Integrated Optical Memristors

Nathan Youngblood[1], Carlos Ríos[2,3], Wolfram Pernice[4] & Harish Bhaskaran[5]

[1] *Department of Electrical & Computer Engineering, University of Pittsburgh, 1238 Benedum Hall, Pittsburgh, PA 1526, US; nathan.youngblood@pitt.edu*

[2] *Department of Materials Science & Engineering, University of Maryland, 8228 Paint Branch Dr., College Park, MD 20742, US; riosc@umd.edu*

[3] *Institute for Research in Electronics & Applied Physics, University of Maryland, 8228 Paint Branch Dr., College Park, MD 20742, US*

[4] *Kirchhoff-Institute for Physics, Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany; wolfram.pernice@kip.uni-heidelberg.de*

[5] *Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK; harish.bhaskaran@materials.ox.ac.uk*

Abstract

Memristors in electronics have shown the potential for a range of applications ranging from circuit elements to neuromorphic computing. Such an ability to vary the conductance of a channel in electronics has enabled in-memory computing in recent years – attracting significant interest in memristors. Optical analogs will require modulation of the transmission of light in a semicontinuous and nonvolatile manner. With the proliferation of photonic computing, such an optical analog, which involves modulating the optical response in integrated circuits while maintaining the modulated state afterwards is being pursued using a range of functional materials. Here we review recent progress in this important and emerging aspect of photonic integrated circuits and provide an overview of the current state-of-the-art. Optical memristors are of particular interest for applications in high-bandwidth neuromorphic computing, machine learning hardware and artificial intelligence, as such these optical analogs of memristors allow for technology that combines ultrafast, high bandwidth communication of optics with local information processing.

1. Introduction

The missing fourth circuit element proposed by Leon Chua in 1971, coined as a memory resistor or "memristor," was later demonstrated in nanoscale systems in which solid-state electronic and ionic transport are coupled under an external bias voltage.[1] The ability to actively modulate electrical signals and hold memory states—comparable to synaptic activity in the mammalian brain—has opened new avenues to reconfigurable integrated circuits. Brain-inspired analog computing is one of them. Mimicking the synaptic response, memristors have been used to carry out computational tasks where both processing and storage are co-located.[2–4] This task has been achieved using various materials and nanoscale devices, although searching for new platforms is a continuing effort.[4] Motivated by the exceptional properties of memristors and their technological potential, the Optics and Photonics community has searched for an optical analog to such device, the optical memristor, a device capable of modulating the light amplitude and holding the state in a nonvolatile manner. Recent years have seen significant progress towards this goal, with materials and device platforms achieving outstanding proofs-of-concept of various optical memristive phenomena (see Figure 1).[5] In particular, on-chip integrated optical memristors have enhanced and opened new paradigms in reprogrammable Photonic integrated circuits (PIC), where nonvolatility had long been elusive.[6] Exploiting the nonvolatile response of optical memristors, new applications have emerged:

- **Trimming:** Post-fabrication trimming of photonic integrated circuits (PICs) is crucial for the correct operation of on-chip optical systems since most PICs are based on fabrication-sensitive structures, such as resonators and interferometers. Trimming optical devices have been achieved using write-once mechanisms such as modifying the composition at the interfaces of the waveguides with optical[7] or electrical pulses.[8] However, dynamic optical memristors enable "active" trimming in devices whose applications need sporadic reprogramming.[9]
- **Optical memories:** data storage is crucial in any computing task. Limited by the von Neumann bottleneck, the efficiency problems in conventional architectures could be solved by fetching and storing data at the speed of light between processor units and memory banks.[10] Thus, optical memories have gathered increasing attention, promising to speed up processing, reduce Joule-heating, and allow for parallel processing (via wavelength division multiplexing (WDM)). This is a task that materials displaying optical memristive behavior—even if between two stable states only—are well suited to perform, especially those with demonstrated long-retention such as phase-change[11] and ferroelectric materials.[12]
- **In-memory computing:** if in addition to the abovementioned qualities of optical memories, the memristive material displays a well-behaved multilevel response, computing can be directly realized on the memory via scalar-scalar multiplication[13] or accumulation-based operations.[14] Computing in memory would complement the von Neumann architecture since the memory–processor dichotomy disappears. This brain-like architecture enables efficient matrix-matrix multiplications—essential for all machine learning tasks—with demonstrated ultra-high throughput resulting from the speed and multiplexing.[15] Computing approaches are performance demanding and thus optical memristors with a linear, precise, and semicontinuous response, long-retention, and large cyclability are necessary.
- **Artificial synapses and brain-inspired architectures:** mimicking long-term synaptic plasticity is the first step towards building spiking integrate-and-fire computing architectures that aim to imitate how a mammalian brain processes information. Like in-memory computing, this brain-inspired approach would bring storage and processing to the same and only place. The combination of nonlinear output and nonvolatile storage is a task a dynamic memristor with long retention is perfectly posed to perform, especially if exploiting, in addition, the high throughput enabled by optical processing.[14,16]

Most demonstrated optical memristors have been reported on the level of one or few devices. System-level research remains challenging due to factors such as the lack of understanding of material's failure mechanisms, and the low yield and complex fabrication, which in some cases is exacerbated by the lack of infrastructure and a "master plan" in the scientific community.[17] Indeed, optical memristors hold promise for unique applications, but a significant, coordinated effort is necessary to reach real-world technology maturity levels. To landscape the current state of optical memristors, we survey in this review the developments, materials, and device platforms, and provide a discussion on the challenges and opportunities in the fast-growing field of optical memristors. We want to note that while optical memristors can be used as nonvolatile multilevel optical memories, not all optical memories are optical memristors. Devices displaying binary, volatile, or bistable storage are not memristors, and therefore, they are not discussed at length in this review. For in-detail information on state-of-the-art optical memories, in the most general sense, we refer the reader to other reviews.[10,18] Lastly, this review focuses on experimental demonstrations using photonic integrated circuits as a platform for seamless scalability.

For optical memristors in free space applications, not included herein, we direct the reader to other comprehensive reviews.[5,19]

2. What makes an "ideal" optical memristor?

Optical memristors modulate the amplitude of light between semicontinuous nonvolatile states. An "ideal" optical memristor simultaneously optimizes retention time, programming speed, cyclability, precision, and modulation depth – beyond the typical size, weight, power, and cost (SWaP-C) metrics. Focusing only on optical devices that are waveguide integrated for on-chip light modulation, some features that an ideal integrated optical memristor should include:

Retention time and stability: these properties are material specific. Some platforms based on carrier mobility or trapping are prone to short lifetimes due to thermal dissipation or external fields. Other materials such as phase-change materials display nonvolatility spanning over decades at room temperature,[20] but this varies at higher temperatures. An ideal memristor should use materials that display retention times over decades but, in addition, phase and chemical stability at high temperatures to make them compatible with CMOS processes and platforms with high operational temperatures due to external heating sources, such as neighboring electronics.

