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Electrically-switchable foundry-processed phase change photonic devices

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ABSTRACT

Optical phase change materials (PCMs) are a unique class of materials which exhibit extraordinarily large optical property change (e.g. refractive index change > 1) when undergoing a solid-state phase transition, and they have witnessed increasing adoption in active integrated photonics and metasurface devices in recent years. Here we report integration of chalcogenide phase change materials in the Lincoln Laboratory 8-inch Si foundry process and the demonstration of electrothermally switched phase-change photonic devices building on a wafer-scale silicon-on-insulator heater platform.

Keywords: Phase change materials, reconfigurable photonics, integrated photonics, metasurfaces

1. OPTICAL PHASE CHANGE MATERIALS FOR ACTIVE PHOTONICS

Chalcogenide phase change materials[1] have been exploited for a plethora of emerging optical applications including optical switching[2–11], photonic memory[12–14], optical computing[15–18], active metamaterial/metasurface[19–30], reflective display[31–33], and thermal camouflage[34–36]. Electrical pulsing is often a preferred option for switching these PCM devices: unlike furnace annealing, it is capable of reversible switching of PCMs; and compared to laser switching, it can be readily integrated with nanophotonic devices to enable chip-scale reconfigurable optical platforms. Electrical switching via heaters made of metal[37,38], ITO[4,6,39], graphene[40,41], and doped Si[42–44] have been demonstrated.

Despite the major strides on PCM-based photonic devices and electrical switching, integration of PCMs into the standard photonics foundry process represents an essential technical milestone for PCMs. Foundry process integration not only is the practical route toward scalable manufacturing of PCM devices, but also eases access to PCM components for the entire photonics community. Notably, PCMs are readily poised for CMOS backend integration with their non-epitaxial nature and low processing temperatures, evidenced by their seamless integration in the 3D XPoint memory architecture. We foresee that achieving the milestone will significantly expedite PCMs' integration into large switching matrices and open up emerging applications such as arbitrary wavefront synthesis, energy-efficient optical switching and routing, quantum optical networks, as well as scalable neuromorphic computing.

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Here we report integration of chalcogenide phase change materials in the Lincoln Laboratory 8-inch Si foundry process and the demonstration of electrothermally switched phase-change photonic devices building on a wafer-scale silicon-on-insulator (SOI) heater platform. We also significantly advance the state-of-the-art by demonstrating integration of low-loss PCMs, $Ge_2Sb_2Se_4Te_1$ (GSST)[45,46] and Sb_2Se_3[47–49], with the foundry-processed SOI heaters.

