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Perspective

Non-volatile phase-change materials for programmable photonics

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Programmability is an essential feature in modern-day photonic systems, and is crucial to enable technologies from next-generation data centers [1] to quantum information processing [2]. Such programmability is generally achieved by traditional modulation methods, such as thermo-optic (TO) effect, free-carrier dispersion, electro-optic (EO) effect, and mechanical tuning. These physical effects are, however, more suitable for modulating light, but not ideal for programmability. This is because modulators are optimized for high-speed and low-power operation, but programmability only requires infrequent switching. Although TO effect and micro-electro-mechanical-systems (MEMS) can offer slow but large extinction ratio (>60 dB) tuning, their large static power consumption (>10 mW) and high driving voltage (>20 V) are prohibitive to future photonic systems. For programmable photonic applications with infrequent switching, zero static energy holding of the programmed states is more important than the power and latency of individual switching event. Hence, a "set-and-forget" reconfiguration will be highly desirable for applications such as routing photons in photonic integrated circuits (PICs), setting phase masks in spatial light modulators (SLMs), or trimming photonic resonators to the same resonance frequency. Chalcogenide-based phase-change materials (PCMs), exemplified by $Ge_2Sb_2Te_5$ (GST), present an ideal solution to the above scenarios thanks to their reversible and bistable phase transition, multilevel operation, and large refractive index contrast ($\Delta n \geq 1$). They can also be programmed in a fast time scale (μs to ns), and moderate switching energy (pJ to fJ) [3–5]. Despite recent progress in PCM-based photonics, several outstanding challenges remain. For example, how to extend the operation range to the visible wavelengths where the material loss becomes critical? How to increase the endurance of the PCM-based devices for practical use, ideally > 10^9 cycles? How to achieve a deterministic multilevel operation? How to attain 2π phase shift using PCMs? How to fabricate PCM-based photonic devices via foundry processes? How to control a large 2D array of phase-change pixels/switches individually, see the Supplementary materials S4? In this perspective, we aim to answer these questions by briefly discussing the advances in the field, the limitations, followed by potential solutions to address these limitations. In Table S1 (online), we compare the key performance metrics of the state-of-the-art in PCM-based programmable photonics. For an in-depth background on PCM photonics, we refer the readers to other review papers [3–5].

Extending the operation range to the visible. In the early days, PCMs were widely used in rewritable compact disks to store data. They were typically designed to be highly absorptive in the visible wavelength so that they can be easily switched by laser pulses. Later they found applications in electronic memory, where data is stored in the high and low resistance of the memory cell, rendering the optical absorption of the materials entirely irrelevant. It is only recently, with the advent of PCM-integrated photonics [4,5] has the loss become critical. The proximity of the PCMs to the optical mode in a waveguide can lead to a significant loss even for a very short PCM segment, e.g., crystalline GST typically gives > 1 dB/μm insertion loss on a waveguide. Apart from PCM, we also need to pay attention to the loss incurred by the microheaters needed to actuate the phase transition electrically. Fig. 1 shows the transparency windows of six different PCMs (in their amorphous state) and microheaters, along with the potential applications in different wavelength ranges. These six PCMs represent the most widely reported PCMs in the field of photonics due to their lower optical losses and reversible switching over many cycles. To simplify the discussion, we only plot the transparency window in the wider bandgap amorphous state because the PCMs need to be transparent in at least one state to be useful. PCMs that have lower loss in the amorphous state but absorptive in the crystalline state (e.g., GeTe, GST, $Ge_2Sb_2Se_4Te_1$ (GSST), and $Ge_2Sb_2Se_5$ (GSSe) in the near IR) can be used for amplitude modulation such as photonic memory [6]. PCMs transparent in both amorphous and crystalline states (e.g., Sb_2Se_3 and Sb_2S_3 in the near IR) are ideal for phase-only modulation [7,8]. It can be seen from Fig. 1 that as new PCMs are discovered, there is a general trend of increasing the bandgap of the PCMs to achieve lower losses. The bandgap of the GST can be widened by gradually substituting Tellurium with Selenium, creating GSST and GSSe [9]. Removing the Germanium further widens the bandgap, yielding Sb_2Se_3 which is transparent in both amorphous and crystalline states in the near IR wavelengths [10]. Finally, the bandgap can be further increased by replacing the Selenium with the more electron affinitive Sulfur, which leads to Sb_2S_3 – the only PCM that has a transparency window in the visible spectrum [11]. Looking at our material toolbox, we now have a wide range of options for a PCM that can work in the near to mid-IR regime. Meanwhile, doped silicon also makes a reliable, scalable,