Programming Speed: this property is the speed at which the transmission of the optical memristor can be modulated for a single operation. Ideally, switching to any state should be close to GHz speeds, and different switching operations, regardless of the initial and final states, should take the same amount of time. However, in reality, the average and maximum switching times are of most interest since some memristive phenomena rely on "asymmetric" processes such as phase transitions or ferroelectric domain orientation that obeys to different excitations depending on the targeted transmittance. This, of course, not only relates to the memristive technology used, but also depends on the modulation methodology (electronic or optical) and associated delays.

Modulation depth: this property is linked to both the optical properties of the memristive material and the light-matter interaction of choice. To improve the modulation depth there are two main options: 1) using materials that display large changes in real (Δn) and imaginary (Δk) refractive index; 2) exploiting physical phenomena that enhance the light-matter interaction in cases where the optical modulation is weak (e.g., filamentation). An ideal scenario would naturally be the combination of both approaches in a single optical memristor that is compact and simultaneously optimizes size and optical response. Additionally, the insertion loss of the "OFF" state, defined as the highest transmission state, should be negligible to minimize energy penalties.

Precision: an ideal memristor should store and address intermediate states in a deterministic and continuous manner. Achieving this depends on the material's switching mechanism and the device geometry, where factors such as poor mode overlap, parasitic losses (especially if proportional to the state of the material, such as scattering), or uncertainty in reproducibility rising from material variation hinder the specific level information.

Fabrication compatibility: CMOS compatibility is the ideal scenario to make the ideal optical memristor a device that can be readily integrated into current foundry processes, either directly or with frontend or backend processes that are scalable.

Footprint, power consumption, and cost: the economics of optical memristors matters, and as with most technologies, an ideal device must possess a small size, power consumption, and cost. Size is directly proportional to the strength of the light-matter interactions, and technologies that maximize integration density are ideal given the cost of chip space. Component weight is negligible for integrated photonics since it is dominated by the packaging of the chip, which in turn depends on the photonic architecture. Power consumption is always critical. However, since memristors are nonvolatile, static power consumption is inherently not an issue. Instead, innovation in optical memristor technologies focuses on developing devices with low-energy switching, long retention time (to avoid refreshing), and ideally, operating with powers (a few mW or less) and voltages (sub-5V) compatible with CMOS architectures. An ideal optical memristor should use abundant materials with simplified fabrication and materials that are compatible with or already part of standardized mass fabrication processes.

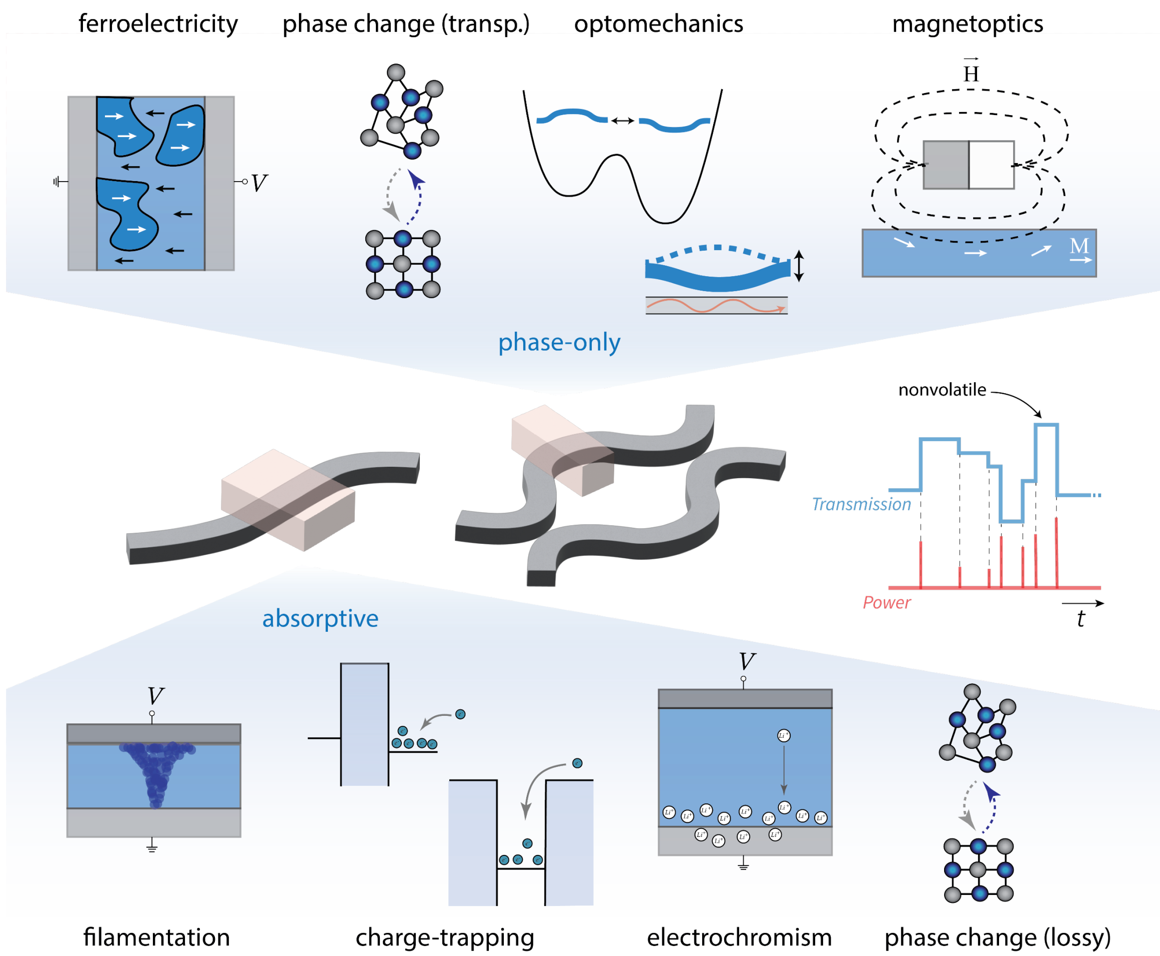

Figure 1 . Optical memristors for nonvolatile transmission modulation using phase and absorptive memristive phenomena

3. Integration and Control Methodologies

The first challenge faced by optical memristors is their fabrication. While the number of active materials with exciting properties are growing, their waveguide integration is not always a seamless process nor is the prospect of making waveguides out of the active material itself. Beyond silicon-based PICs, the surge of active optical materials such as Al_2N_3, $LiNbO_3$, $BaTiO_3$ (BTO), GaAs, InP, etc. expands the library of on-chip waveguiding platforms, each with its fabrication and compatibility restrictions.[6,21–23] Essential aspects such as lattice coherency, adhesion strength, electrical contact type, and temperature processing compatibility are crucial to achieving successful integration with the correct phase state and minimal losses by, for instance, avoiding interfacial defects. To a large extent, the choice of platform has been influenced by the proliferation of CMOS foundries with dedicated photonics process lines, making CMOS-compatible processes at the frontend, backend, or throughout the most sought-after goal. However, as described throughout this review, optical memristors have been demonstrated in a variety of platforms that may or may not meet these strict requirements.

