Nonvolatile programmable silicon photonics based on phase-change materials

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We demonstrate nonvolatile electrically tunable silicon photonics switches based on PIN diode and graphene heater. Emerging PCMs Sb₂Se₃ and Sb₃S₇ 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 (Δn > 1) between amorphous and crystalline states
  - Nonvolatile ~10 years
  - Fast (ns), low-energy (fJ/bit), reversible switching with high cyclability (10¹⁰)
  - Excellent scalability

Highlights
- A low-loss, compact, nonvolatile, programmable Si photonics platform.
- High endurance with cyclability > 1000
- Ultra low switching energy down to 8.7aJ/nm³
- A low-loss phase shifter enabled by Sb₃S₇
- Applications in microwave photonics, data centers, neural networks, quantum information processing ...

Photonics Switches based on PIN microheater

- Design and fabrication
  - 120 nm partially etched WGs
  - Heavily doped (10¹⁸ cm⁻³) PIN junctions, 200 nm away from ribs
  - Near-zero extra loss is achieved after doping
  - Encapsulated by 40 nm ALD Al2O3

- Performance characterization
  - Rectiﬁcation IV curve (GST not in the circuit)
  - Reversibly switched with a high extinction ratio >10 dB over a broad bandwidth
  - High cyclability: >500 cycles

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

- Design of broadband 2x2 switches:
  - Middle waveguide used to circumvent the high crystalline GST loss

Low-loss Sb₃S₇ on silicon microrings

- Wide bandgap PCM Sb₃S₇ (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 Sb₃S₇ by an integrated ITO heater
  - No observable resonance 1550nm, 0.05dB insertion loss
  - 0.17π phase modulation desirable for phase shifters!

Graphene heater for ultra-low energy switching

- Design and fabrication
  - Planarized SOI waveguides
  - ALD Al2O3 spacer between graphene and PCM
  - Encapsulated by 40 nm ALD Al2O3
  - Near Zero loss induced by the graphene (~0.047dB/um)
  - Compatible with dielectric platforms e.g., Si:Ni

- Performance characterization
  - Broadband switching based on GST and phase shifter enabled by Sb₃S₇
  - Ultra-low switching energy density per bit ~8.7aJ/nm³
  - Energy efficiency approaching fundamental limit 1.2 aJ/bit
  - High cyclability: >1,000 cycles

Acknowledgements: This work is funded by SRC grant 2017-I0-2743, NSF-1640988, NSF-2023509 , ONR-YIP Award, NSF-EBF-1640988, AFOSR grant FA9550-17-C-0277, and UW Royalty Research Fund. Industry interaction: Intel.