Programmable Integrated Photonics with Phase-Change Materials

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Abstract. Phase-change materials (PCMs) have emerged as a promising platform for nonvolatile light modulation. The reversible switching between their stable amorphous and crystalline states leads to an impressive refractive index contrast (*Δn, Δk ~ 1–3*). Integrated photonics has benefited from the progress of PCMs such as Sb_2Se_3 and $Ge_2Sb_2Te_5$ for ultra-compact phase and amplitude modulators using all-optical and electro-thermal approaches. These devices allow small-form-factor silicon photonics with zero-static power yet reconfigurability, which are crucial properties in applications such as in-memory computing, optical synapses, switches, trimming, etc. Here, we review the various switching mechanisms and integration methods of PCMs in integrated photonic platforms.

Keywords: phase change materials · photonic integrated circuits · photonic materials

1 PCM Cells Embedded on Cladding

Due to the contrast between the optical properties of stable crystalline and amorphous phases, PCMs are considered ideal candidates for nonvolatile modulation in integrated photonics. One of the most common integration methods of PCMs has been to deposit them directly onto the waveguide and switch either via an evanescent coupling from within the waveguide or by a waveguide-integrated microheater (e.g. doped silicon, graphene, etc.). Chalcogenide-based PCMs like tellurides (e.g. $Ge_2Sb_2Te_5$), selenides (e.g. Sb_2Se_3), and sulfides (e.g. Sb_2S_3) have all been tested in such a platform, as they can switch between two physical states in response to appropriate heat stimuli: annealing (crystallization) or melt-quenching processes (amorphization) [1]. They can be switched on a sub-microsecond timescale with high reproducibility, enabling ultrafast operation over 10^6 switching cycles [1]. In addition, at normal operating temperatures both states of the PCMs are highly stable for years, which is a key requirement for a truly non-volatile response. PCMs like $Ge_2Sb_2Te_5$ (GST) show a significant change in refractive index in the near-infrared wavelength regime, the spectral region of choice for telecommunication applications. Because of its data retention capabilities [2] and high state discrimination [3] down to nanoscale cell sizes, which enables dense packaging and low-power memory switching, researchers have demonstrated fast and repeatable all-optical, multi-level, multi-bit, non-volatile memory operations, with wavelength division multiplexed

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(WDM) access on a chip at telecommunication wavelengths compatible with on-chip optical interconnects. These all-optical memories with GST cell placed directly on top of the nanophotonic waveguide are not restricted in size by the diffraction limit of the input light and can hence be miniaturized to nanoscale dimensions. Figure 1(A) shows how a PCM on top of a waveguide can be programmed to set and reset states and subsequently read out as a change in transmission of the waveguide [4]. The use of microheaters has gained more space in PCM integrated photonics since it enables a scalable platform to integrate many PCM cells and accessing them individually. Moreover, the all-optical evanescent method shown in Fig. 1(A) only works with absorptive PCMs, such as GST. For low- or zero-loss PCMs in the telecommunication bands, such as Sb_2Se_3, microheaters are the only option. Hence, the field has seen a growing number of proposals for microheater materials and geometries aiming to build phase shifters based on low-loss PCMs and amplitude modulation, mainly for computing applications, based on lossy PCMs (e.g. GST) [1].

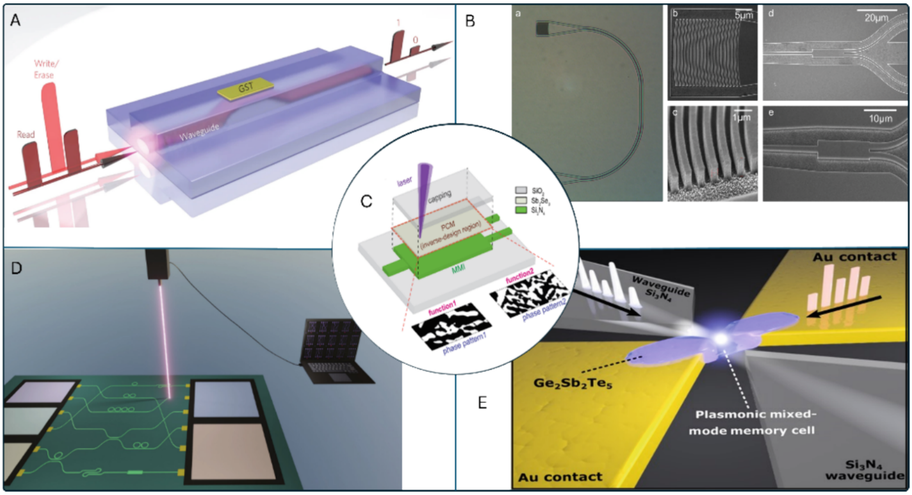

Fig. 1. (A) Illustration of a nanophotonic waveguide with GST programmable cell placed on top, (B) Optical and SEM images of PIC components on GSST platform, (C) Illustration of transferring inverse-designed phase pattern to Sb_2Se_3 thin-film on top of a multi-functional photonic MMI using DLW technique, (D) Illustration of freeform writing and rewriting PICs on Sb_2Se_3 thin film using simple, fast-turnaround, and low-cost approach, (E) Illustration of a device concept where light is delivered to the nanoscale device via a photonic waveguide, while the Au contacts serve as both device electrodes and plasmonic nanogap to focus incoming light to change the phase of GST cell.