Evanescently coupled memristive materials

Most optical memristors on PICs rely on evanescent coupling of a waveguide mode to an active material embedded in the cladding which often simplifies fabrication. This methodology also guarantees a straightforward CMOS-backend integration if the active material can be deposited onto silicon-based materials and high temperatures are avoided—annealing over ~800 K is detrimental to metal contacts. An alternative approach, while not demonstrated yet in this context, is to deposit optical memristive materials under the waveguide by processing the rear side of the wafer.[23]

Active materials that are deposited in the amorphous state are compatible with, virtually, any substrate which makes evanescent coupling an obvious choice. Since lattice coherence is not a concern, amorphous materials are good candidates for simplified CMOS-backend deposition, especially onto passive waveguides in which the material is usually embedded in the cladding. Most chalcogenide PCMs fall in this category since they are deposited in a glassy state and at room temperature. Sputtering,[24] thermal evaporation,[25] and pulsed laser deposition are all proven fabrication methods which, when combined with lift-off[9,15,26] or etching,[27] enable a variety of photonic devices for nonvolatile programming, storage, and computing as discussed in Section 4. Silicon or silicon nitride rib waveguides are frequently employed due to their simplified fabrication and imminent standardization through photonic foundries.

Materials with more stringent fabrication restrictions, such as 2D materials, are typically first grown on a compatible wafer, then transferred onto photonic substrates which enables evanescent coupling to waveguides which are typically pre-patterned.[23,28] Other heterogeneous integration methods transfer active materials using a wafer bonding process[23,29] or direct deposition which requires special consideration of crystalline orientations and the possible need for a buffer layer.[30] Examples of this are materials grown at high-temperature by Chemical Vapor Deposition (CVD) or Molecular Beam Epitaxy (MBE) for high-quality crystals, such as MBE-grown In_2Se_3.[3132]

Waveguides comprised of materials with memristive functionality

Using memristive materials to guide the optical mode can further enhance the modulation efficiency since the overlap of the optical mode with the active material is much larger than with evanescent coupling. Many typical waveguide materials can be manipulated to exhibit optical memristive properties in addition to optical transparency, as in the case of optomechanical modulation of waveguide microbeams[32] and other electrically controlled mechanical photonic circuits (see *Optical memristors from micro-electromechanical systems* in Section 4).[33,34] Other possibilities include building reconfigurable, nonvolatile photonic integrated circuits with ferroelectric materials such as BTO,[12] chalcogenide waveguides with tailorable properties via external light excitation,[33] or by using bistable effects in semiconductor waveguides[34] or locally doped semiconductor waveguide.[7,8] The recent years have also seen a surge in the integration of electrochromic effects on PICs, some of which exploit both the optical waveguiding and the ionic conductivity of $LiNbO_3$ to create an optical memristor in combination with an electrochromic oxide to modulate transmission in PICs.[35]

Addressing memristive materials

While all-optical switching has use in certain applications, such as photonic neuromorphic architectures,[14,15] the relative ease of generating, routing, and interfacing with external electrical signals makes electronic programmability of optical memristors an obvious choice. Achieving electrical control of nonvolatile materials on PICs is a direct route for scalable optical memristor technologies, especially if using CMOS-compatible materials and voltages. Optical memristors with electrical programming have been achieved by exploiting a variety of physical phenomena, geometries, and material platforms. The electrical tunability of active nonvolatile materials is achieved mainly via the following types of devices:

Capacitors and band-engineered devices. Charge trapping in capacitors placed in the vicinity of the waveguides results in nonvolatile light modulation because of refractive index and absorption variations in the presence of charges. Devices employing metal-oxide-semiconductor (MOS) capacitors have been demonstrated and are arguably the fastest route for CMOS-compatible optical memristors given their complete foundry compatibility but can be limited by large footprints and weak nonvolatility.[36] Similar approaches use quantum wells to trap charges in metal-nitride-metal wells built on top of the waveguide cladding. [37]

Microheaters. Electro-thermal switching of large-area ($>0.25\mu m^2$) PCMs using integrated microheaters has gained terrain. CMOS processes involving the fabrication of doped-silicon structures as resistive heaters, including the silicon waveguide itself, are the most explored platform thus far.[9,26] Another alternative is to use CMOS-compatible metals to build on-chip microheaters. However, the trade-off between losses for metals in the proximity of the waveguide or long thermal constants for the metal heater far from the active material has been a continuing challenge. Recent demonstrations have shown waveguide integrated switching of “slow” PCMs (i.e., those with transitions in the microsecond time scale) such as $Ge_2Sb_2Se_5$ using metal heaters,[38] and the adoption of a hybrid plasmonic structure was used to bring the metal heater close to the waveguide.[39] In either case, PCM deposition remains a back-end process although the $Ge_2Sb_2Te_5$ integration to microelectronics foundry processes allows one to be optimistic about the future of these materials in photonic foundries.[3]

Polarizing electrodes. Electric fields inside a ferroelectric material embedded between two metal electrodes result in a polarization that enables nonvolatile optical modulation through the Pockels effect. As explained in detail below, this effect has been exploited mainly using BTO. However, this material requires high temperatures and a high-quality crystalline template for deposition. Molecular Beam Epitaxy of BTO on $SrTiO_3$-buffered silicon-on-insulator (SOI) substrates, followed by a wafer bonding process has been successfully demonstrated as a CMOS-frontend process.[40] Importantly, the optical transparency of BTO allows it to be used as either the waveguide or as the cladding material.

