Electrical Pulse Driven Multi-Level Nonvolatile Photonic Memories Using Broadband Transparent Phase Change Materials

Jiawei Meng¹, Mario Miscuglio¹, Nicola Peserico¹, Xiaoxuan Ma¹, Yifei Zhang², Cosmin-Costantin Popescu², Myungkoo Kang³, Kathleen Richardson³, Juejun Hu² and Volker J. Sorger¹*

¹ Department of Electrical and Computer Engineering, George Washington University, Washington, DC 20052, USA
² Department of Materials Science & Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
³ CREOL, The College of Optics & Photonics, University of Central Florida, Orlando, FL 32816, USA

*Corresponding Author: sorger@gwu.edu

Here we demonstrate a multi-state electrically programmed low-loss nonvolatile photonic memory based on a broadband transparent phase change material (Ge₂Sb₂Se₅, GSSe) with ultra-low absorption in the amorphous state. A zero-static-power, and electrically driven high-state photonic memory was realized on a silicon-on-insulator platform, featuring amplitude modulation up to 0.2 dB/μm and an ultra-low insertion loss of 0.0015 dB/μm, with a newly designed paired micro-heaters along the both sides of waveguide without horizontal contact. The step size (absorption per state) and total resolution of PRAM is cascaded with the length of GSSe material and the number of paired heaters to tune the number of individual memory islands. We also proposed a partial amorphization scheme with single pair of unsymmetric heaters to realize 6 states response to enhance energy and footprint efficiency of PCM devices. A cyclability test was performed over the proposed PRAM reaching half-million set-reset cycles with stable bi-state optical responses.

Keywords: Memory, Photonic, Coherent, Phase Change Material, Integrated Photonic, Network

Introduction

Photonic computing is one of the main answers to the novel and exponentially increasing data processing for artificial intelligence and machine learning ¹,². While the benefits given by the intrinsic electromagnetic nature of the optical signals as an energy-efficient way to transmit information are clear, those can potentially be hindered by the optoelectrical and electro-optical transductions, as well as by the repeated access to digital and non-volatile memory³. This last aspect impacts the overall operation speed while producing considerable additional energy loss⁴. Since performing Neural Networks (NN) inference, such as classification Machine Learning (ML) task, accounts for more than 90% of the computing effort, having weight bank elements that do not require additional energy can reduce the energy consumption of those tasks⁵,⁶. For these reasons, having a heterogeneously integrated optimized photonic memory, which retains information in a non-volatile fashion, poses a great advantage, especially when implementing NN-performing inference where the trained weights are only rarely updated (i.e., depending on the application daily, monthly, yearly, if ever)⁷.
For photonic computing, photonic memories are one of the most important and yet difficult to realize essential devices compatible with Photonic Integrate Circuits (PICs). Previous studies based on photonic crystals, micro-ring, or other actively tuned electro-optic modulators cannot achieve the feature of non-volatility\textsuperscript{8–10}, which is the key for low-cost, long-term stable photonic memory. Phase-Change Material (PCM) based photonic memories have appeared recently as a competitive candidate for real non-volatile photonic memory\textsuperscript{11–14}. PCMs can be switched between two structural states, the amorphous and crystalline states, with distinct optical and electrical properties. Those states can be reversibly cycled under appropriate thermal or optical stimulation with long-term stability\textsuperscript{15}. One of the commonly used PCM materials for photonic memory is GST (Ge-Sb-Te) which exhibits a relatively large contrast of both refractive index (Δn) and optical loss (Δk) when switching between amorphous and crystalline states.\textsuperscript{16,17,18,19} However, GST is characterized by a high absorption coefficient even in the amorphous state. For large photonic networks such as the one implementing deep NNs, the multi-layer design requires the photonic memory containing the kernel memory to be very low loss\textsuperscript{20}, an aspect that cannot be met by GST-based photonic memory due to its high absorption coefficient.