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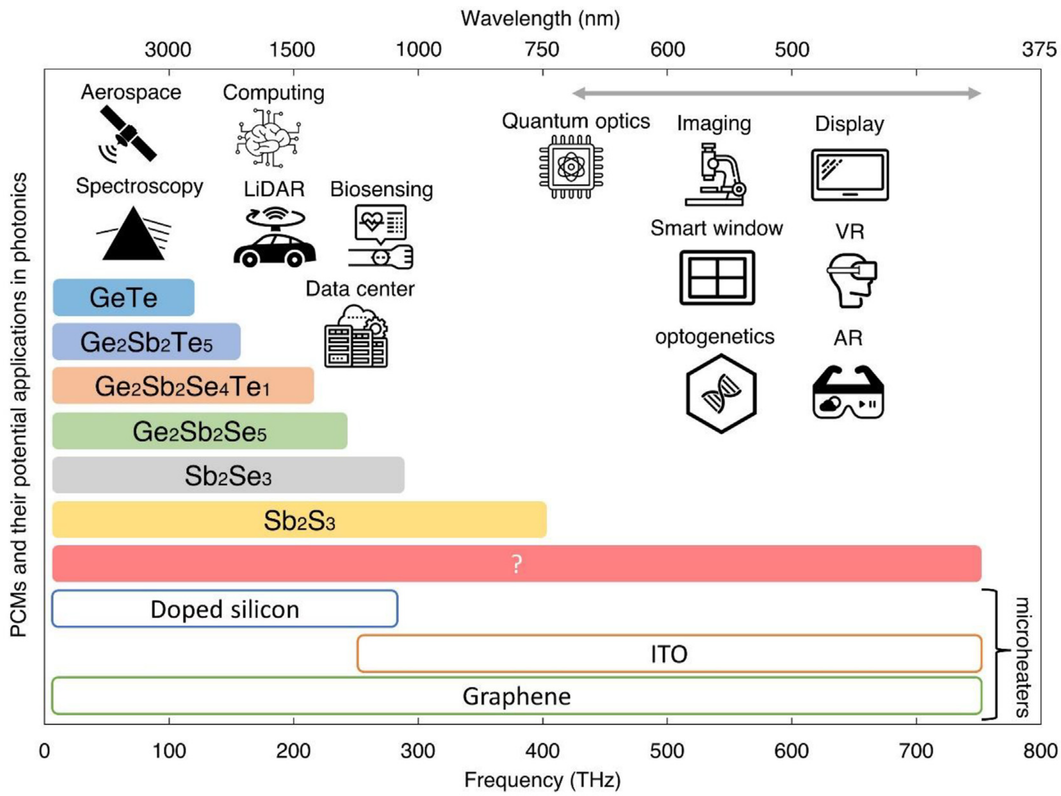

Fig. 1. (Color online) Transparency windows of PCMs and microheaters from visible to mid-IR wavelengths and their potential applications in photonics.

