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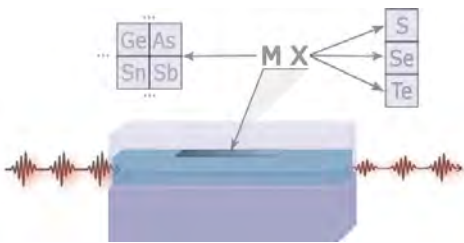
PHASE-CHANGE MATERIALS FOR PHOTONIC APPLICATIONS

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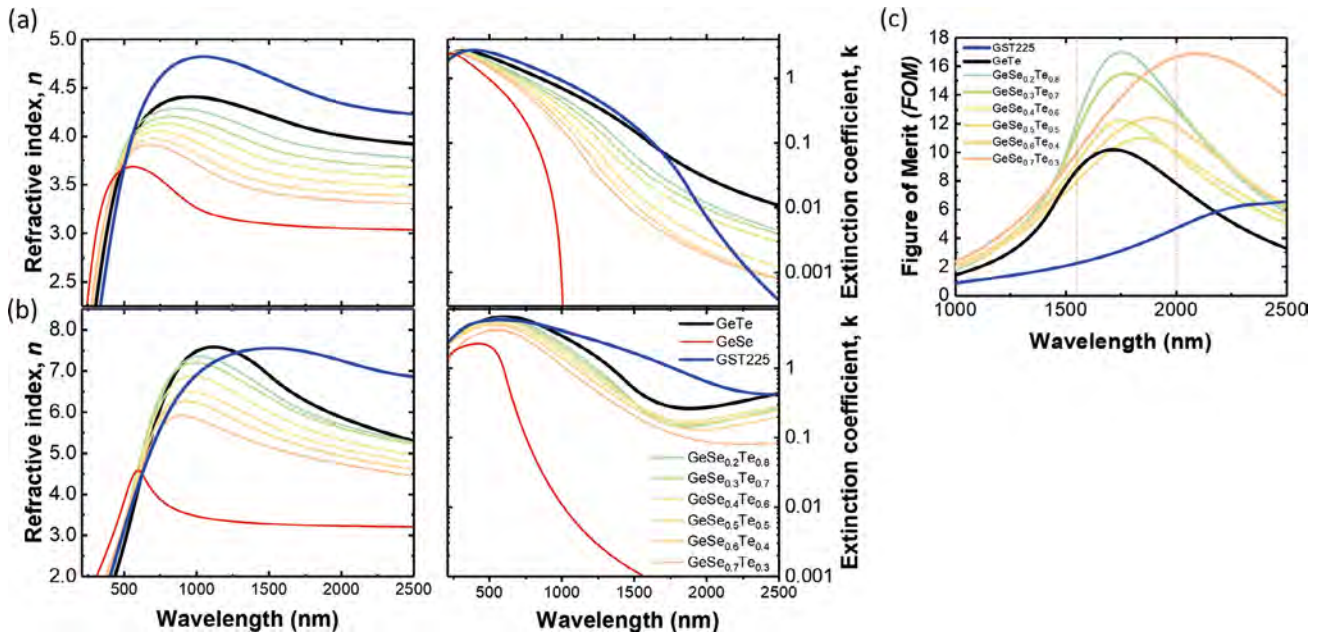
Phase-change materials (PCMs) have been growing in interest over the last decade for photonic applications. In this article, we will firstly review their properties and their key benefits with respect to concurring technologies for reconfigurable photonic devices and systems. Then, we will highlight some key open challenges PCMs are currently facing for their ubiquitous adoption. Finally, we will provide some potential routes for addressing these challenges with a focus on current activities in the Grenoble (France) region.

The need for reconfigurability in integrated optics has been a key driving force since the very first demonstrations in this field. In particular, reconfigurable photonic devices such as Mach-Zehnder (MZ) and ring resonator (RR) modulators are fundamental building blocks in the vast majority of integrated optics applications. Reconfigurability provides several benefits such as compensation for fabrication tolerances, arbitrary splitting/combining ratios in interferometers, or modulation of light beams in waveguides.

