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# Are phase change materials ideal for programmable photonics?: opinion

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**Abstract:** The objective of this Opinion is to stimulate new research into materials that can meet the needs of tomorrow's programmable photonics components. Herein, we argue that the inherent property portfolios of the common telluride phase change materials, which have been successfully applied in data storage technologies, are unsuitable for most emerging programmable photonics applications. We believe that newer PCMs with wider bandgaps, such as $Sb_2S_3$, $Sb_2Se_3$, and $Ge_2Sb_2Se_4Te$ (GSST), can be optimized to meet the demands of holographic displays, optical neural network memories, and beam steering devices.

## 1. Main text

We advocate using phase change materials to add programmability or tunability to optical and photonics components. These materials exhibit enormous contrast in their optical properties, and they can be switched on nanosecond time scales. Moreover, many optical phase change materials also exhibit substantial electrical contrast, which lends them to nano electro-photonics hybrid devices. However, a concerted effort from the optical materials research community is required to design PCMs for specific photonics applications.

The first phase change chalcogenides were developed in the 1960s by a serial innovator called Stanford Ovshinsky [1]. He showed that a substantial electrical current can flow in amorphous chalcogenide films when the voltage applied to the film exceeds a threshold [2], hence the effect's name: Ovonic Threshold Switching (OTS). This effect is important because it can allow amorphous chalcogenides, which have an enormous resistance at low voltages, to be electrically Joule heated when the applied voltage is above the OTS voltage. Now, more than a half-century later, this same OTS effect is being exploited in selector devices to replace transistors in new forms of 3D random access memory architectures [3]. Ovshinsky described that Joule heat can lead to reversible amorphous-crystal phase transition when current pulses are applied to materials with low proportions of cross-linking atoms [2]; i.e. the advent of phase change materials. Although Ovshinsky published widely on topics relating to optically induced phase transitions in chalcogenide materials, including their application in optical cognitive computing [4], a Japanese company called Matsushita, which later became Panasonic, developed the first commercially successful PCMs for optical data storage in the 1990s [5]. These optical discs were specifically designed to strongly absorb the red and near-infrared laser diode wavelengths that were used in CD-RW and DVD-RW players. More recently, phase change material-based electrical random access memory devices have been commercialized by Numonyx and Intel [1,6]. The optical application of PCMs is experiencing somewhat of a renaissance and in the last decade there has been an explosion of interest in using PCMs to control metamaterials and waveguides. Most of the papers exploit the Matsushita/Panasonic family of $Sb_2Te_3$-GeTe PCMs, however, herein we question whether these telluride PCMs are well-suited for programmable photonics. We

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then assess the properties of existing and emerging candidate PCMs for future programmable photonics applications.

Typically, the properties of a photonics device are fixed during fabrication, but tunable photonic devices are required for displays, routing light through photonic circuits on a chip [7,8], optical neural networks (ONNs) and other forms of new optical computing, filters [9,10], holographic displays [11,12], and compact beam-steering devices [13]. There are principally two ways to change the optical characteristics of a photonics device: (1) changing the geometry of the structure, and (2) changing the refractive index of the material. Here, we focus on materials with a tunable refractive index. Refractive index tuning is often achieved using thermal optical effects, liquid crystals, Pockels cells, and semiconductor excitation. These methods generally produce relatively small changes in refractive index and require a constant energy supply to hold the state, i.e. they are volatile switches. The real advantage of chalcogenide phase change materials is their non-volatility. This effect comes from the optical properties of the materials depending on the material's crystal structure, which is readily switched using heat. The traditional data storage PCMs also tend to exhibit an extremely large refractive index change between their different structures. The crystalline state has an extraordinarily large refractive index, which stems from the readily polarizable and somewhat delocalized nature of p-orbital bonds that tie the crystalline state together [14–16]. However, these data storage PCMs have a relatively small bandgap and consequently strongly absorb visible and near-IR light [17,18]. This optical-loss raises an important question: are the properties of the data storage PCMs ideal for programmable photonics?

Re-writeable DVDs and electrical phase change RAM require long-term stability. Typically, PCMs in data storage applications are designed to be stable for several decades at room temperature [19]. There are even efforts to increase this archival stability further for application in extreme environments [20]. Moreover, the most well-known PCMs, which exist along the GeTe-$Sb_2Te_3$ pseudo-binary tie line were originally designed to absorb visible and near infrared light because the CD, DVD, and blue-ray discs use 780 nm, 650 nm, and 405 nm laser light to heat the material when writing and erasing data [5,19]. The archival stability requirements for photonics applications are usually not nearly as stringent but there may be strict requirements on the absorption of the material.