Filamentation. Leveraging the accumulated know-how from resistive filamentation in conventional memristors, new photonic devices have taken on the quest of integrating them into PICs while simultaneously achieving a measurable optical read-out—a non-trivial task given the reduced interaction area between an optical mode and the filament. Filamentation is observed in several metals, oxides, and phase-change materials. The latter has seen integration to PICs using plasmonic effects to enhance the optical modulation of the reprogrammable filamentation mechanism.[41] Waveguide-coupled plasmonic effects have also been exploited to optically probe a filament of silver atoms penetrating amorphous silicon under controlled electrical pulsing.[42] While gold and silver were used in these plasmonic demonstrations, other CMOS-compatible metals such as copper, nickel, aluminium, and chromium can be considered. Notably, an approach with CMOS compatibility has been demonstrated using filamentation of oxides such as HfO_2 on a waveguide cladding, employing doped semiconductors as electrodes.[43]

Ion conductors. Ion dynamics in solid-state electrolytes can trigger electrochromic effects via ion intercalation in metal oxides such as WO_3, MoO_3, TiO_2, and others. However, these transport-limited effects are slow, and integrating such devices is a challenge due to their total CMOS incompatibility.[44] On the other hand, the maturity of battery and fuel cell fabrication employing these materials could be leveraged to create a hybrid process that brings this platform closer to non-CMOS scalable photonic technologies.

Magnets. Magnetic fields can induce optical modulation in magneto-optical (MO) alloys such as Cerium-substituted yttrium iron garnet ($CeY_2Fe_5O_{12}$ or Ce:YIG). While some devices employ external magnets to control on-chip MO materials,[45,46] the real challenge is to achieve a tunable magnetic field in a fully integrated manner. An alternative is to use the magnetic field induced by electrical currents to control the nonvolatile magnetization of alloys such as CoFeB, which in turn acts as the magnet that controls the MO response of Ce:YIG.[47]

4. Survey of Optical Memristor Technologies

Phase-change materials for optical memristors (phase and amplitude)

In recent years, chalcogenide-based phase-change materials have received significant attention as a promising material platform for integrated optical memory and reconfigurable photonic devices. This can be attributed to this material family's unique combination of large optical contrast ($\Delta n \sim 0.5$ to 3.5), fast switching speed (~1–100 ns), high cyclability (10^9–10^{12}), mixed phase stability (>64 intermediate optical states[27]), long-term retention (estimated to be >10 years), extremely flexible tuning of stoichiometry and thus material properties,[48,49] and ease of deposition (thermal evaporation, sputtering, solution-based, etc.). Additionally, these materials exhibit significant changes to their electrical, thermal, and mechanical properties,[50–52] giving rise to the intriguing concept of "mixed-mode" memory cells[39,53] which could provide efficient transduction between electrons, photons, and phonons. Here, we discuss recent progress in phase-change devices for waveguide-integrated optical memristors and highlight important areas of research for continued innovation in this field. We refer the reader to other review articles on this topic for a more comprehensive and historical overview of optical phase-change materials (O-PCMs) and devices.[54–56]

With recent demonstrations of photonic integrated memory[11,57], switches[58,59], and analog computation[13–15], there has been a concerted effort in the last few years to reduce optical loss of O-PCMs while still maintaining large optical contrast at these wavelengths. A common figure of merit (FOM) used by the optical phase-change community is the ratio of the real and imaginary refractive index contrasts when the materials is switched between the amorphous and crystalline states:

$$\mathrm{FOM}_{\mathrm{phase-mod}} = \frac{\Delta n}{\Delta k}$$

where $\Delta n = n_{cry} - n_{am}$ and $\Delta k = k_{cry} - k_{am}$. While ideal for phase-modulated devices, this FOM choice does not necessarily optimize the material for optical attenuation or reduced insertion loss in the amorphous state. Thus, for absorption-modulated optical memristors, a preferred metric is:

$$\mathrm{FOM}_{\mathrm{abs-mod}} = \frac{\Delta k}{k_{am}}$$

With these two FOM in mind, we compare Δn and Δk for various O-PCMs in **Figure 2**.

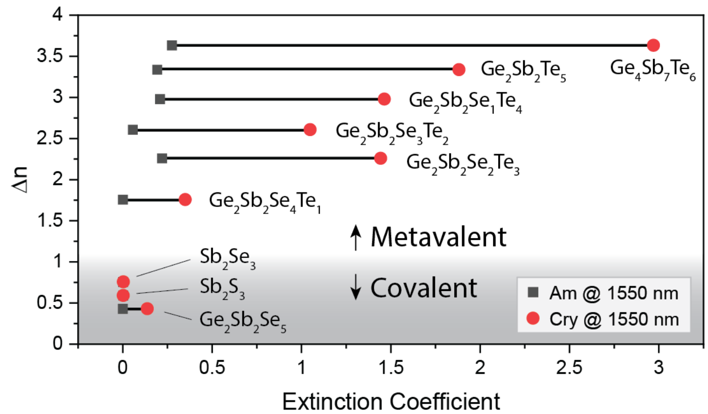

Figure 2: Comparison of various PCMs for optical memristors. Metavalent PCMs typically show higher modulation of refractive index and have faster crystallization dynamics compared to covalent PCMs, but with higher optical losses. The extinction coefficient refers to the imaginary part of the complex refractive index.

Extending the transparency window of O-PCMs in the near- to mid-infrared has seen significant progress in the past few years. $Ge_2Sb_2Se_4Te_1$, a cousin of GST, is a notable new addition to the O-PCM family[25]. Zhang et al. demonstrated that it was possible to increase the bandgap and reduce free carrier absorption of $Ge_2Sb_2Te_5$ by substituting lighter Se atoms for the heavier Te ones. This leads to an O-PCM with negligible absorption in the amorphous state for λ > 1.2 µm. Advances in materials discovery through machine learning (ML) have also yielded successful results in the field of O-PCMs. Recent work by Kusne et al.[60], used ML techniques to find a new composition of GST ($Ge_4Sb_6Te_7$) which maximized the change in optical bandgap over commonly used $Ge_2Sb_2Te_5$[60]. Finally, Sb_2S_3 and Sb_2Se_3 have emerged as promising O-PCM candidates with very low optical losses in both the crystalline and amorphous states[24,61,62]. Unlike GST and its close cousins which transition from metavalent to covalent bonding upon transition from the crystalline to amorphous phase[63], these low-loss O-PCMs are covalently bonded in both states. This limits both the maximum optical contrast and switching speed in these materials since changes in refractive index are primarily due to changes in density rather than bond type[64]. Despite this, Sb_2S_3 and Sb_2Se_3 have shown great promise for nonvolatile phase control in reconfigurable photonic circuits.[9,24,62,65] For emerging applications, such as quantum computing and networking, continued exploration is needed to find new O-PCMs which reduce optical losses at quantum relevant wavelengths (both visible and near-infrared).