Depending on the application requirements, there are a series of constraints for reconfigurability *e.g.*, power consumption, compactness, losses, non-volatile character,

or CMOS-compatibility. Standard mechanisms are based on the thermo-optic effect through microheaters in proximity of waveguides, through electro-optic effects of different nature such as free-carriers absorption/dispersion, Pockels effect, or quantum-confined Stark effect (QCSE). While these effects are strongly used in modulators, they lack a non-volatile character and their strength in terms of refractive index contrast Δn is generally low *e.g.*, using p-n junction modulators (free-carriers dispersion effect) Δn is on the order of 10^{-3} – 10^{-4} while by using microheaters (thermo-optic effect) is on the order of 10^{-2} – 10^{-3} for standard driving conditions. These contrasts are relatively weak for implementing *e.g.*, a π shift and thus long devices (hundreds of μm to mm lengths) are

often required to compensate for this weakness. Besides, these effects are volatile *i.e.*, the stimulus needs to be constantly applied during the entire device operation. While for some applications, this can be tolerated because of continuous switching *e.g.*, in datacom applications for data encoding, for other applications where the reconfigurability time interval is much longer than the characteristic switching time, this can be deleterious from an energy-efficiency perspective. Examples of this latter category are packets switching in routers where large idle times are present or inference operation in photonic neural networks where the trained weights *e.g.*, implemented through phase shifters, shall not be modified any longer until the next training phase.



However, chalcogenide-based phase-change materials (PCMs) have been emerging as a class of materials capable of addressing both these issues.

OPTICAL AND MATERIAL PROPERTIES

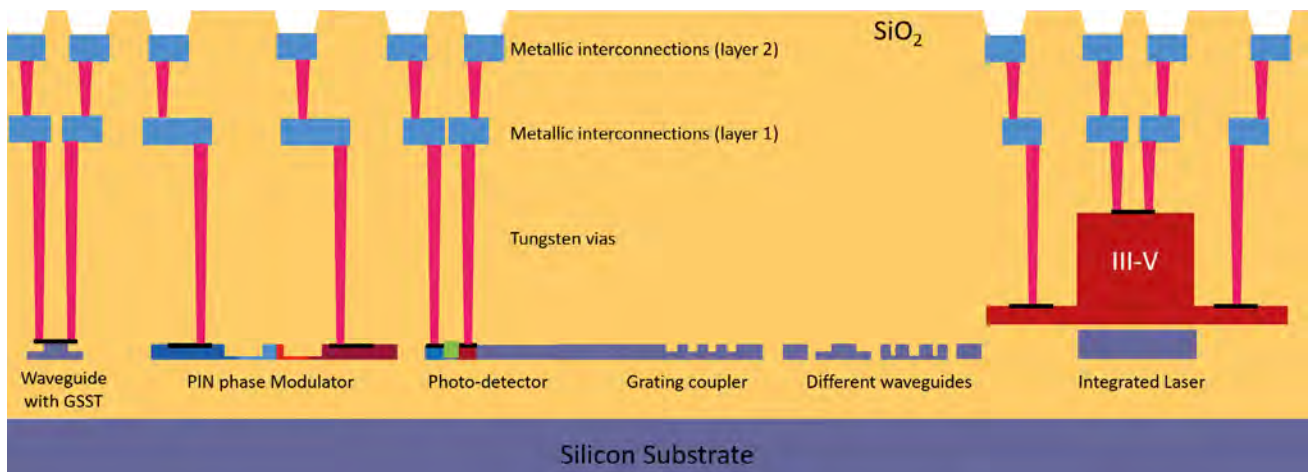
Chalcogenide materials have long been widely studied for their unusual electronic, structural, and optical properties. These exceptional properties are behind a huge number of applications in the fields of optics, electronics, and more recently photonics. The most known optical applications range from

Figure 1. Linear refractive index (n) and extinction coefficient (k) as a function of wavelength for (a) the amorphous and (b) the crystalline phase of GeSe_{1-x}Te_x (continuous) and GST225 (dashed) thin films obtained by spectroscopic ellipsometry data modelling. (c) Figure of merit (FOM = Δn/Δk) as a function of wavelength for the GeSe_{1-x}Te_x and GST-225 thin films. All the GeSe_{1-x}Te_x thin films have a FOM higher than the GST225 reference material. To be noticed, GeSe film is not plotted in a) because the as-defined FOM value tends to infinite. In fact, for this material Δk tends to zero [3].

infrared (IR) optics and nonlinear photonics to non-volatile memory devices for photonic computing [1]. Among the large family of

chalcogenides, phase-change materials (PCMs) are now recognized as the most attractive candidate for producing reconfigurable photonic

Figure 2. Platform under development in the NEUROPLUS project at CEA-LETI. Reproduced with permission from [7].



devices based on electro-optical switchable materials and metamaterials and on their ease of integration in CMOS-compatible platforms [2].