It is unrealistic to expect a single material to satisfy the requirements of all photonics applications. Therefore, we really need to consider the minimum viable properties that a photonics application needs to meet, and then design new materials specifically for that application. Table 1 shows the importance of the main PCM properties that need to be considered when designing new PCMs for battery operated non-volatile displays (e.g. watch face), holographic displays (e.g. for augmented reality), beam steering (e.g. for solid-state LiDAR in autonomous vehicles), and optical neural networks (ONNs) for image recognition tasks. For the purpose of comparison, we have also included the requirements for optical data storage (e.g. DVD-RW), for which the first Ge-Sb-Te and Ag-In-Sb-Te PCMs were developed to meet [19]. It should be immediately clear that the requirements for optical data storage are very different to those of most candidate photonics applications. Moreover, we rank low optical absorption as being a key enabler of these new photonics technologies. It is, therefore, surprising that so few new low-loss PCMs are being developed to meet their requirements.

Most research groups in the phase change photonics field are repurposing the telluride phase change data storage materials for photonics applications. Typically GeTe-$Sb_2Te_3$-based materials are used, which are the most well-known phase change data storage materials [19]. However, the high absorption of these materials limits their wide-spread application in photonics. The strong absorption in visible and near-IR stems from the relatively small band gap of the GeTe-$Sb_2Te_3$ alloys, while their crystalline state is characterized by a high concentration of holes and significant free carrier absorption across much of the infrared spectrum. The bandgap of $Ge_2Sb_2Te_5$ (GST) is

**Table 1. Importance of PCM properties for different photonics applications.**

| | Optical data storage | Displays | Displays (Holographic) | LiDAR Beam Steering | ONNs (Offline) | ONNs (Online) |
|---|---|---|---|---|---|---|
| **Large refractive index change** | Medium | Medium | High | High | Medium | Medium |
| **Low absorption at operating wavelength** | High | Medium | High | High | High | High |
| **Archive Stability** | High | Low | Low | Low | Medium | Low |
| **Switching speed** | High | Low | Medium | Medium | High | Medium |
| **Peak Power** | Medium | High | High | Low | Low | High |
| **Switching Energy** | Medium | Medium | Low | Low | Low | Medium |
| **Fabrication Precision** | Medium | Medium | High | High | High | High |
| **Multi-state/Analogue** | Low | Medium | High | High | High | High |
| **Write-Erase Cyclability** | Medium | Low | Medium | High | Low | High |
| **High Refractive Index** | Low | Low | High | High | Medium | Medium |

0.5 eV and 0.7 eV for the crystalline and amorphous states respectively [17,18]. As GST is a direct bandgap semiconductor, it and other GeTe-$Sb_2Te_3$ alloys readily absorb visible and near infrared light through electronic interband transitions [18]. If GST must be used for phase change visible photonics, clearly the amount GST interacting with light needs to be minimal to avoid excessive losses. However, for programmable photonics devices that rely of optical phase differences, such as interferometers, there is a design contradiction because the less the light interacts with the PCM, the longer the path length necessary for optical phase accumulation. Some photonics devices, such as thin film Fabry Perot reflective color filters, can exploit absorption in PCMs to alter the reflected field amplitudes from resonantly absorbed light to change the interference spectrum for display applications [21,22]. With the exception of these absorptive displays, Table 1 shows that optical absorption needs to be low for nearly all the proposed PCM programmable photonics applications. We propose, therefore, that the traditional data storage PCMs, such as GST, are best suited to applications leveraging absorption modulation, for instance, intensity-coded photonic memories and switchable plasmonic nanophotonics [23–25]. Clearly, for visible and near infrared photonics a large-bandgap phase change material is needed to decrease the optical absorption.

Rather than repurposing the data storage tellurides, which strongly absorb visible and near-IR light and are unsuitable for many visible photonics applications, we strongly believe that wider bandgap PCMs need to be developed specifically for visible photonics applications. As a rule, the bandgap of a material will increase when one moves up the periodic table and replaces heavier atoms with light atoms of the same group. Thus, of the chalcogen atoms, sulfides and oxides tend to have larger bandgaps than selenides and tellurides. $Sb_2S_3$, $Sb_2Se_3$ and GSST are all prototype PCMs which have recently been developed for low-loss visible and near-IR photonics [21,26–28]. These prototypes have followed the approach of replacing tellurium atoms with sulfur atoms. The widest bandgap PCM, $Sb_2S_3$, transmits light with wavelengths longer than ~ 600 nm. $Sb_2Se_3$ and GSST start to transmit light at slightly longer wavelengths in the near-IR but exhibit a larger change in refractive index between their amorphous and crystalline states [29].