In this paper, we develop and demonstrate a non-volatile electrically controlled photonic memory based on the phase-change material Ge\textsubscript{2}Sb\textsubscript{2}Se\textsubscript{5} (GSSe). We chose GSSe since it presents a broadband transparent region for telecommunication wavelengths while in its amorphous state. In fact, amorphous state GSSe is characterized by a remarkably low extinction coefficient 2.0 × 10\textsuperscript{-5} at 1550 nm wavelength, enabling near-lossless devices monolithically co-integrated with PICs (as shown in Fig. 1e)\textsuperscript{21}. This low absorption coefficient is over two orders of magnitude lower than regularly employed GST at 1550 nm. Meanwhile, when in its crystalline state, the absorption coefficient increases to 0.14, which results in an absorption contrast between the two states. Based on GSSe’s unique optical property, we developed our multi-state PCM memory.

Remarkably, we demonstrated that the optical absorption in the amorphous state is vanishingly close to zero when heterogeneously integrated into silicon photonics of 60-μm-long lengths. Moreover, the relatively low variation of the absorption coefficient changes in each state makes it a promising material for very stable high order multistate devices, avoiding the utilization of high input laser power and extremely low noise equivalent power detectors. Assuming a continuous film, for the fundamental TM mode of the waveguide, the phase transition produces a variation of the effective absorption coefficient equal to 0.015 which corresponds to 0.1 dB/μm. Meanwhile, all electrical pulsed programming method through micro-metal heaters for our proposed PRAM gain a significant advantage for the ease of controlling compare to all-optical laser heating for PCM setting and resetting. Also from the packaging perspective, electrical control is still one of the best options especially for future mass implementation of PRAM in large-scale photonic tensor computing circuits.

Results

To demonstrate this photonic non-volatile memory, a thin layer of GSSe film is directly deposited on the top of a planarized silicon waveguide, as shown in Fig. 1a. The obtained memory states are programmed by selectively ‘writing/erasing’ portions of the GSSe film via local electro-thermal heating. This allows electrically driven change of GSSe’s structural state.
(crystalline/amorphous) and consequently results in the strong imaginary-part variation of the effective refractive index, leading to a significant optical absorption change.

In our scheme, heat is applied to the material externally via joule heating of a tungsten-titanium (W/Ti) metal layer in contact with 20 nm aluminum oxide dielectric layer over the GSSe film to protect GSSe from oxidization, whose mode and thermal profile are simulated, as shown in Fig. 1f. According to the type of transition wanted, different pulse train profiles are applied to the metal wire via electrical connections to the device. With the 3D mode simulation through Comsol (Supplementary Note 7), we optimized the position of the heaters regarding the waveguide to minimize the ohmic losses due to the presence of metal and concurrently lower the threshold voltage for delivering the necessary amount of heat for inducing the phase transition. The optimized heaters configuration consists of two non-plasmonic tungsten resistive heaters placed in contact with a thin spacer of aluminum oxide deposited on top of the GSSe film, as shown in Fig. 1g.h. The heaters are placed 500 nm away on the side of the waveguide, thus providing heat to the film locally, which not only lowers the switching threshold but also temporally store the heat for successive pulses.

To reach the multi-state power output response, a sequence of paired heaters are placed along the waveguide in series. Each pair of heaters are individually tuned to Joule heat the GSSe material locally for solid-state phase transition. Whereas, in the crystalline state, the GSSe becomes much lossier with a linear absorption coefficient of ~0.1 dB/μm obtained by experimental data and close to zero insertion loss in the amorphous state. This configuration takes advantage of this near-lossless characteristic of the GSSe material in its amorphous state, as the optical signal loss in the waveguide is minimal even for long strips. We precisely control the state of each portion of material by tuning each pair of heaters to obtain a stepwise extinction ratio. When N pairs of heaters are placed, a total of N+1 memory states of power intensity response are realized.

As shown in Figure 1a,b), our photonic memories comprise one single 30-nm thin GSSe pad with paralleled pairs of W-Ti micro-heaters arranged along the waveguide, as each pair of heaters correspond to a quantized state. The double-sided heater design leads to the highest thermal energy efficiency for the phase transition of GSSe. Furthermore, this design prevents the extra optical insertion loss introduced by the metal heaters, since the metal strips are not directly deposited over the waveguide, but instead have a few hundred nm horizontal distance from the side of the waveguide.