Conventional PCM alloys lying on the GeTe-Sb₂Te₃ pseudo-binary line of the Ge-Sb-Te ternary phase diagram, such as GeTe or Ge₂Sb₂Te₅ (GST225), have been widely studied for years for optical data storage, such as CD-RW, DVD-RAM and Blu-ray disks. These alloys exhibit relatively low crystallization temperature ($T_x \approx 150\text{-}230^\circ\text{C}$), and a huge and uncommon refractive index contrast in the visible range between their amorphous and crystalline phases. The transition between both phases can be easily, quasi-infinitely and reversibly obtained by means of laser pulse applications of various duration and power (e.g., $\Delta n = n_{cr} - n_{am} = 2.97$ at 1550 nm for GST). However, at telecom wavelengths (1.55 μm), these Ge-Sb-Te alloys are absorbing with extinction coefficient k values that increase by an order of magnitude (e.g., from $\Delta k = k_{cr} - k_{am} \approx 1.5 - 0.1$ for GST225) upon crystallization (see Figure 1) [3]. This is particularly detrimental for most integrated optics applications. Therefore, at telecom wavelengths, new PCMs with large Δn , but small Δk upon phase-change are desired for low-loss reconfigurable photonic platforms.

In order to compare PCMs, a very simple figure of merit (*FOM*) can be used and is defined as $FOM = \Delta n / \Delta k$. It should be noted that this simple *FOM* could be considerably improved by taking into account insertion loss and contrast ratio in real optical devices. Standard GST225 and GeTe thin films exhibit a $FOM = 2.2$ and 6.2, while one of the recently introduced PCM compounds Ge₂Sb₂Se₄Te₁ exhibits $FOM \approx 4.2$ at 1.55 μm . In this context, to further improve these *FOMs*, innovative PCM alloys have recently been introduced, based on compounds located along the Ge-Se-Te ternary phase diagram. These GeSe_xTe_{1-x} alloys offer a compromise between the high transparency of covalently bonded GeSe alloys and the phase-change properties

of "metavalently" bonded GeTe, with properties that can be finely tuned between the two alloys simply by modifying the Te/Se ratio in the GeSe_xTe_{1-x} composition (see Figure 1). With the exception of GeSe, for which the *FOM* tends towards infinity due to near-zero absorption in both phases, the *FOM* of all GeSe_{1-x}Te_x films shows very high *FOM* values compared to other materials in literature making it an ideal candidate for low-loss phase shifters. Controlling the Se/Te content makes it possible to tailor the alloy's properties to the desired applications. It should be noted that PCMs Sb₂S₃ and Sb₂Se₃ with similar ultra-low-loss characteristics have also recently been introduced [4].

PCM-BASED OPTICAL DEVICES AND RELATED APPLICATIONS

One of the key challenges to achieve ubiquitous adoption of thin-film PCMs for photonics consists of their integration in already existing CMOS-compatible Silicon photonics platforms. Major efforts in the Grenoble region are focusing on integrating thin-film patches (below 100 nm) above Silicon waveguides next to III-V materials for additional functionalities. Their integration acts generally as a perturbation allowing to modify the effective refractive index of the unperturbed optical waveguide mode.

In particular, Figure 2 shows the cross-section of the platform that we are developing within the framework of the Horizon Europe project NEURO-PULS which aims to develop secure low-power neuromorphic photonic accelerators for edge-computing. Devices under development in this platform are ultra-low-loss non-volatile phase shifters and MZ interferometers (MZI) based on GeSe which presents very low losses around 1550 nm wavelength as discussed in the previous section. MZIs with very low optical loss and non-volatile phase setting are a key component to enable matrix vector multiplication (MVM) cores for neuromorphic applications.

Here, the phase values encoded in the PCM-based MZIs may act ●●●



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as weights in analogy to classical artificial neural networks (ANNs). One of the goals of the NEUROPLUS project is to develop a low-power architecture where no energy is used for weights (phase) setting in the inference phase. Besides, we are currently considering novel energy-efficient spiking neuromorphic architectures where the accumulation-like behaviour of PCM-based devices i.e., the act of gradually changing their crystalline versus amorphous ratio in a distributed patch, can be used to integrate different signals both statically, but also dynamically i.e., without reaching thermal equilibrium between two consecutive stimuli. Other works have taken advantage of this accumulation property to build spiking neuronal circuits where a PCM patch was used to sum optical spikes after weighting based on PCMs and then, depending on the sum value, would allow an optical spike at the output as shown in Figure 3 [5]. Such system could allow pattern recognition in the optical domain using an unsupervised training approach based on spiking time dependent plasticity (STDP).