In display and hologram applications, PCMs are promising candidates that exhibit large shifts in optical properties. Of particular interest is in the area of reflective (non-emissive) displays where candidate materials with high contrast, energy efficiency, and high-resolution are needed. Here, PCMs that exhibit a large refractive index change in the visible spectrum promise a solution that can meet these requirements [22,30]. However, more work is needed to demonstrate highly power efficient switching that interfaces with industry standard electronics. Similarly, holographic displays that are currently largely based on liquid crystal spatial light modulators could benefit from the significantly larger changes in refractive index exhibited by many chalcogenide PCMs.

LiDAR beam steering for autonomous vehicles can benefit from operating at near-IR wavelengths, where scattering is lower and higher power laser pulses can be used without damaging eyes. $Sb_2S_3$, $Sb_2Se_3$, and GSST all exhibit relatively low loss in the near-IR but GSST has the largest refractive index and the largest refractive index contrast. Dielectric resonances in PCMs can be used to steer beams of light using a phase-array approach [31]. The large refractive index of GSST makes it particularly well suited in beam steering. Indeed, recently it has been used in a prototype a polarization-insensitive phase-gradient metasurface to realize dynamic optical beam steering [32]. The operating speed of this early prototype is relatively slow, and the next stage of PCM development will involve shortening the recrystallisation time and improving the cycling endurance.

Recently, the suitability of $Sb_2S_3$, $Sb_2Se_3$, GSST, and GST were assessed for programming the coupling ratio of Si photonics couplers [29]. Programmable couplers are key elements in programmable photonic networks, such as on-chip ONNs. For ONN image recognition, several layers of Mach Zehnder Interferometers (MZIs), are coupled together to form the network. Even recognizing low resolution (28 pixel by 28 pixel) grayscale handwritten digit images requires three neural network layers with 4, 4, and 10 MZI neurons [33]. Clearly, optical losses need to be minimized. Moreover, if high power programing pulses are required, then the heat accumulation in a dense network will influence its stability via thermal crosstalk [34]. Therefore, the programming power should also be minimized. Finally, a material with multiple optical states can be used to set a range of different coupling ratios/interconnection weights, and therefore the PCM should be readily programmed with different refractive index states. Of all the emergent wider-bandgap PCMs, $Sb_2S_3$ was found to be the optimal choice for minimizing insertion losses in the visible and near-infrared, which is an important factor in PCM programmed ONNs. Its smaller refractive index contrast, however, requires longer coupling lengths than $Sb_2Se_3$ and GSST. $Sb_2S_3$ can be programmed with different optical refractive indices [30], which is also desirable. However, the sulfur and selenium based PCMs tend to have a higher crystallization temperature, which means that these ONNs are likely to be power-hungry. For this reason, $Sb_2S_3$ is well suited to offline-trained ONNs rather than online edge computing, which requires low-power programming [35]. Therefore, there is an opportunity to develop bespoke materials for low power back-propagation ONN architectures with online-training.

In conclusion, PCMs can introduce programmability into metamaterials and photonics integrated circuits, and this will enable new displays, compact LiDAR beam steering systems, and optical neural networks. No singular PCM is suited to all these applications, and the high absorption of the traditional data storage telluride PCMs limits their application in the visible and near infrared. Different sulfide and selenide PCMs meet many of the minimum viable properties required for displays, LiDAR, and off-line trained ONNs. Their properties can be further optimized for these applications to ensure that PCM photonics follows in the footsteps of PCM data storage and becomes a commercial success.