Improving the endurance and scalable control of O-PCMs are additional challenges which have seen substantial progress recently. While integrating O-PCMs can be as simple as depositing the material directly onto a waveguide, recent work has highlighted the importance of minimizing reflow of the O-PCM through nanopatterning and encapsulation techniques. These techniques have significantly improved cyclability and optical contrast[59] and were also used to create tunable compact mode converters, giving rise to an additional degree of freedom for information storage.[27,66] To enable scalable control of many phase-change devices on a single chip, the development of electrically switched O-PCMs has been a major research focus in recent years. The main challenge of this electro-thermal approach lies in the combined requirements of high temperatures for amorphization ($T_{melt} \approx 900$ K), high cooling rates for the melt-quench process (>10 °C/ns), and high endurance of the microheater and surrounding layers. Resistive microheaters using metal[25,67], conductive oxides[68], doped silicon[9,26,69], and graphene[70] electrodes have

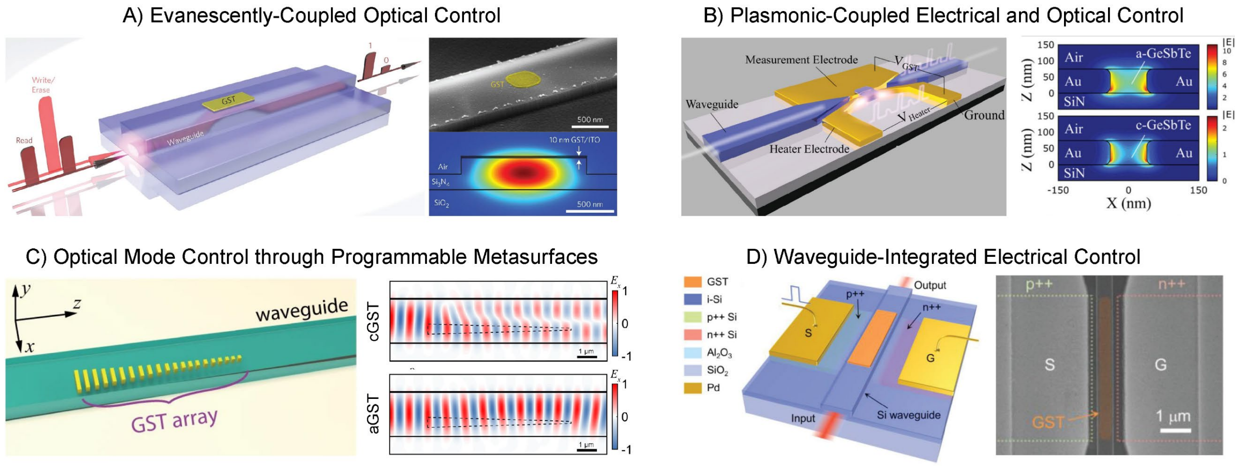

Figure 1: Integration approaches to phase-change optical memristors. a) Evanescent coupling enables easy device fabrication and provides convenient access for optical control.[54] **b)** Waveguide-integrated plasmonic electrodes can provide strong optical and electrical coupling and enable mixed-mode operation for conversion of information between optical and electrical domains.[42] **c)** Nanopatterning techniques have been used to enable tunable mode converters. A differential measurement scheme can then be used to measure the optical contrast between the TE_0 and TE_1 waveguide modes for computing applications.[25] **d)** Waveguide integrated microheaters (e.g., doped silicon, PIN diodes, metallic, etc.) enable a scalable method for control of a large number of devices.[24]

been successful in reversibly switching various O-PCMs on the 1 μm^2 to 100 μm^2 scale. Achieving high switching efficiency and high cycling endurance, however, remains an outstanding challenge for electrically switched O-PCMs. Integrated microheater designs such as doped silicon waveguides[9,26] and graphene sheets[70,71] could address these challenges by reducing the thermal mass of the microheater.

Optically addressable electronic memristors (amplitude)

In addition to phase-change materials, other mechanisms which enable nonvolatile electrical memory (e.g., nanoscale electromigration in metal-oxide memristors) can induce optical changes as well. However, typical dimensions of electronic memristors range from tens to hundreds of nanometers, which limits light-matter interaction and can cause coupling difficulties in traditional PICs. Nanoplasmonics is an effective method to address both challenges since light is no longer diffraction limited and can therefore be focused into volumes much smaller than the optical wavelength—greatly enhancing interaction with nanoscale electronics[72,73]. This approach has been used to couple filamentary resistive memory[42,74,75] and electronic phase-change memory[39,41] to photonic waveguides which combines both optical and electrical readout in the same memory cell. A notable exception to this plasmonic approach has been the use of modulating semiconductor-oxide-semiconductor memristors comprised of a III-V material, Al_2O_3 or HfO_2 oxide, and doped silicon waveguide.[76] Conductive filaments of oxygen vacancies created by an applied electric field in the oxide layer switches the device between low and high resistance states. The refractive index can then be modulated when a voltage bias is applied due to either the plasma dispersion effect (high resistance state) or thermo-optic effect due to Joule heating (low resistance state). However, this approach requires a constant electrical bias (and constant power dissipation in the low resistance state) to observe a change in the optical signal.

A major challenge for plasmonic memristor approaches is optical insertion loss due to propagation loss of the plasmonic mode as well as conversion losses between the photonic and plasmonic modes. While theory predicts high coupling efficiencies between plasmonic and photonic waveguides, surface roughness and resistive losses of the metal typically reduce measured efficiencies in fabricated devices[77]. Additionally, experimental devices with nonvolatility have also shown relatively small optical extinction ratios which limits the number of stored bits which can be resolved. Despite these limitations, a hybrid plasmonic-photonic approach has enabled optical memory cells with the smallest footprints to date, making them highly attractive for emerging applications in photonic computing.[72]

While lacking optical readout, filamentation of oxides has been enhanced by optical signals in waveguides which allows for a better performance of electric-only memristor.[78] In such devices, light-enhanced memristors in recognition applications displayed accuracies closer to ideally performing memristors and much higher than those without light.

Charge-based optical memristors (phase and amplitude)

Techniques for introducing bistability in electronic memory cells (e.g., nonvolatile flash memory) can also be applied to photonic devices. A typical approach is to replace the gate oxide of a metal-oxide-semiconductor (MOS) capacitor with additional oxide and charge storage layers using a charge-trapping or floating-gate approach[79]. For photonic applications, the intermediate charge storage layer can be a semiconductor (e.g., doped silicon[80]), dielectric (e.g., silicon nitride[81]), or more exotic material with enhanced optical response (e.g., ITO[82] and graphene[83]). The trapped charges can then be used to modulate the optical properties of the waveguide through the plasma dispersion effect in a nonvolatile manner. Notably, this approach is compatible with current CMOS process flows and is not limited to binary operation[80]. However, charge-based effects are relatively weak in bulk optical materials, which require either devices with resonance or a large footprint.