2. DEVICE FABRICATION

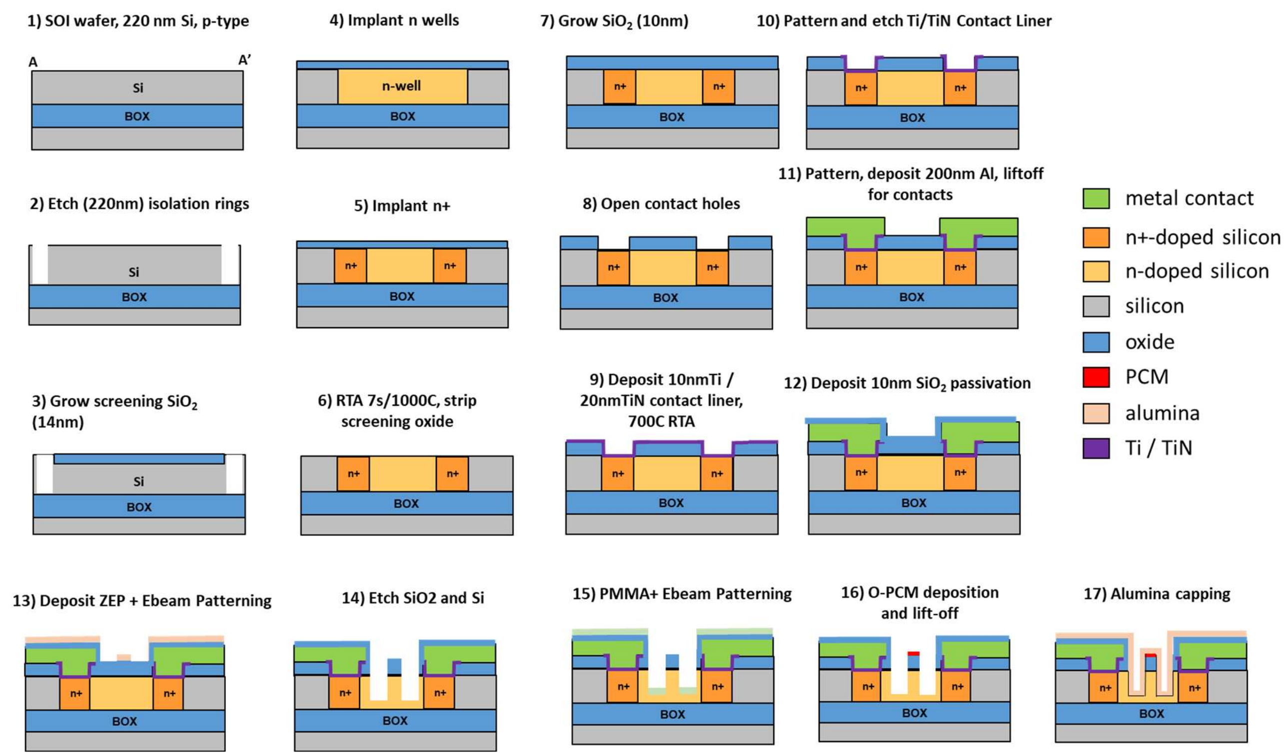

Figure 1. Schematic fabrication process flow for the PCM-based integrated photonic devices

The schematic fabrication process flow for the PCM-based integrated photonic devices is illustrated in Fig. 1. 220 nm SOI wafers were fabricated with varying n-doping concentrations using the 90-nm CMOS line in Lincoln Laboratory's 200 mm wafer foundry. The doping of silicon was carried out using ion implantation of phosphorous with varying dose and implantation energy. The n^{++} region was formed with a dose of 10^{16} cm^2 and an ion energy of 80 keV. The n region of ~4 × 10^{18} cm^{-3} was formed with a dose of 10^{14} cm^{-2} and an ion energy of 80 keV. The contact was fabricated with a Ti/TiN barrier following a metallization with aluminum and passivation with SiO_2. 500 nm-wide SOI waveguides and PCM cells were fabricated following two electron beam lithography fabrication steps on an Elionix ELS-F125 system. The waveguides were patterned using ZEP 520A positive photoresist followed by chlorine etching of half the silicon thickness. A lift-off process with polymethyl methacrylate (PMMA) resist was used to open the windows for the subsequent thermal evaporation of PCM. The film deposition was performed using thermal evaporation from PCM bulk materials following previously established protocols. Bulk starting PCMs were synthesized using a standard melt-quench technique from high-purity (99.999%) raw elements[50]. The samples were annealed in an argon environment before depositing 15 nm of Al_2O_3 by atomic layer deposition to obtain a conformal protective layer. The metasurface devices were fabricated using a similar process, with the only differences being that: 1) in step 14 in Fig. 1, the entire heater is blanket etched to a target thickness of 80 nm; and 2) the wafer backside was mechanically polished to enable metasurface devices operating in a transmissive mode. The devices were subsequently wire bonded (using 0.8 mil 99% Al-1% Si wires) and mounted onto a custom-designed PCB, which allowed for reproducible electrical contact (as compared to using contact probes).

Two low-loss PCMs were explored in this work. For metasurface applications, GSST offer enhanced index contrast. This is critical to enabling full 2π phase coverage while maintaining an ultra-thin profile amenable to electrothermal switching[51]. For reconfigurable integrated photonic applications at 1550 nm, Sb_2Se_3 was adopted to realize phase-only modulation, since both of amorphous and crystalline states of Sb_2Se_3 offers vanishingly small losses[47].

3. PHASE-ONLY WAVEGUIDE MODULATORS

The quest for efficient programmable photonic circuits requires active optical components with low insertion loss, small form factor, and low electrical power consumption[52–54]. The most common low-loss phase shifter – the key building block – employs electrically driven heaters to exploit thermo-optic effects. However, these devices require a constant power supply, suffer from thermal crosstalk, and their sizes are typically >100 µm. Here, we demonstrate a novel alternative that meets all the aforementioned requirements. We use SOI waveguides with patterned n^{++} - n - n^{++} doped-silicon microheaters to electro-thermally switch, with a single pulse, a cell of Sb_2Se_3 between its two optically distinct, nonvolatile states: amorphous and crystalline. Sb_2Se_3 is an emerging PCM at the telecommunications wavelengths while offers a $\Delta n \approx 0.77$ upon switching between states with near-zero losses. This unique set of properties allows for phase-only modulation, which sets a precedent in a growing PCM photonics field familiar with PCMs for amplitude modulation at the telecom band.

