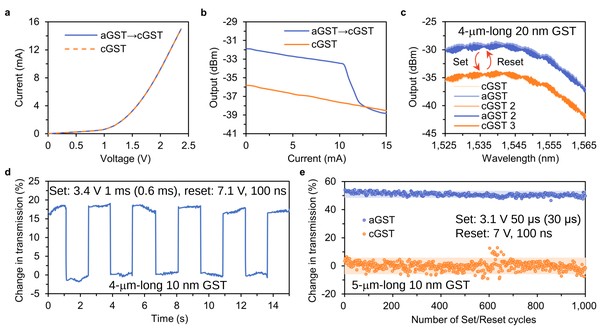
Photonic Switches based on PIN microheater

- Design and fabrication
  - ✓ 120 nm partially etched WGs
  - ✓ Heavily doped (10^{20} cm^{-3}) PIN junctions, 200 nm away from ribs
  - ✓ Near-zero extra loss is achieved after doping
  - ✓ Encapsulated by 40 nm ALD Al_2O_3

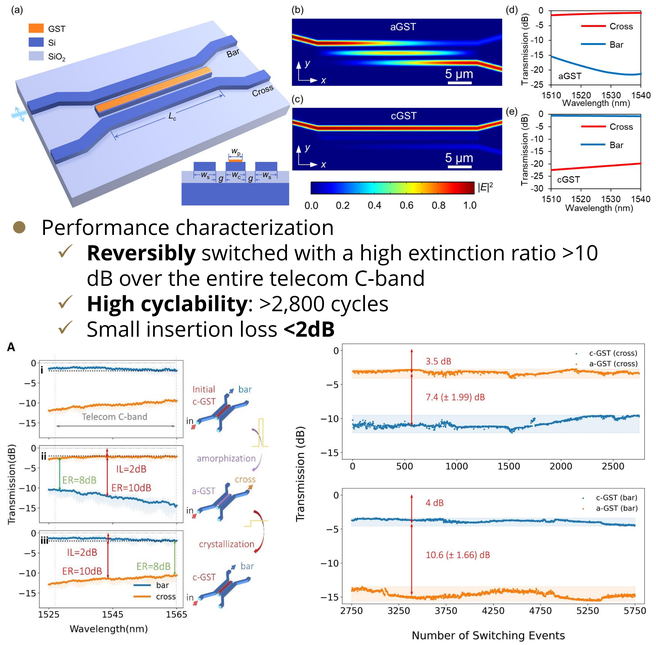


- Performance characterization
  - ✓ Rectification IV curve (GST not in the circuit)
  - ✓ **Reversibly** switched with a high extinction ratio ~5 dB over a broad bandwidth
  - ✓ **High cyclability**: >500 cycles

- Operating principle
  - ✓ A 5-μm-long switching unit with 10 nm GST
  - ✓ Reset: 7V (~110 mW), 100 ns
  - ✓ Set: 3.5 V (~10 mW), 50 μs (30 μs falling edge)



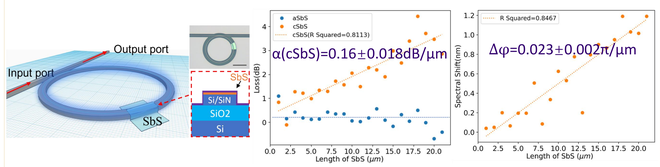
- Design of broadband 2×2 switches:
  - ✓ Middle waveguide used to circumvent the high crystalline GST loss



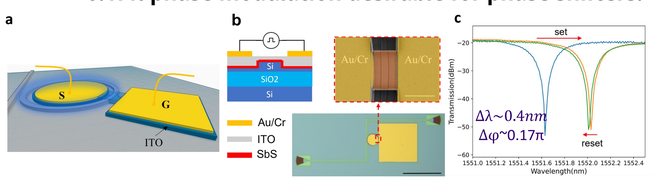
- Performance characterization
  - ✓ **Reversibly** switched with a high extinction ratio >10 dB over the entire telecom C-band
  - ✓ **High cyclability**: >2,800 cycles
  - ✓ Small insertion loss **<2dB**

Low-loss Sb_2S_3 on silicon microrings

- Wide bandgap PCM Sb_2S_3 (SbS)
  - ✓ Broadband transparency from 610nm to near IR
  - ✓ **Zero** loss in amorphous state and 0.16dB/um in crystalline state near 1550nm, , almost **50 times smaller** than that of cGST

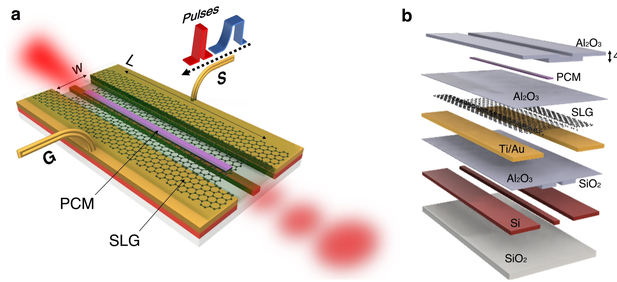


- Electrical actuation of 8 μm Sb_2S_3 by an integrated ITO heater
  - ✓ No observable resonance broadening
  - ✓ 0.48dB insertion loss
  - ✓ **0.17π phase modulation desirable for phase shifters!**

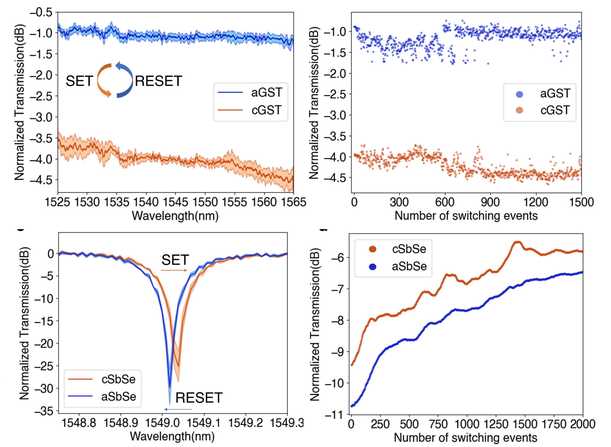


Graphene heater for ultra-low energy switching

- Design and fabrication
  - ✓ Planarized SOI waveguides
  - ✓ ALD Al_2O_3 spacer between graphene and PCM
  - ✓ Encapsulated by 40 nm ALD Al_2O_3
  - ✓ **Near Zero** loss induced by the graphene (~0.047dB/μm)
  - ✓ Compatible with dielectric platforms e.g., Si_3N_4



- Performance characterization
  - ✓ Broadband switching based on GST and phase shifter based on Sb_2Se_3
  - ✓ **Ultra-low** switching energy density per bit ~8.7aJ/nm^3
  - ✓ Energy efficiency approaching fundamental limit 1.2 aJ/nm^3
  - ✓ **High cyclability**: >1,000 cycles



Acknowledgements: This work is funded by SRC grant 2017-IN-2743, NSF-1640986, NSF-2003509 , ONR-YIP Award, NSF-EFRI-1640986, AFOSR grant FA9550-17-C-0017, and UW Royalty Research Fund. Industry interaction: Intel.