Flash-based approaches are limited by the capacitance and thickness of the trapping oxide and therefore are relatively slow, require high programming voltages, and can have limited cycling endurance due to damage to the oxide[79]. The lifetime of the memory cell is dependent on the discharge of the capacitor through leakage currents and any defects or damage to the oxide will render the device inoperable. Using tunneling effects rather than hot carrier injection can reduce the operating voltage and improve the cycling endurance and several charge-trapping memories have been proposed[82,84,85]. To date there has been few experimental demonstrations of charge-based optical memory, but with the advent of photonic computing architectures in need of tunable nonvolatile weights, we expect to see more device demonstrations from the research community in the near future.

Ferroelectric optical memristors (phase)

While the plasma dispersion effect in silicon has many advantages in terms of ease of integration with current CMOS process flows, it is not possible to modulate the optical phase without introducing loss due to free carrier absorption. For phase only modulation, nonlinear optical materials are needed which respond to the electric field through mechanisms such as the Pockels or Kerr effects. The Pockels effect, in particular, has the advantage of responding linearly to the applied electric field (compared to the Kerr effect which depends on the electric field squared[86]), leading to ultra-low power devices. However, typical waveguide materials do not display a Pockels effect. Some are centro-symmetric with a vanishing Pockels effect, like unstrained silicon, while others are amorphous and lack electro-optical activity, like silicon nitride. $BaTiO_3$ (BTO) has recently emerged as a promising nonlinear material for efficient phase-only modulation with one of the highest Pockels coefficients reported ($r_{42} \sim 923$ pm V^{-1}). While typically challenging to integrate on silicon,[87] Abel et al. recently demonstrated a high yield approach for large scale integration of BTO with silicon-based photonic circuits using a combination of epitaxial growth and direct

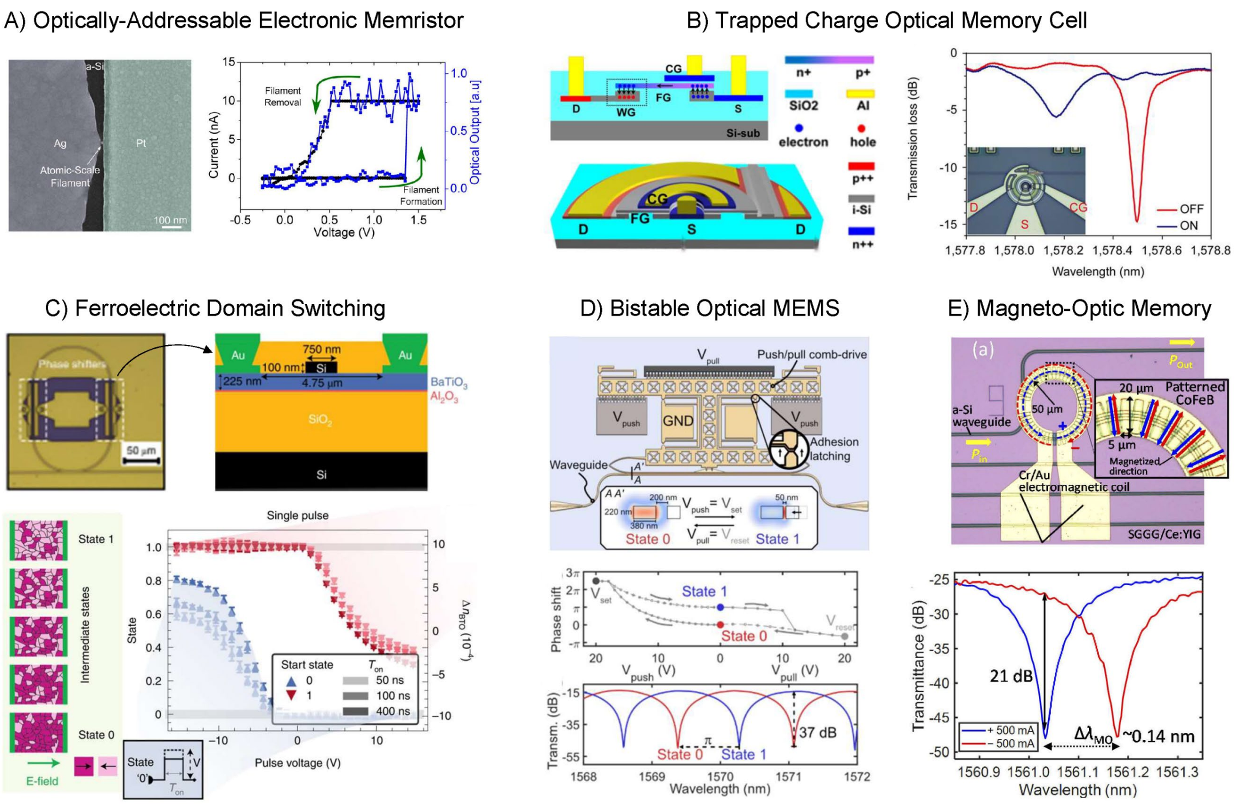

Figure 3: Survey of nonvolatile, waveguide-integrated optical memristor technologies. A) Optically-addressable electronic memristors typically rely on using a filament to modulate a plasmonic device, such as that demonstrated by Emboras *et al*.[75] **B)** Optical memory cells with floating gates can be used to trap charge in a nonvolatile manner similar to electronic flash-based memory. The trapped charge modulates the optical properties of the sil[75] through the plasma-dispersion effect.[80] **C)** Ferroelectric domains within materials, such as BTO, have been demonstrated to retain their state after switching with an electric field. A constant bias field is required to observe the stored state optically.[12] **D)** Mechanical bistability is a promising method for achieving high contrast, single bit optical memory.[92] **E)** Magneto-optic materials, such as Ce:YIG, can be made bistable when combined with a magnetic layer, such as CoFeB. The result is high contrast, multilevel optical memory as demonstrated by Murai *et al*.[47]

wafer bonding[29]. Because BTO is a ferroelectric material, this also allows storage of optical information by switching nonvolatile ferroelectric domains through the application of an electric field. While initial demonstrations of nonvolatile storage were limited to 10 levels, recent reports have demonstrated over 100 levels (>6-bits) with over 10 hours of stability in BTO-Si microring resonators[12], although further validation of these results are required to establish the reliability of these materials and devices.