and transparent microheater for the electrical control of PCMs in this range [12]. Indeed, proof-of-concept PCM-integrated photonic devices have been demonstrated for relevant applications in this regime, including optical computing and optical interconnects. However, the choices become scarce when the wavelength extends to the visible ($\lambda \sim$ 400–700 nm), where Sb_2S_3 is the only candidate, whose transparency window only partially covers the visible range ($\sim$600–700 nm). A transparent PCM in the entire visible range can unlock several emerging applications from augmented/virtual reality (AR/VR) display to quantum photonics. For example, AR displays require selected pixels to be dimmed so that the displayed image is not overpowered by the ambient light (https://www.magicleap.com/webinar-four-optics-breakthroughs-to-power-enterprise-ar). Such "local dimming" functionality requires reversible sub-*ms* switching between the bistable transparent and opaque states. A PCM transparent (absorptive) in the amorphous (crystalline) state in the visible range will be ideal for achieving unpolarized dimming, compared to the current polarized dimming based on liquid crystals which blocks > 50% of the ambient light in the transparent state. Secondly, photonic quantum information technologies require single photons to be routed in a PIC with low loss and energy consumption. Currently, the quantum PIC is generally tuned by thermo-optic phase shifters which are prohibitive in terms of power consumption. A PCM transparent in both states in the visible can provide non-volatile and energy-efficient routing of solid-state single photon emitters (generally ranging from $\sim$ 400–900 nm) [13]. To push the PCMs' bandgap wider, materials with stronger covalent bond formers, such as Oxygen, may have to replace Sulfur to create semiconductor or metal oxides that have bandgap in the ultra-violet range [14]. It is also worth investigating when the phase-change properties of the material cease to exist as the material bandgap keeps increasing, which can be modelled using density functional theory and molecular dynamics simulations. In terms of electrical control, both graphene and Indium Tin Oxide (ITO) are transparent microheaters in this range (though ITO has lower absorption than graphene). In particular, graphene has recently been shown to be a very robust and energy-efficient microheater thanks to their atomically thin nature [7].

Increasing the device endurance. Commercialization of PCM-based photonic devices depends heavily on their endurance, i.e., how many cycles the device can be switched reversibly before failure. Previous commercialized PCM technologies, such as electronic memory, exhibit a typical endurance of > 1 billion cycles [15]. It seems natural that PCM-based photonic devices should also target an endurance of at least 1 billion cycles. In practice, this is a challenging proposition for photonic devices because, depending on the applications, the switching volume of the PCMs is around five to six orders of magnitude larger than in electronic memory ($\sim$100 μm^2 vs. $\sim$100 nm^2, assuming the same thickness). Such a large switching volume renders many failure mechanisms, which play relatively minor roles in electronic memory, dominant in photonics. These include surface oxidation, drastic volume change, elemental segregation, and dewetting in the molten state [16]. For these reasons, the best record in electrical switching so far has been $\sim$5000 cycles in PIC [17]. Hence, instead of focusing solely on the formidable challenge of increasing the cyclability from 10^3 to 10^9, we ask: how many cycles do we actually need for relevant applications? First, consider the scenario where a PCM-based non-volatile phase shifter is used to correct the phase error in a Mach-Zehnder interferometer (MZI) or trim a microring's resonance wavelength [8]. Once these calibrations are completed after the fabrication, which can be accomplished within a few switching events, any further adjustments will hardly be required since an on-chip laser normally has a fixed emitting wavelength. In this case, an endurance of 1000 cycles will be more than enough, which has already been reported [7,17]. Another relevant application is in-memory optical computing, where PCMs have shown promising results for expressing weights [5]. If used purely for inference, a low endurance may be sufficient. However, for general purpose computing, the weights need to be constantly updated, and very high endurance comparable to the phase-change electronic memory will likely to be necessary for any practical use.