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## References

1. L. Hoddeson and P. Garrett, “The discovery of Ovshinsky switching and phase-change memory,” Phys. Today **71**(6), 44–51 (2018).
2. S. R. Ovshinsky, “Reversible electrical switching phenomena in disordered structures,” Phys. Rev. Lett. **21**(20), 1450–1453 (1968).
3. M. Zhu, K. Ren, and Z. T. Song, “Ovonic threshold switching selectors for three-dimensional stackable phase-change memory,” MRS Bull. **44**(09), 715–720 (2019).
4. S. R. Ovshinsky, “Optical cognitive information processing- a new field,” Jpn. J. Appl. Phys. **43**(7B), 4695–4699 (2004).
5. N. Yamada, E. Ohno, K. Nishiuchi, N. Akahira, and M. Takao, “Rapid-phase transitions of GeTe-$Sb_2Te_3$ pseudobinary amorphous thin-films for an optical disk memory,” J. Appl. Phys. **69**(5), 2849–2856 (1991).
6. numonyx, “,Intel, STMicroelectronics Deliver Industry’s First Phase Change Memory Prototypes,” (phys.org, 2008).
7. Y. Ikuma, T. Saiki, and H. Tsuda, “Proposal of a small self-holding $2 \times 2$ optical switch using phase-change material,” IEICE Electron. Express **5**(12), 442–445 (2008).
8. P. P. Xu, J. J. Zheng, J. K. Doylend, and A. Majumdar, “Low-loss and broadband nonvolatile phase-change directional coupler switches,” ACS Photonics **6**(2), 553–557 (2019).
9. A. Hessler, S. Wahl, T. Leuteritz, A. Antonopoulos, C. Stergianou, C. F. Schon, L. Naumann, N. Eicker, M. Lewin, T. W. W. Mass, M. Wuttig, S. Linden, and T. Taubner, “$In_3SbTe_2$ as a programmable nanophotonics material platform for the infrared,” Nat. Commun. **12**(1), 924 (2021).
10. A. Tittl, A. K. Michel, M. Schaferling, X. Yin, B. Gholipour, L. Cui, M. Wuttig, T. Taubner, F. Neubrech, and H. Giessen, “A switchable mid-infrared plasmonic perfect absorber with multispectral thermal imaging capability,” Adv. Mater. **27**(31), 4597–4603 (2015).
11. Q. Wang, E. T. F. Rogers, B. Gholipour, C. M. Wang, G. H. Yuan, J. H. Teng, and N. I. Zheludev, “Optically reconfigurable metasurfaces and photonic devices based on phase change materials,” Nat. Photonics **10**(1), 60–65 (2016).
12. S. Y. Lee, Y. H. Kim, S. M. Cho, G. H. Kim, T. Y. Kim, H. Ryu, H. N. Kim, H. B. Kang, C. Y. Hwang, and C. S. Hwang, “Holographic image generation with a thin-film resonance caused by chalcogenide phase-change material,” Sci. Rep. 7(1), 41152 (2017).
13. X. H. Yin, T. Steinle, L. L. Huang, T. Taubner, M. Wuttig, T. Zentgraf, and H. Giessen, “Beam switching and bifocal zoom lensing using active plasmonic metasurfaces,” Light: Sci. Appl. **6**(7), e17016 (2017).
14. K. Shportko, S. Kremers, M. Woda, D. Lencer, J. Robertson, and M. Wuttig, “Resonant bonding in crystalline phase-change materials,” Nat. Mater. **7**(8), 653–658 (2008).
15. T. H. Lee and S. R. Elliott, “Chemical bonding in chalcogenides: the concept of multicenter hyperbonding,” Adv. Mater. **32**(28), 2000340 (2020).
16. M. Wuttig, V. L. Deringer, X. Gonze, C. Bichara, and J. Y. Raty, “Incipient metals: functional materials with a unique bonding mechanism,” Adv. Mater. **30**(51), 1 (2018).
17. L. T. Chew, W. L. Dong, L. Lu, X. L. Zhou, J. Behera, H. L. Liu, K. V. Sreekanth, L. B. Mao, T. Cao, J. Yang, and R. E. Simpson, “Chalcogenide active photonics,” Active Photonic Platforms Ix **10345**, 10345 (2017).
18. B. S. Lee, J. R. Abelson, S. G. Bishop, D. H. Kang, B. K. Cheong, and K. B. Kim, “Investigation of the optical and electronic properties of $Ge_2Sb_2Te_5$ phase change material in its amorphous, cubic, and hexagonal phases,” J. Appl. Phys. **97**(9), 093509 (2005).
19. M. Wuttig and N. Yamada, “Phase-change materials for rewriteable data storage,” Nat. Mater. **6**(11), 824–832 (2007).
20. P. Zuliani, E. Palumbo, M. Borghi, G. D. Libera, and R. Annunziata, “Engineering of chalcogenide materials for embedded applications of phase change memory,” Solid-State Electron. **111**, 27–31 (2015).
21. W. Dong, H. Liu, J. K. Behera, L. Lu, R. J. H. Ng, K. V. Sreekanth, X. Zhou, J. K. W. Yang, and R. E. Simpson, “Wide Bandgap phase change material tuned visible photonics,” Adv. Funct. Mater. **29**(6), 1806181 (2019).
22. P. Hosseini, C. D. Wright, and H. Bhaskaran, “An optoelectronic framework enabled by low-dimensional phase-change films,” Nature **511**(7508), 206–211 (2014).
23. C. Rios, M. Stegmaier, P. Hosseini, D. Wang, T. Scherer, C. D. Wright, H. Bhaskaran, and W. H. P. Pernice, “Integrated all-photonic non-volatile multi-level memory,” Nat. Photonics **9**(11), 725–732 (2015).
24. M. Rudé, R. E. Simpson, R. Quidant, V. Pruneri, and J. Renger, “Active control of surface plasmon waveguides with a phase change material,” ACS Photonics **2**(6), 669–674 (2015).
25. B. Gholipour, A. Karvounis, J. Yin, C. Soci, K. F. MacDonald, and N. I. Zheludev, “Phase-change-driven dielectric-plasmonic transitions in chalcogenide metasurfaces,” NPG Asia Mater **10**(6), 533–539 (2018).
26. Y. Zhang, J. B. Chou, J. Li, H. Li, Q. Du, A. Yadav, S. Zhou, M. Y. Shalaginov, Z. Fang, H. Zhong, and others, “Extreme broadband transparent optical phase change materials for high-performance nonvolatile photonics,” arXiv preprint arXiv:1811.00526 (2018).
27. M. Delaney, I. Zeimpekis, D. Lawson, D. W. Hewak, and O. L. Muskens, “A new family of ultralow loss reversible phase-change materials for photonic integrated circuits: $Sb_2S_3$and $Sb_2Se_3$,” Adv. Funct. Mater. **30**(36), 2002447 (2020).
28. Y. F. Zhang, J. B. Chou, J. Y. Li, H. S. Li, Q. Y. Du, A. Yadav, S. Zhou, M. Y. Shalaginov, Z. R. Fang, H. K. Zhong, C. Roberts, P. Robinson, B. Bohlin, C. Rios, H. T. Lin, M. Kang, T. Gu, J. Warner, V. Liberman, K. Richardson, and