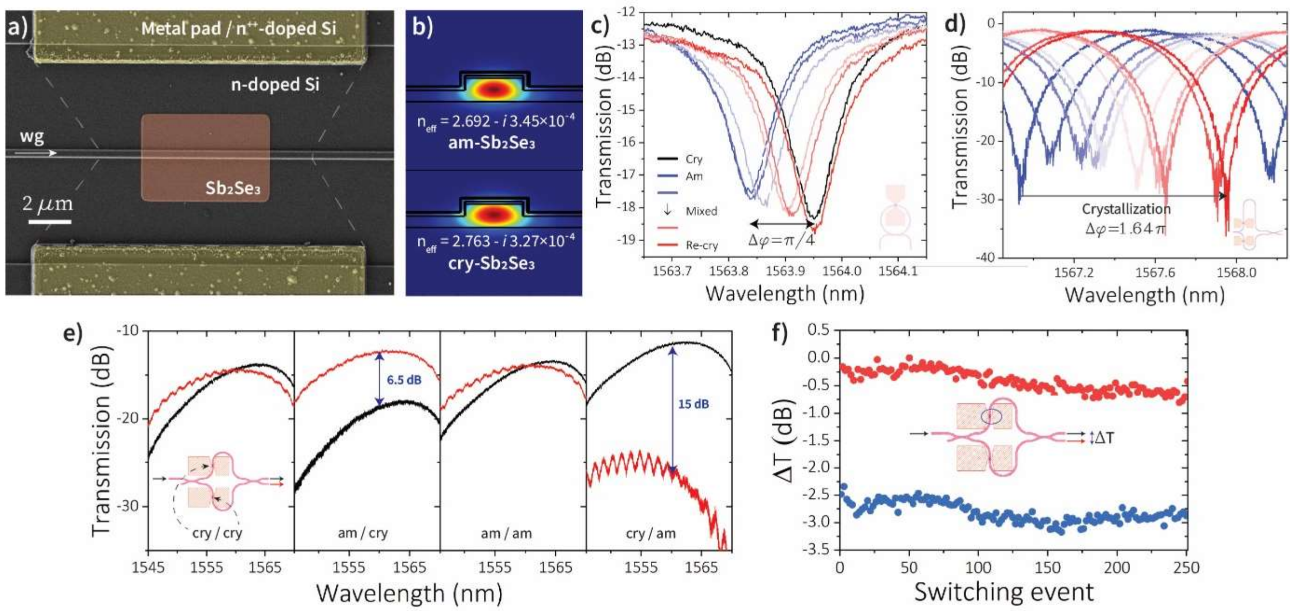

Figure 2. (a) Colored SEM image of a π/2 phase shifter – the dotted lines marked the doped region. b) Simulated optical modes for Sb_2Se_3 in both states. c) Reversible and continuous switching in a ring resonator with 3 µm-long Sb_2Se_3. d) Continuous tuning of an unbalanced MZI. e) MZI switch with the four end-point states of the two 6 µm-long Sb_2Se_3 cells. f) Reversible switching of the top phase shifter in an MZI switch with a total of 125 complete cycles shown.

We used the device shown in Fig. 2a. The heater is built using phosphorus implantation with concentrations $n \sim 4 \times 10^{18}$ cm^{-3} and $n^{++} \sim 10^{20}$ cm^{-3}. We patterned a 500 nm waveguide on half-etched 220 nm SOI and thermally evaporated and annealed Sb_2Se_3 with 30 nm thickness. The length of Sb_2Se_3 is defined based on the target phase shift. From mode simulations (Fig. 2b), we found a $\Delta n_{eff} \approx 0.071$, which leads to a phase shift of 0.09 π/µm. The non-negligible extinction coefficient result from the doped-silicon losses, which theoretically leads to 0.011 dB/µm. Experimentally, the total insertion loss was 0.03 dB/µm due to other effects such as scattering. To reversibly switch, we used 3.2 V × 100 µs or 3.2 V × 1 ms pulses to either crystallize partially or fully, and single 16 V × 1 µs or 21 V × 400 ns to amorphize. We demonstrate reversible and continuous (multi-state) switching of a 3 µm-long Sb_2Se_3 in Fig. 2c, which displays a phase shift of π/4, in excellent agreement with the theoretical value. We show a 1.64π phase shift in an MZI in Fig. 2d. We further demonstrated a 2 × 2 MZI switch – key in programmable architectures – in which light can be switched between two outputs by applying π/2 phase shift in both arms. We achieve this by using an ultra-compact 10 µm-long heater with 6 µm-long Sb_2Se_3 (Fig. 2e). Lastly, we show device cyclability over 250 switching events in Fig. 2f. Our results pave the way to zero static power consumption programmable photonics for applications in computing, quantum, telecom, and others.