In addition to PICs, PCMs can also be used in tunable meta-optics [3]. For example, a non-volatile spatial light modulator (SLM) will be highly desirable in the scenario where a stable phase mask is required. Liquid-crystal-based SLMs commonly suffer from phase jitter and pixel crosstalk, which can be circumvented by controlling the optical phase with PCMs, as no bias is required to maintain the optical phase distribution. Consider static usage, such as laser beam shaping, where the phase mask does not constantly change and assume $\sim$10 reconfigurations per day, an endurance of 10^4 cycles will lead to a lifetime of almost 3 years. However, certain applications of SLMs, such as displays, require constant refreshing of the pixels (>60 Hz), so high endurance (>10^{10}) may be needed to operate up to 5 years. Similarly, recent works have demonstrated non-volatile beam steering using PCMs in phase-gradient metasurfaces [18], with potential application in ranging. Ranging requires constant scanning of the laser beam; hence very high endurance (>10^9) will be necessary. Finally, we would like to emphasize that traditional switching metrics, like switching speed, may not be appropriate for evaluating PCM-based photonic devices. These metrics are relevant only when a device is constantly being turned on and off, for example a modulator. In such cases, a switch being turned on and off in nano-second time scale, will last only for 10 s, even with an endurance of 10^{10}. Hence, improving PCM switching speed has little or no significance in practical applications.

There are several potential strategies to reach endurance greater than a billion cycles. Two important lessons we can learn from the electronic memory to improve the endurance is to reduce switching volume and use backup devices. Instead of switching a large area of PCMs (>100 μm^2), we can pattern the PCMs into discrete subwavelength patches to minimize dewetting and stresses from the drastic volume change. Secondly, backup switches can be used to improve the overall endurance of a group of switches. Once a switch in the group failed, it will be automatically connected to a working one. Such scheme is particularly attractive for PICs but has issues in free space because a wavefront will always interact with all the pixels, including the failed ones.

Deterministic multilevel operation. The crystallization of PCMs is based on nucleation and growth, which are intrinsically stochastic processes [19]. Partial phase transition will inevitably lead to variation in the optical state as the volume and location of the switched material are slightly different each time. There has been tremendous progress in pushing the number of attainable levels in PCM-based photonics, reaching up to 5-bit operation via optical switching [20] and, more recently, in electrical switching [8] using low-loss PCMs Sb_2S_3, see Table S1 (online). Conventionally, different amplitudes or pulse durations are used to tune the degree of partial phase transition to achieve multi-levels. Recently, it was shown that multilevel operation could be obtained in Sb_2S_3 by exciting it with multiple electrical pulses with the same duration and amplitude [8], leading to an additional degree of freedom in fine tuning the optical states. In this way, the optical states of the devices can be controlled simply by the number of excitation pulses without the need to change the pulse shape. Despite the progress in increasing the optical levels, there has not been an effective solution for the optical state variation caused by the non-deterministic phase transition. For many applications, such as SLMs and optical computing, precise control of the optical levels is necessary. One potential solution is to use many PCM cells and exploit the complete phase transition of each cell. Complete phase transition is found to be highly deterministic as the entire volume of materials is switched. For example, one requires $N-1$ discrete cells of PCMs on a waveguide to achieve N number of transmission levels. The contrast between the levels can be controlled by the size of the PCM cells. However, such a scheme only works for integrated photonics where light is tightly confined in the waveguide, and the optical mode has a limited spatial extent. In addition, N levels will also require $N-1$ control signals, leading to complicated electrical routing as N becomes large. In the free space, spatial light modulation requires the light to interact with multiple pixels simultaneously, which collectively generates a phase mask. The light interacting with any individual pixel will only experience a binary switching of phase or amplitude if there is only a complete phase transition. One solution is to stack multiple layers of PCMs along the optical axis, where each layer is individually controlled by microheaters. However, this method will require complicated electrical wiring and suffer from significant optical losses as light passes through layers of PCMs and microheaters. A simple solution for the multilevel control of a 2D array of phase-change pixels will be a promising future research direction.