We also present an alternative layout, shown in Figure 1d), that comprises 30-nm-thin and 5000-nm-wide programable PCM-wires arranged in a grating fashion (duty cycle 50%), with a series of single-sided heaters to Joule-heat each PCM wire, exploiting the same electrical local Joule-heating concept. The single-side heater concept shown here is mainly used for optical memory with a high order of bit number resolution which requires a larger amount of GSSe material cell along with the required number of micro-heaters, metal pads, and routing.

By using this layout, an all-electrical controlled 4-bit photonic memory element is implemented. Considering as the highest state as the condition in which all GSSe wires are in the amorphous phase, 15 reprogrammable wires are sufficient for implementing the 4-bit memory with an overall length of just 80 μm, excluding electrical circuitry. The insertion loss, defined as the optical power loss when all the wires are in an amorphous state, is only 0.12 dB for the 4-bit multilevel memory. The optical power transmitted decreases when the GSSe wires are written/SET (switching to crystalline), leading to discrete power levels for each quantized state. The insertion losses for the multistate memory device with different quantization states are measured and shown in Fig. 2a) which realized 16 quantization states for 4bit. The
photonic memory implemented in this configuration provides a uniform quantization. For a 4-bit photonic memory, the quantization step is 0.75 dB/state with the total maximum extinction ratio of 12 dB achieved along with 16 output power states.

Figure 1. (a) 3D schematic of a planarized waveguide with 30nm GSSe layer on top of the waveguide and multiple parallel double-sided tungsten-titanium heaters (b). Detailed optical image of GSSE on waveguide with discrete double-sided heaters (c) Zoom-in detailed image of Fig b. Discrete double-sided heaters are arranged along the waveguide over the GSSe film. (d) Detailed optical image of GSSe strip array with single-sided heaters for measurement of high order bit memory. (e) Experimentally obtained (ellipsometry) optical properties of GSSe film. Absorption coefficient contrast (imaginary part of the refractive indices of amorphous and crystalline alloys) of GSSe for crystalline and amorphous states at 1550 nm. The GSSe shows a strong unity $\Delta k$, while simultaneously showing a small, induced loss at the amorphous state. (f) Normalized electric field mode profile of hybrid Si-GSSe waveguide for TE and TM mode with 0.54dB/um absorption coefficient between amorphous and crystalline state. The effective refractive index of $k$ in the amorphous state is $-2.18 \times 10^{-5}$ which leads to an exceedingly small unit passive absorption of the memory. (g) 2D cross-section schematic of the lateral thermoelectric switching configuration. One pair of tungsten-titanium heaters is deposited on the side of the Si waveguide on top of the GSSe film. The electrical current running through the W-Ti circuit dissipates energy in the form of local heat, inducing local material phase transition. (h) Cross-section SEM image of the device.

To further enhance the speed and energy efficiency of electro-thermally switched PCM devices, we optimized the micro-heaters position. We tested different distances between waveguide and heaters, from 0.125 $\mu$m to 5 $\mu$m with the previously shown design of double-sided heaters. With the same amount of electrical energy applied to each heater pair, the total extinction ratio (ER) achieved decreased with the increasing distance, while concurrently the unit insertion loss introduced by the GSSe cell decreased, as shown in Figure 2b,e. To balance the phase transition energy efficiency and insertion loss (IL), we calculated the Figure-Of-Merit (FOM) as ER/IL for each distance, and the optimized position is shown in Figure 2c).
indicating 500 nm distance as the best value. At this distance, we compared the FOM of our proposed device along with three other PCM photonic memories as shown in Figure 2e,f). With the same theoretical unit insertion loss, our devices achieved the highest unit extinction ratio.

To evaluate the endurance of our device, a cyclability measurement was conducted and a total of half-million set-reset cycles was successfully achieved, as shown in Figure 2d), with stable power responses in either state. The main limitation which prevents memory from achieving higher set-reset cycles was the failure of micro-heaters on the two sides of the waveguide. With the large number of heating-cool down cycles for GSSe set-reset, the initial tungsten micro-heaters were easily broken due to oxidation under the fast temperature change, as shown in the lower right subfigure of Figure 2d). To overcome the issue, we replaced the heater material from tungsten to tungsten-titanium with a 200nm thick dual layer of aluminum deposited over the W/Ti on the routing part. The Al layer reduces the electrical resistance, enhances heat uniformity and protects the W/Ti heaters. Meanwhile, a 600 nm thick layer of Al₂O₃ is deposited over the device to prevent further oxidization and physical bend of metal. Such structure allows the heater to survive after half-million cycles, as shown in the upper right subfigure of Figure 2b). Up to our knowledge, this is the longest cycle test on PCM integrated into a photonic circuit with stable set-reset photonic responses.

