Optics in 2023

Multilevel Nonvolatile Programmable Units in Silicon

RESEARCHERS

Rui Chen, **Zhuoran Fang**, **Forrest Miller**, **Khushboo Kumari**, **Abhi Saxena**, **Jiajiu Zheng** and **Arka Majumdar** (arka@uw.edu), University of Washington, Seattle, WA, USA

Christopher Perez and **Kenneth E. Goodson**, Stanford University, Stanford, CA, USA

Sarah J. Geiger, The Charles Stark Draper Laboratory, Cambridge, MA, USA

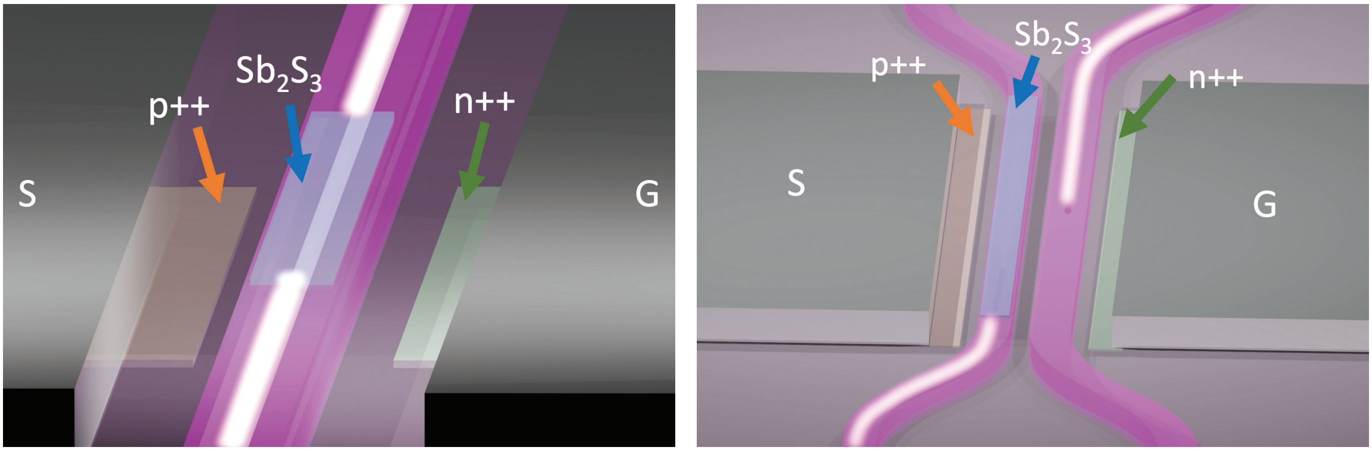
Emerging programmable photonic integrated circuits (PICs) can dramatically change the current landscape of information processing.[1] A key requirement for such programmable PICs is nonvolatility—the ability to hold the system state after programming—to achieve near-zero static energy consumption. Most tuning methods in PICs are volatile, however, which leads to a large energy waste. Moreover, they are usually quite weak, necessitating large device footprints.

Chalcogenide-based nonvolatile phase-change materials (PCMs) could mitigate these problems thanks to their strong index modulation and zero static power consumption.[2] Yet these materials often suffer from large absorptive loss, low cyclability and a lack of multilevel operation. While new, wide-bandgap PCMs have been explored to mitigate the loss, until now they have had limited endurance. An even more fundamental problem is a low number of operational levels, as the microscopic phase transition dynamics become inherently stochastic when a large area of PCM is switched.[3] Traditional modulation of pulse amplitude (or width) leads to large uncertainties in the intermediate levels, precluding its use in practice.

We recently demonstrated a wide-bandgap, PCM antimony sulfide (Sb_2S_3)-clad silicon photonic platform that simultaneously achieves losses of less than 1.0 dB, extinction ratios greater than 10 dB, high cyclability (more than 1,600 switching events) and, most importantly, 5-bit operation.[4] Our team was able to program these Sb_2S_3-based devices, including phase shifters and directional couplers, within sub-ms timescales via on-chip silicon PIN diode heaters.

One remarkable finding was that Sb_2S_3, as a PCM, could be amorphized into fine intermediate states by applying different numbers of near-identical pulses. Such stepwise programming enabled precise control of operation levels by gradually approaching the targeting transmission, beyond the reach of traditional pulse amplitude (or width) modulation. Through dynamic-feedback pulse control, we achieved 5-bit (32-level) operation, rendering 0.50 ± 0.16 dB per step.

This multilevel behavior immediately enables many practical applications. As an example, we demonstrated trimming of a balanced broadband Mach-Zehnder interferometer to correct the random phase error. We believe this work lays down the base for future energy-efficient systems that use PCMs in large-scale programmable gate arrays, with applications in on-chip optical routing and information processing.[5] OPN



Low-loss and multi-bit PIC devices enabled by Sb_2S_3 and doped silicon PIN diodes. Schematics for a low-loss phase shifter (left) and a tunable beam splitter (right).

REFERENCES

1. W. Bogaerts et al. Nature **586**, 207 (2020).
2. Z. Fang et al. IEEE J. Sel. Top. Quantum Electron. **28**, 8200317 (2022).
3. T. Tuma et al. Nat. Nanotechnol. **11**, 693 (2016).
4. R. Chen et al. Nat. Commun. **14**, 3465 (2023).
5. R. Chen et al. ACS Photon. **9**, 3181 (2022).