2π phase control. In integrated photonics, a maximum of π phase shift is generally enough for modulating MZIs or microrings. Thanks to the large effective index change of PCM-silicon hybrid waveguides, the typical L_π can be as short as a few tens of microns [8,21]. In free space, however, full 2π phase control is necessary for spatial light modulation. In liquid–crystal-based SLMs, 2π phase shift is achieved by using a very thick (>1 μm) LC layer. Switching the same thickness of PCM turns out to be extremely difficult because as PCM becomes thicker, the cooling during amorphization becomes slower, and at some point the material can no longer hit the critical cooling rate for amorphization. For example, GST is a fast PCM that typically requires a cooling rate of $\sim$1 K/ns to reach the amorphous state and reversible switching is difficult for thickness > 30 nm. Instead of using fast PCMs, PCMs with slow phase-change kinetics can be used, such as GSST, Sb_2S_3, and Sb_2Se_3, which also happen to have lower losses. For example, 250-nm-thick GSST can be switched by long pulses of 5 μs (amorphization) and 200 ms (crystallization) to yield large modulation, but at the cost of limited cyclability (40 cycles) [18]. Another approach to enhance the phase shift is via optical resonators such as metasurfaces. Recent work shows that by patterning Sb_2S_3 into a Huygen's metasurface, near 2π phase shift can be obtained in the visible range through the spectral overlap of the electric and magnetic dipole resonances [22]. However, the thick material (160 nm) causes difficulty in reversible switching, and only two cycles have been demonstrated (Table S1 online). Using resonant metasurfaces also limits the bandwidth that 2π phase shift is maintained. Hence, although there is no perfect solution yet to achieve 2π phase shift, high endurance, and broadband at the same time, the combination of optical resonance and the slow PCMs could potentially provide a solution towards a larger phase modulation.

Fabrication via foundry processes. So far, all PCMs-based photonic devices have only been fabricated either completely or partially in the university cleanroom. One recent work has reported the fabrication of silicon waveguides in a foundry, but the deposition, patterning, and encapsulation of PCMs were performed in a back-end-of-the-line process [21]. Foundry fabrication is a crucial step towards the scalability and the ultimate commercialization of PCM-based photonic technology. Large companies like Intel and IBM already have products on the market based on phase-change electronic memory with GST in their fabrication line. One would assume bringing PCMs into silicon photonics foundry would be straightforward. However, foundry compatibility proves to be a more challenging task. In fact, silicon photonics fabrication has very different processes from the memory cell, including material deposition, etching, metallization, and oxide cladding. The potential risks of introducing PCMs into a photonics foundry process, such as contamination, are extremely difficult to evaluate. Working with well-known PCMs such as GST may have an edge on this because the toxicity of the materials is very well-studied, compared to new PCMs such as Sb_2Se_3, where Selenium is highly volatile and toxic. One potential solution will be dedicating a line solely to PCM-based photonics. Demonstrating an application using PCMs that have a large market will help to draw investment interest from big semiconductor companies. Electronic memory has set an excellent example for the commercialization of PCMs, which we can all learn from. Further discussion on the foundry compatibility is included in the Supplementary materials S3.

To summarize, we have discussed important open questions in the field of PCM-based programmable photonics. We proposed potential solutions and future research directions. We believe that the visible range hosts enormous opportunities for PCMs with many unexplored applications, from quantum optics to AR/VR. A wide-bandgap PCM that is transparent across the entire visible spectrum will be a game changer. Secondly, we argued that device endurance should be evaluated based on applications, and similarly the potential applications should be guided by the available endurance. Next, we discussed the factors that are currently limiting the precision of optical levels and maximum phase shift and proposed strategies to address these issues. Finally, we addressed another essential element for scalability: the foundry compatibility of phase-change photonic devices. A dedicated fab line for PCMs-based photonic devices will be a crucial step before commercialization. Still, before getting there, a scalable prototype must be demonstrated to draw market interest from investors and large semiconductor manufacturers.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2023.03.034.