Figure 2. Figure 2. a) Optical power response for a 4-bit photonic memory as a function of digital states, for an increasing number of crystalline-wire the ER increases linearly and uniformly. b) Unit insertion loss and extinction ratio per unit insertion loss vs. heater position. c) Unit insertion loss and unit extinction ratio comparison between PCM-based photonic memories. d) Bi-State optical responses change over more than 500,000 switching cycles. For heaters exposed to air with no Al₂O₃ layer protection, the maximum set-reset cycles achieved is 10,000 and then heaters were broken due to heavy oxidization or physical deformation as shown. With a thick Al₂O₃ layer on top of the heaters, the maximum cycles reached is 500,000 and heaters are still alive as shown in the lower right subfigure. e) Heater performance vs position of the heater. The distance between the edge of the waveguide and the double heater is swept from 125 nm to 5000 nm. Left axis: Total energy applied vs. heater-waveguide distance for reaching 6-dB extinction ratio. Right axis: With
the same applied energy, the ER change corresponds to the heater position. f) Figure of merit comparison for different PIC-based non-volatile photonic memories.

For GSSe material, the amorphization temperature is the melting point (>900K), while for crystallization a certain temperature (~600K) must be applied and kept constant for approximately 20µs. Crystallization is achieved by applying the pulse setting shown in Fig 3c) to keep the material temperature consistent in the desired range for over 20µs, while the amorphization is achieved by adding a threshold voltage 10-12V (~2 µs) to the local heater up to 900K. The voltage range takes into consideration the fabrication variability of micro-heaters. The real-time continuous set-reset measurement for two states of memory is shown in Fig 3a).

Since the total extinction ratio that we want to achieve is proportional to the area of the GSSe cell covering the waveguide, the phase transition time required is also proportional to the desired extinction ratio, for the different thermal volumes of PCM material. We then experimentally mapped the amount of ER that can be achieved as a function of transition time at the falling edge of the real-time transmission trace in Figure 3a), and the results are shown in Figure 3b). To achieve 0.2 dB ER, 0.5 ms is needed compared to 500 ms required for 6 dB total ER response.

Figure 3. a) Time-dependent trace of transmission. b) The time taken for reaching different levels of extinction ratio is varied as shown in the figure from 0.5 ms to 500 ms. c) Simulated pre-
programmed voltage pulses are applied for each heater and a two-sided neighbor works simultaneously for GSSe to transient from amorphous to crystalline state.

Besides the concept of multi-heater pairs that we proposed for the multi-states optical memory, here we propose another design concept for the optical memory, as shown in Figure 4a). As we described, the multi-state optical power response is realized by tuning the ratio of GSSe film over the waveguide through local Joule-heating to introduce a different level of insertion loss. Based on this theory, we developed the non-equal heater pair memory cell. The shorter heater on the right side works for the amorphization of the GSSe cell. The COMSOL electrical-thermal simulation results, as shown in Fig 4b), indicate that with different energies applied to the heater, the above-melting-point hot area changes, which introduces the different amorphous areas and by so the different absorption levels. Fig 4d) displays the numeric results which more clearly show the distribution of hot area (>900K) with the increasing of electrical energy applied to the micro-heater. On the other side, the longer heater on the left side works as the resetting button to change the full GSSe cell into its crystalline state and erases all the previously stored information set by the right heater. The experimental result for 6 different states (2.58-bit) has been achieved as shown in Fig 4c) for different energy levels from 80 to 400 nJ. The clear advantage of this design is the reduction of electrical tracks and pads, allowing a better integration into large photonic NN. On the other hand, the main drawback is the difficulty of programming compared to the multi-heater pair design. In the first designs, the programming pulse setting for each heater pair is fixed, and the ultimate power response is the result of an accumulation for all parallel paired heaters. For this design, there is not an a priori known relationship between ER and applied energy. To get the multi-state power response with fixed step size, a pulse setting for each state needs to be individually set, introducing an extra program difficulty.
Figure 4. a) Schematic of single pair heater multi-level power response device with a different crystalline-amorphous ratio on a single GSSe pad. Detailed optical image of asymmetric paired heaters stands along the waveguide over the GSSe pad. The longer heater on the left side is used as the resetting heater to change the phase of all GSSe film from amorphous to crystalline. The shorter heater on the right side is used as the setting heater to control the area of amorphous state film by applying different levels of Joule-heating energy to the W-Ti microheater. As more energy is applied, a larger area of GSSe film will be transient to the amorphous state and the total absorption will decrease. Based on different levels of absorption, a multi-level power response function is achieved. b) COMSOL thermal simulation of temperature distribution along with the heater which also indicates the area ratio of GSSe material in the amorphous and crystalline state. c) Measured 6-state power responses achieved. d) GSSe material temperature distribution along the heater from COMSOL thermal simulation with different energy applied to micro-heater.