Despite the ferroelectric nature of BTO, a constant field bias is needed to observe a change in refractive index. While a nonvolatile phase shift was observed at zero field bias in early demonstrations of the platform, this was due to effects unrelated to ferroelectric domain switching, such as the charging of defect states which were also a cause of high propagation losses (47–98 dB/cm). Later implementations addressed this issue through a post-process annealing step which successfully removed unwanted hydrogen from the BTO films[88], thus removing the nonvolatile phase shift at zero applied bias[12,29]. It is also worth noting that more traditional ferroelectrics (e.g., $Hf_{0.5}Zr_{0.5}O_2$) can be combined with silicon photonics to create nonvolatile optical memory through electrostatic doping[89]. While this approach does not require a constant bias to readout the state of the memory cell, it is fundamentally different than that of the

Pockels effect since the modulation depends on the plasma dispersion effect in silicon rather than the ferroelectric itself.

Optical memristors from micro-electromechanical systems (phase and amplitude)

Combining integrated photonics with micro-electromechanical systems (MEMS) is another approach which can be used to reconfigure photonic devices for memory and routing applications. Both optical phase[90] and transmission[91] can be modulated by physically changing the gap between two waveguides through electrostatic forces applied to a moveable cantilever.[32] Also, by designing the MEMS switch to have mechanical bistability through adhesion forces[92], latching[93], or buckling of a membrane[94], it is possible to design binary optical devices with nonvolatile memory. It is important to note that while analog phase control has been demonstrated in MEMS-based phase shifters[90,95], nonvolatile control has been limited to binary states (i.e., “off” or “on”). While not meeting our definition of an optical memristor, adding latching functionality to analog photonic MEMS devices would allow nonvolatile, continuous control of the optical field.

Low power switching (nW/device), low insertion loss (<0.1dB/device), high extinction ratios (>30dB), and foundry compatibility are the main advantages of MEMS-based PICs[95]. However, these devices typically have large footprints (50 μm^2 – 200 μm^2), are relatively slow (100 kHz – 10 MHz), and typically require high operating voltages (5V–60V) compared to other solid-state approaches. Many of these challenges can be addressed by employing hybrid plasmonic-photonic devices[96] which was shown to significantly reduce the switching voltage (1.4V) and footprint (10 μm^2).

Magneto-optic memristors (phase)

Magneto-optic (MO) materials on integrated photonics have been employed to break time reversal symmetry and achieve optical isolators.[45] These devices use the polarization and refractive index dependance of the material as a function of an external magnetic field. The challenge of integrating MO materials into PICs is applying the magnetic field that locks in the optical response. Traditionally, this is achieved using external magnets; however, this is detrimental to the packaging and portability of such devices, including also co-lateral effects in other magnetic sensitive on-chip components. The realization of magneto-optic memristors face this challenge but the fact that the MO modulation is a volatile effect that requires a constant magnetic field. To overcome the latter, a light-induced thermomagnetic approach was proposed to record information in thin-films of CoFeB evanescently coupled to a silicon waveguide.[46] However, an external coil was used to apply the magnetic field. A clever approach to solve both issues simultaneously used two magnetic materials: one as a nonvolatile tunable magnet, and the second as the magneto-optic modulator evanescently coupled to the waveguide. [47] The device, shown in Fig. 3e, uses the MO Ce:YIG under a silicon waveguide and a CoFeB magnet strip array in the cladding that displays nonvolatile magnetization upon a current-induced magnetic field. This way, the optical response of the magneto-optic memristor can be control by simply applying a current through a metal path, a process that should, in principle, led to a high cyclability and yield. The fabrication, however, is complex, the currents are large (~400 mA) to compensate for the relatively weak modulation (~250 µm to achieve $\pi/2$ phase modulation).

Emerging Technologies

Other emerging platforms include electrochromic-based devices that use ion intercalation from a solid-state electrolyte into an electrochromic metal oxide to modulate the complex refractive index of the material. Such modulation, which is in principle nonvolatile if the ions remain within the metal oxide, has been used as optical memristors by modulating the electro-absorption as a function of ion conductivity. Devices employing this mechanism have been demonstrated by sandwiching both the electrolyte and electrochromic material between the waveguide (acting as an electrode) and a top metal electrode, where the electrochromic metal oxide is in direct contact with the waveguide.[44] Moreover, the first instance of a quantum-optical memristor was recently demonstrated using laser-written integrated photonic circuits fully reconfigurable by means of thermo-optical phase shifters. Such device can produce memristive dynamics on single-photon states through a scheme of measurement and classical feedback. [97]

More recently, an optoelectronic memristor with multi-factor in-memory processing through the interaction of two distinct signals, an electrical and an optical signal, was demonstrated. Using reconfigurable germanium selenide ($GeSe_3$) memristive nano-cavities, these devices produced either potentiation or inhibitory responses only when both optical and electrical signals were present. Such an optically active memristor was shown to have advanced neurosynaptic mechanisms emulated by these devices, namely three-factor plasticity for reinforcement learning and dendritic computation for nonlinear logic.[98] This area of multifactor computations using both electronics and optics and including other degrees of freedom in optics such as polarization[99] is a new emerging area that could potentially form an important aspect of the computing landscape in future.

5. Discussion and outlook

Despite the diverse technical approaches used to achieve nonvolatile optical memory on-chip, there has yet to emerge a clear winner in terms of optical performance, storage density, switching speed and energy. To illustrate this, we plot the experimentally demonstrated performance of devices across six different optical memristor technologies in **Figure 5**. One can see from these figures that while bistable optical MEMs and ferroelectric BTO can achieve very low switching energies, their storage density is low due to their large footprint. Storage density is much higher for PCMs, but the energies associated with crystallization limit their efficiencies to >1 nJ. While electronic memristors have been demonstrated with 10's of fJ switching efficiencies, the high optical insertion loss and low modulation efficiency of these devices limits their applications. It is also worth noting that an optical memristor with sub-10 ns switching speeds (for both WRITE and ERASE operations) has yet to be demonstrated in a single platform. The need for fast memory updating is important for applications in photonic computing where the stored weight array requires retraining or the size of the matrix operation exceeds the physical number of photonic memory cells.