4. ELECTRICALLY SWITCHABLE PCM METASURFACES

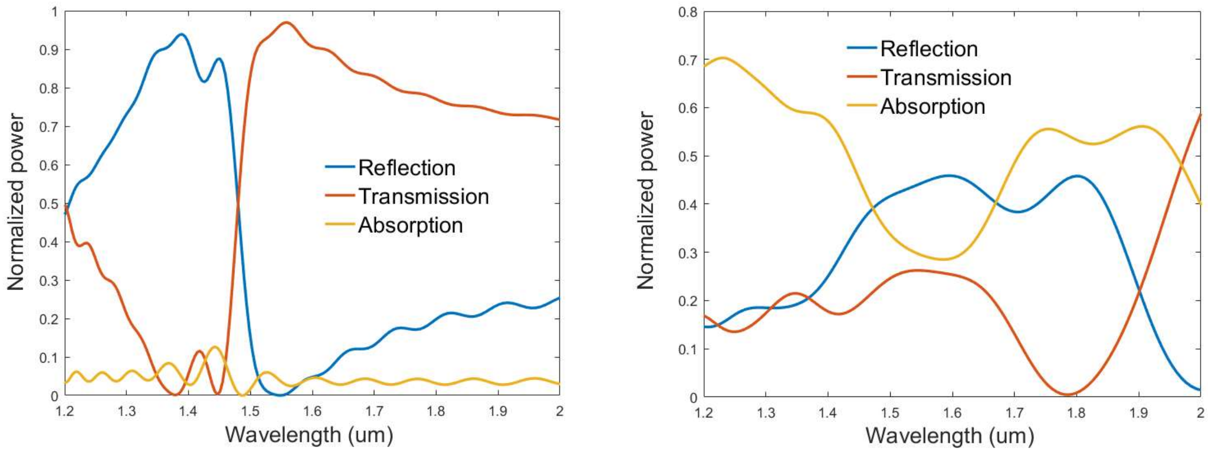

Figure 3. Simulated optical spectra of the PCM metasurface in (left) amorphous and (right) crystalline states

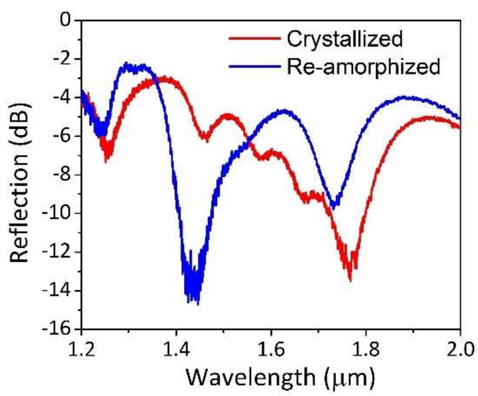

Figure 4. Measured reflectance spectra of the PCM metasurface

The metasurface consists of a GSST pillar array with a lateral size of 360 nm and a 780 nm square pitch size. Unlike devices reported by others where the PCM layer is limited to an ultrathin (< 100 nm) form factor to facilitate rapid quenching during re-amorphization and hence switching reversibility, the GSST layer in our device has a total thickness of 230 nm. Our previous work has proved that GSST exhibits improved amorphous phase stability compared to the classical GeSbTe alloys, which enables a much larger PCM thickness while maintaining fully reversible switching capability. The increased PCM volume affords substantially enhanced light confinement and interaction with the PCM layer. The simulated optical spectra of the metasurface is presented in Fig. 3. The metasurface is designed to exhibit large optical contrasts at the telecom wave band. A Thermo Fisher FTIR6700 Fourier transform infrared spectrometer with an attached microscope was used to obtain the reflectance spectra of the devices. The reflectance spectra were calibrated using a standard gold mirror. The corresponding measured reflectance spectra upon switching can be seen in Fig. 4. The change of 10 dB at 1430 nm shows the potential of such device as an active filter or amplitude modulator if intermediate crystallization states can be reliably reached. A Renishaw Invia Reflex micro-Raman system was used for collecting Raman spectra on the devices to validate that the observed optical contrast results from phase transformation of the PCM. The Raman spectra in Fig. 5 confirms reversible electrothermal switching between amorphous and crystalline states over multiple cycles.

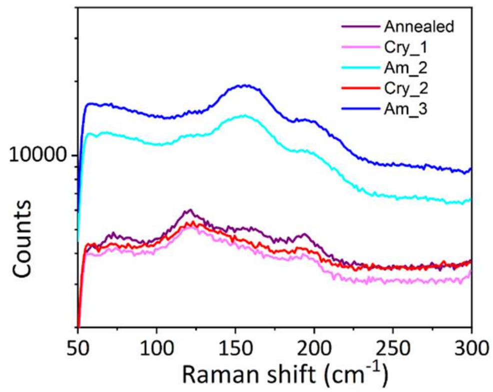

Figure 5. Measured Raman spectra of the PCM metasurface confirming reversible switching

5. SUMMARY

In the scope of this work, we demonstrated electrothermally switched PCM metasurface and waveguide devices, both fabricated leveraging standard Si photonic foundry processes. These results enable a new path for scalable manufacturing of PCM photonic devices and electrically driven infrared light control for both free-space and integrated photonics applications, such as tunable imaging optics, spatial light modulators, tunable spectral filters, subwavelength phased arrays, beam steering, and dynamic holography.

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