Discussion
In this paper, we presented a novel ultralow insertion loss phase change material GSSe, implementing non-volatile electrical-controlled photonic memory as various reconfigurable devices following a similar concept. We proved the device’s endurance with over half a million switching cycles. The number is mainly limited by the durability of metal heaters, as they were physically broken after a large number of heating and cooling cycles. Following that, we improved the lifetime of heaters with a thick oxide layer covered on the top. Novel structures and devices could be optimized to enhance further the photonic memory cyclability by improving the design of the materials stack for the heaters.

A few key PRAM performance characteristics have been compared with two other demonstrated PRAM approaches, as shown in Table 1. Though this work has larger setting energy and smaller unit extinction ratio compared to the all-optical setting GST-based PRAM, we hold the best figure-of-merit (ER/IL) due to our ultra-low insertion loss benefitting from the transparent GSSe material and a novel double-sided metal heater design. Moreover, we have successfully demonstrated half-million set-reset cycles with very stable performance which is far more than other PRAM’s cyclability results, as shown in Table 1.

Table 1. Main PRAM performance comparison

| Material        | Program method          | Setting energy (nJ/dB * \(\mu\text{m}\)) | Unit ER (dB/\(\mu\text{m}\)) | Unit IL (dB * \(\mu\text{m}\)) | FOM (ER/IL) | System implementation complexity | Set-Reset Cycles |
|-----------------|-------------------------|------------------------------------------|-------------------------------|---------------------------------|-------------|----------------------------------|-----------------|
| GST 24          | Optical absorption      | 1                                        | 0.8                           | 0.02                            | 40          | High                             | 10,000          |
| GST 25          | Doped silicon heater    | 0.12                                     | 10                            | 1                               | 10          | Medium                           | 1000            |
| GSSe (This work)| On chip integrated heater | 0.3                                     | 0.1                           | 0.0015                          | 66          | Low                              | 500,000         |

From simulations, we expected an extinction ratio of 0.4 dB/\(\mu\text{m}\), while from the experimental demonstration we obtained about 0.1 dB/\(\mu\text{m}\). The main reason for this difference is due to the heat distribution applied to the PCM cell through the micro-heater, as not the whole PCM reached the transition temperature. As shown in Fig 4b), the heat spread follows an ellipse shape which results in a non-uniform temperature map, that caused the lower extinction ratio compared to the simulations. The different crystalline-amorphous ratios caused by the non-uniform heating lead to our second proposed PRAM design, which compromises a smaller volume of PCM, and by so a more uniform heat distribution.

As we described before, the total extinction ratio of our PRAM could be achieved is based on the length of GSSe cell which could be transitioned through micro-heater. Then the highest bit resolution that could be achieved by each device is limited by the minimum detected dynamic extinction ratio for every single state through an optical power meter. Based on our current measurement setup, the minimum detectable power range is 35 pW which means that we could achieve 1 binary state as small as over 35 pW difference in theory. Then for traditional 4- or 5-bit memory, the length of the active region for each memory could be sub-micrometer long and could be cascaded for different bit resolution required.
The non-volatility of our PRAM results in the zero static power consumption for state maintenance and exceptionally low insertion loss introduced by active PCM material GSSe. Meanwhile, the setting energy of our PRAM is also relatively low, computed around 0.3 $nJ/(dB \cdot \mu m)$. As we discussed previously, the bit resolution is limited by the minimum dynamic extinction ratio in dB that could be detected over the system noise level, which means that the required energy for each bit set-reset and the required footprint could be as small as nW level as shown in Table 1 for our device.