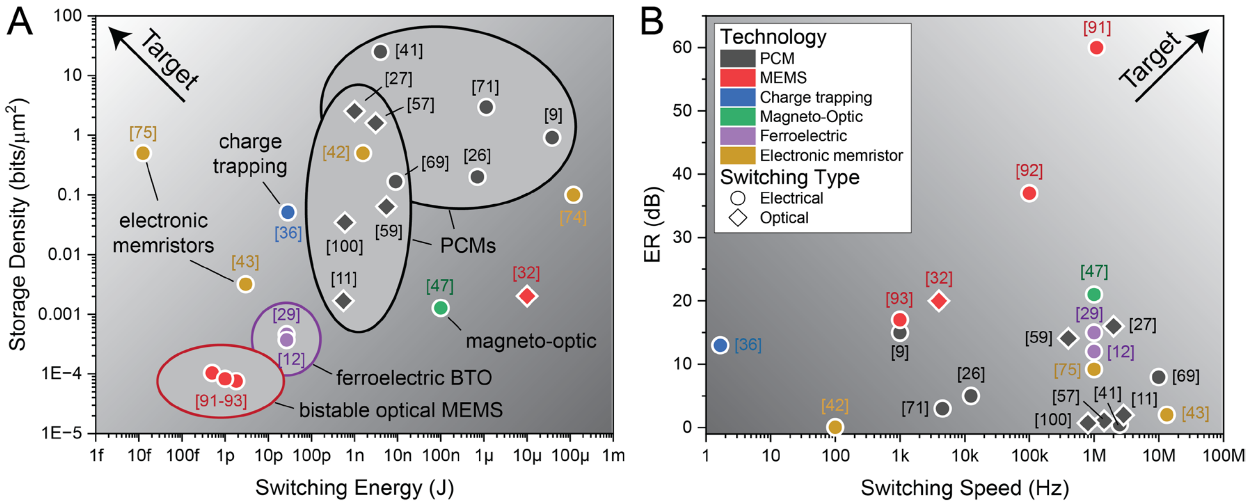

Figure 4: Comparison of different nonvolatile, waveguide-integrated optical memristor technologies. a) Storage density versus switching energy and **b)** extinction ratio versus switching speed for six different optical memristor technology types. For both switching energy and speed, the switching operation which limits the overall performance has been plotted (e.g., the slower and more energy-hungry crystallization process in the case of PCM technology). From these plots, we see that no single technology has yet been able to maximize storage density, extinction ratio, switching energy and speed simultaneously.

Table 1 provides a detailed comparison of the technologies shown in **Figure 3**. Here, we can more clearly see the relative advantages and limitations of various optical memristor approaches. For example, the single-bit resolution of bistable MEMS and electronic memristors limits their use for in-memory photonic computing architectures since there is no ability to continuously tune the optical transmission of these binary devices. In the case of charge-based floating gate optical memory, which has excellent switching energy, storage density, and extinction ratio, the programming speed requires significant improvement before this approach to optical memory becomes competitive with other technologies.

Technology (E/O switched)	Switching Speed[a]	Switching Energy[a]	Bits Stored	Footprint (µm²)	ER[b] (dB)	IL (dB)	Max. cycles demonstrated[c]
MEMS (O)	4 kHz	10 µJ	1-bit	400	20	1	>30
MEMS (E)	0.1–1 MHz	0.5–1 pJ	1-bit	>10,000	60	>0.025	10^{10}
Memristor (E)	1 MHz	12.5 fJ	1-bit	2	9.2	25	$>10^3$
Magneto-optic (E)	1 MHz	100 nJ	>3-bits	8000	21	2.5	>7
Ferroelectric (E)	1 MHz	30 pJ	>3-bits	>20,000	12	>0.07	300
Trapped charge (E)	1 Hz	30 pJ	4-bits	315	13	2	>30
PCM (E)	1–10 MHz	4nJ–10 µJ	4-bits	1–500	0.5–15	>0.4	5×10^5
PCM (O)	1–10 MHz	0.1–1 nJ	6-bits	1–310	0.7–16	>0.75	10^6

Table 1: Performance metrics of optical memristor technologies surveyed. Devices employing electrical and optical switching techniques are denoted by (E) and (O), respectively. [a]Switching energy and speed shown was chosen to be the limiting operation for the technology (i.e., WRITE or ERASE operation). [b]For PCM technologies, a high extinction ratio accompanies a larger footprint since MZI or MRRs were used to achieve high switching contrast. [c]Maximum cycles demonstrated for MEMS, Magneto-optic, Ferroelectric, and trapped charge technologies were limited by experimental choice, rather than degradation of the device under test.

A final observation is the notable difference between switching energy and cyclability when comparing electrically-switched and optically-switched PCMs. In the case of optical switching, thermal energy is much more efficiently delivered to the PCM (and removed through a fast melt-quench process), since the surrounding materials guiding the optical mode have negligible optical absorption. This results in a much more efficient switching energy during both crystallization and amorphization compared to electro-thermally switched PCMs. Additionally, in the case of electrical switching, a resistive microheater is typically required to heat the PCM above the melting temperature. Thus, the temperature of the microheater must at minimum reach the melting temperature of the PCM which causes thermal fatigue and eventual damage to the device. This effect can be seen when comparing the number of cycles between optically (O) and electrically (E) switched PCMs in **Table 1**.

Future trends and necessary improvements.

Based on our survey of the field, we have identified the following areas in most need of improvement to enable next generation integrated photonic systems:

1. **Non-volatile, multi-bit photonic MEMS:** The exceptionally high endurance and low switching energy of MEMS makes it a highly attractive platform for reconfigurable photonic systems. However, for optical memristor applications, there is an immediate need to push nonvolatile MEMS systems beyond single-bit operation. This would enable new applications for MEMS in the field of photonic computing.
2. **High-speed, trapped charge photonics:** Initial demonstrations of floating gate photonic devices are very promising especially given the promise of their compatibility with standard CMOS processes and materials. However, programming speed must improve by at least 6 orders of magnitude (sub-microsecond switching) in order for this approach to be viable.
3. **Improving endurance and efficiency in electrically programmable phase-change photonics:** The high optical contrast and multi-level programmability that has been convincingly demonstrated using phase change photonics has caused a surge of research interest in the field. This is also the only technique with demonstrations of using either only optical signals or using a combination of both optical and electronic signals to change the state of the memristor. Addressing the fundamental issues of energy efficiency and cyclability in electrically programmable phase-change photonics is an outstanding challenge.
4. **Exploring new nonvolatile materials with high switching speeds:** The best platform for optical memristor technology is still an open question. Developing new materials (e.g., magneto-optic, ferroelectric, etc.) could enable the field to expand beyond the 10 MHz speed limit we have identified. Note that high switching speeds for both WRITE and ERASE operations is crucial in practical systems—especially photonic processors. Multifactor devices and systems that are emerging (such as optoelectronic devices) will also influence the direction of the field and further research in these areas will ultimately determine the technology that will come out on top.

The optical memristor field is ripe for innovation given the growing demand for tunable photonic components, ultra-low latency photonic computing, and general purpose, reconfigurable photonic circuits. It is worthwhile noting that phase change materials remain the only technology that can effectively emulate an electronic memristor all optically (i.e., use the light within the waveguide to change the transmission of the waveguide). They can also be switched electrically using either heaters or plasmonic nanogaps. Other technologies require electrical addressing, which may be important for large-scale integration and interfacing with CMOS electronics. In any case, it is evident that a concerted effort is needed on many fronts—new materials, integration strategies, etc.—to enable integrated photonic platforms with completely new functionalities.

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