J. J. Hu, "Broadband transparent optical phase change materials for high-performance nonvolatile photonics," Nat. Commun. **E10**(7766), 1–E10 (2019).

29. T. Y. Teo, M. Krbal, J. Mistrik, J. Prikryl, L. Lu, and R. E. Simpson, "Comparison and analysis of phase change materials-based reconfigurable silicon photonic directional couplers," Opt. Mater. Express **12**(2), 606–621 (2022).
30. H. Liu, W. Dong, H. Wang, L. Lu, Q. Ruan, Y. S. Tan, R. E. Simpson, and J. K. W. Yang, "Rewritable color nanoprints in antimony trisulfide films," Sci. Adv. **6**(51), eabb7171 (2020).
31. C. R. de Galarreta, I. Sinev, A. M. Alexeev, P. Trofimov, K. Ladutenko, S. G.-C. Carrillo, E. Gemo, A. Baldycheva, V. K. Nagareddy, J. Bertolotti, and others, "All-dielectric silicon/phase-change optical metasurfaces with independent and reconfigurable control of resonant modes," *arXiv preprint arXiv*:1901.04955 (2019).
32. Y. F. Zhang, C. Fowler, J. H. Liang, B. Azhar, M. Y. Shalaginov, S. Deckoff-Jones, S. S. An, J. F. B. Chou, C. M. Roberts, V. Liberman, M. K. Kang, C. Rios, K. A. Richardson, C. Rivero-Baleine, T. Gu, H. L. Zhang, and J. J. Hu, "Electrically reconfigurable non-volatile metasurface using low-loss optical phase-change material," Nat. Nanotechnol. **16**(6), 661–666 (2021).
33. H. Zhang, M. Gu, X. D. Jiang, J. Thompson, H. Cai, S. Paesani, R. Santagati, A. Laing, Y. Zhang, M. H. Yung, Y. Z. Shi, F. K. Muhammad, G. Q. Lo, X. S. Luo, B. Dong, D. L. Kwong, L. C. Kwek, and A. Q. Liu, "An optical neural chip for implementing complex-valued neural network," Nat. Commun. **12**(1), 457 (2021).
34. D. Thomson, A. Zilkie, J. E. Bowers, T. Komljenovic, G. T. Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Virot, J. M. Fedeli, J. M. Hartmann, J. H. Schmid, D. X. Xu, F. Boeuf, P. O'Brien, G. Z. Mashanovich, and M. Nedeljkovic, "Roadmap on silicon photonics," J. Opt. **18**(7), 073003 (2016).
35. O. Krestinskaya, A. P. James, and L. O. Chua, "Neuromemristive circuits for edge computing: a review," IEEE Trans. Neural Netw. Learning Syst. **31**(1), 4–23 (2020).