In large-scale photonic computing architectures, such as high order matrix MAC operation required for deep neural networks, the stringent energy requirements motivate the implementation of multiple photonic memories for weight bank\textsuperscript{526}. For these challenges, our devices can perform even orders of magnitude better than volatile memories in terms of energy consumption and footprint.

Besides the low operating energy consumption for high dimension photonic tensor operations, our proposed PRAM takes advantage of all-electrical micro-heaters, and by so reducing the packaging complexity compared to all-optical laser heating PRAMs compared in Table 1. When tens or thousands of PRAMs need to be implemented, electrical control is the only feasible way for memory programming and large-scale photonic circuit packaging\textsuperscript{27}.

**Conclusion**

In conclusion, we have experimentally demonstrated a new class of electrically driven optical non-volatile memory with low insertion loss and low power consumption, which exploits the unique optical properties of the phase-change material GSSe to achieve zero-static-power consumption and low-dynamic-power consumption in ultra-compact devices. Two different PRAM designs with similar basic concepts were demonstrated which could be utilized in low-energy programmable photonic integrated circuits. Our results are promising for applications in photonic computing architectures such as weight banks in optical neural networks, optical switching for telecommunication, quantum networks, and others.

**Methods**

**Device fabrication**

20 nm GSSe thin film layer was deposited by using single-source thermal evaporation and a 20 nm layer of $Al_2O_3$ was deposited by using atomic layer deposition (ALD) as a protection coating to prevent GSSe from oxidation. The tungsten-titanium microheater was fabricated in the nanofabrication and imaging center at George Washington University. A 200 nm think tungsten titanium layer is sputtered. Then another 200 nm think Al is deposited over the W/Ti route to decrease the overall resistance, increase the heat spread over the micro-heaters and to protect the W/Ti layer from oxidation. Then a thick 400 nm $Al_2O_3$ layer is deposited over the full circuit using the ALD for oxidation prevention. Contact pad windows are opened using oxide layer plasma dry etch for electrical probes to connect with circuits for micro-heaters driving.
Electro-thermal simulation/optical mode simulation and microheater modeling:

The Joule heating process and heat dissipation model were performed using a three-dimensional finite-element method in COMSOL Multiphysics. We used the AC/DC Joule-heating module coupled with the heat transfer module, which accounts for surface radiation as well as thermal boundary resistance.