References

[1] Cheng Q, Rumley S, Bahadori M, et al. Photonic switching in high performance datacenters. Opt Express 2018;26:16022–43.
[2] Arrazola JM, Bergholm V, Brádler K, et al. Quantum circuits with many photons on a programmable nanophotonic chip. Nature 2021;591:54–60.
[3] Abdollahramezani S, Hemmatyar O, Taghinejad H, et al. Tunable nanophotonics enabled by chalcogenide phase-change materials. Nanophotonics 2020;9:1189–241.
[4] Wuttig M, Bhaskaran H, Taubner T. Phase-change materials for non-volatile photonic applications. Nat Photonics 2017;11:465–76.
[5] Fang Z, Chen R, Zheng J, et al. Non-volatile reconfigurable silicon photonics based on phase-change materials. IEEE J Selected Topics Quan Electron 2021;28:8200317.
[6] Ríos C, Stegmaier M, Hosseini P, et al. Integrated all-photonic non-volatile multi-level memory. Nat Photonics 2015;9:725–32.
[7] Fang Z, Chen R, Zheng J, et al. Ultra-low-energy programmable non-volatile silicon photonics based on phase-change materials with graphene heaters. Nat Nanotechnol 2022;17:842–8.
[8] Chen R, Fang Z, Perez C, et al. Non-volatile electrically programmable integrated photonics with a 5-bit operation 2023. arXiv.2301.00468, 2023.
[9] Zhang Y, Chou JB, Li J, et al. Broadband transparent optical phase change materials for high-performance nonvolatile photonics. Nat Commun 2019;10:4279.
[10] Delaney M, Zeimpekis I, Lawson D, et al. A new family of ultralow loss reversible phase-change materials for photonic integrated circuits: Sb_2S_3 and Sb_2Se_3. Adv Func Mater 2020;30:2002447.
[11] Dong W, Liu H, Behera JK, et al. Wide bandgap phase change material tuned visible photonics. Adv Func Mater 2019;29:1806181.
[12] Zheng J, Fang Z, Wu C, et al. Nonvolatile electrically reconfigurable integrated photonic switch enabled by a silicon PIN diode heater. Adv Mater 2020;32:2001218.
[13] Fang Z, Zheng J, Saxena A, et al. Non-volatile reconfigurable integrated photonics enabled by broadband low-loss phase change material. Adv Opt Mater 2021;9:2002049.
[14] Saseendran SS, Kongnyuy TD, Figeys B, Sundar KJ, Soulie JP, Goosens D, et al. MoOx: A transparent phase change material for integrated photonics applications? 2022 IEEE Photonics Conference (IPC), 2022, p. 1–2. https://doi.org/10.1109/IPC53466.2022.9975594.
[15] Burr GW, Breitwisch MJ, Franceschini M, et al. Phase change memory technology. J Vacu Sci Technol B 2010;28:223–62.
[16] Martin-Monier L, Popescu CC, Ranno L, et al. Endurance of chalcogenide optical phase change materials: a review. Opt Mater Express 2022;12:2145–67.
[17] Chen R, Fang Z, Fröch JE, et al. Broadband nonvolatile electrically controlled programmable units in silicon photonics. ACS Photonics 2022;9:2142–50.
[18] Zhang Y, Fowler C, Liang J, et al. Electrically reconfigurable non-volatile metasurface using low-loss optical phase-change material. Nat Nanotechnol 2021;16:661–6.
[19] Tuma T, Pantazi A, Le Gallo M, et al. Stochastic phase-change neurons. Nat Nanotechnol 2016;11:693–9.
[20] Li X, Youngblood N, Ríos C, et al. Fast and reliable storage using a 5 bit, nonvolatile photonic memory cell. Optica 2019;6:1–6.
[21] Ríos C, Du Q, Zhang Y, et al. Ultra-compact nonvolatile phase shifter based on electrically reprogrammable transparent phase change materials. PhotoniX 2022;3:26.
[22] Moitra P, Wang Y, Liang X, et al. Programmable wavefront control in the visible spectrum using low-loss chalcogenide phase-change metasurfaces. Adv Mater, doi: 10.1002/adma.202205367.

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