References
1. Shastri, B. J. et al. Photonics for artificial intelligence and neuromorphic computing. Nature Photonics 2021 15:2 15, 102–114 (2021).
2. Miscuglio, M., Adam, G. C., Kuzum, D. & Sorger, V. J. Roadmap on material-function mapping for photonic-electronic hybrid neural networks. APL Materials 7, 100903 (2019).
3. Zhang, H. et al. An optical neural chip for implementing complex-valued neural network. Nature Communications 2021 12:1 12, 1–11 (2021).
4. Rios, C. et al. In-memory computing on a photonic platform. Science Advances 5, (2019).
5. Miscuglio, M. & Sorger, V. J. Photonic tensor cores for machine learning. Applied Physics Reviews 7, 031404 (2020).
6. Chakraborty, I., Saha, G. & Roy, K. Photonic In-Memory Computing Primitive for Spiking Neural Networks Using Phase-Change Materials. Physical Review Applied 11, 014063 (2019).
7. Miscuglio, M. et al. Artificial Synapse with Mnemonic Functionality using GSST-based Photonic Integrated Memory. 2020 International Applied Computational Electromagnetics Society Symposium, ACES-Monterey 2020 (2020) doi:10.23919/ACES49320.2020.9196183.
8. Suer, C. et al. Sub-wavelength GHz-fast broadband ITO Mach–Zehnder modulator on silicon photonics. Optica, Vol. 7, Issue 4, pp. 333-335 7, 333–335 (2020).
9. Li, G. et al. Ring resonator modulators in silicon for interchip photonic links. IEEE Journal on Selected Topics in Quantum Electronics 19, (2013).
10. Shinya, A. et al. All-optical memories based on photonic crystal nanocavities. 2009 International Conference on Photonics in Switching, PS ’09 (2009) doi:10.1109/PS.2009.5307771.
11. Wuttig, M., Bhaskaran, H. & Taubner, T. Phase-change materials for non-volatile photonic applications. Nature Photonics 2017 11:8 11, 465–476 (2017).
12. Rios, C. et al. Integrated all-photonic non-volatile multi-level memory. Nature Photonics 2015 9:11 9, 725–732 (2015).
13. Rios, C. et al. On-Chip Photonic Memory Elements Employing Phase-Change Materials. Advanced Materials 26, 1372–1377 (2014).
14. le Gallo, M. & Sebastian, A. An overview of phase-change memory device physics. Journal of Physics D: Applied Physics 53, (2020).
15. Zhang, Y. et al. Myths and truths about optical phase change materials: A perspective. Applied Physics Letters vol. 118 (2021).
16. Alexoudi, T., Kanellos, G. T. & Pleros, N. Optical RAM and integrated optical memories: a survey. *Light: Science & Applications* 2020 9:1 9, 1–16 (2020).
17. Zhang, H. *et al.* Comparison of the phase change process in a GST-loaded silicon waveguide and MMI. *Optics Express, Vol. 29, Issue 3, pp. 3503-3514* 29, 3503–3514 (2021).
18. Wu, C. *et al.* Low-Loss Integrated Photonic Switch Using Subwavelength Patterned Phase Change Material. *ACS Photonics* 6, 87–92 (2019).
19. Li, P. *et al.* Reversible optical switching of highly confined phonon–polaritons with an ultrathin phase-change material. *Nature Materials* 2016 15:8 15, 870–875 (2016).
20. Sui, X., Wu, Q., Liu, J., Chen, Q. & Gu, G. A review of optical neural networks. *IEEE Access* 8, 70773–70783 (2020).
21. Xu, M., Slovin, G., Paramesh, J., Schlesinger, T. E. & Bain, J. A. Thermometry of a high temperature high speed micro heater. *Review of Scientific Instruments* 87, (2016).
22. Zhang, Y. *et al.* Broadband transparent optical phase change materials for high-performance nonvolatile photonics. *Nature Communications* 10, (2019).
23. Ríos, C. *et al.* Ultra-compact nonvolatile photonics based on electrically reprogrammable transparent phase change materials. (2021).
24. Li, X. *et al.* Fast and reliable storage using a 5 bit, nonvolatile photonic memory cell. *Optica* 6, 1 (2019).
25. Zhang, H. *et al.* Miniature Multilevel Optical Memristive Switch Using Phase Change Material. *ACS Photonics* vol. 6 2205–2212 (2019).
26. Feldmann, J. *et al.* Parallel convolutional processing using an integrated photonic tensor core. *Nature 2020 589:7840* 589, 52–58 (2021).
27. Peserico, N., de Lima, T. F., Prucnal, P. R. & Sorger, V. J. Emerging Devices and Packaging Strategies for Electronic-Photonic AI Accelerators. *Opt. Mater. Express* 12, 1347-1351(2022).

**Acknowledge**

This work was performed in part at the George Washington University Nanofabrication and Imaging Center (GWNIC). Thin film material analysis is supported from NIST Center for Nanosacle Science and Nanotechnology (CNST), and J.A. Woollam Co. V.J.S. is supported by AFOSR (FA9550-20-1-0193) under the Presidential Early Career Award in Science and Engineering (PECASE).

**Contributions**

M.M., J.M. and V.J.S. initiated the project and conceived the experiments. J.M. and C.P. fabricated the devices. J.M. performed the measurements and data analysis. J.M. and M.M. provided modelling and the theoretical analysis. X.M. performed supporting experiments. D.V.T. provided planarized photonic chips. J.M., N.P and V.J.S. co-wrote the manuscript, and J.J. provided suggestions throughout the project. All authors discussed and commented on the manuscript.