Another application where thin-film PCMs have found a lot of interest is for photonic memories. In this case, the state of the PCM patch is associated with a certain value of the optical attenuation at the output of the device. By carefully adjusting the input optical power in the writing phase, it is possible to achieve a multi-level operation during the read-out phase where a lower optical power is needed to probe the memory value. This type of memory can operate above GHz speeds due to the rapid phase change which can be well below hundreds of ps or shorter. In a pioneering work, PCM photonic memories with up to 8 levels (3-bit) with 13.4 pJ of switching energy were demonstrated using tens of ns pulse duration [6]. Our current focus concerns the modelling of this type of memories by

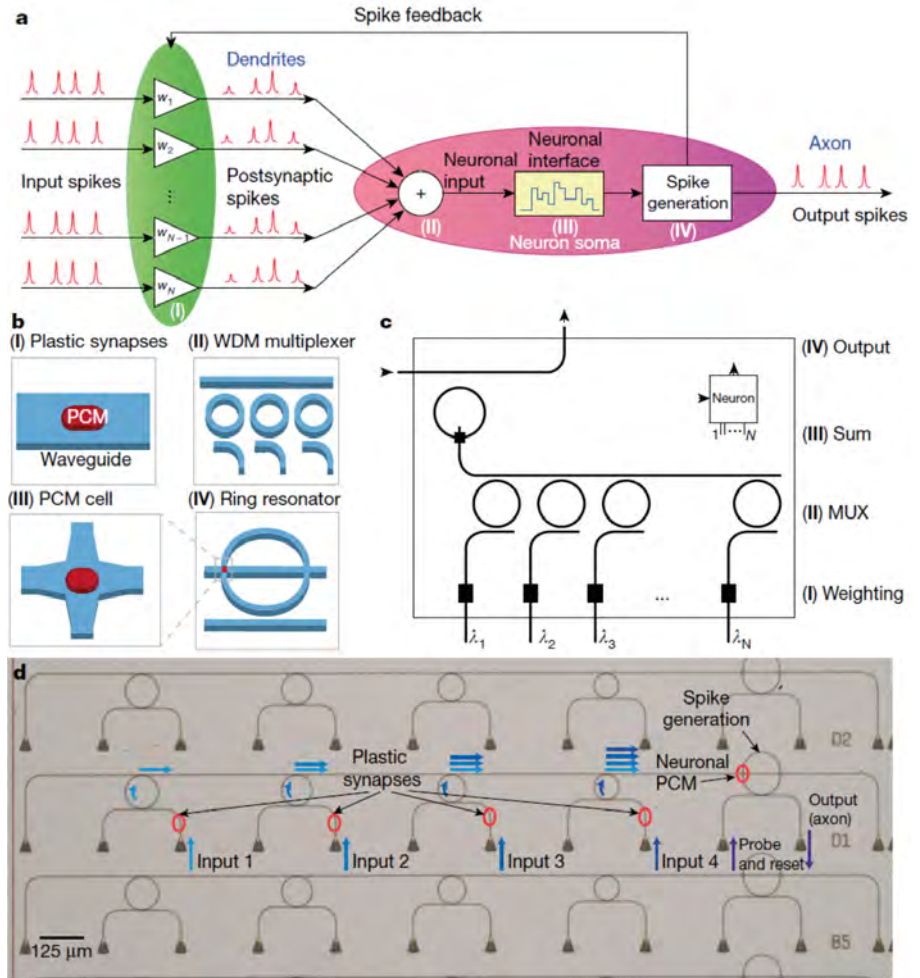


Figure 3. All-optical spiking neuronal circuits. a, b, Schematic of the network realized in this study, consisting of several pre-synaptic input neurons and one post-synaptic output neuron connected via PCM synapses. The input spikes are weighted using PCM cells and summed up using a WDM multiplexer (MUX). If the integrated power of the postsynaptic spikes surpasses a certain threshold, the PCM cell on the ring resonator switches and an output pulse (neuronal spike) is generated. c, Photonic circuit diagram of an integrated optical neuron with symbol block shown in the inset (top right). Several of these blocks can be connected to larger networks using the wavelength inputs and outputs. d, Optical micrograph of three fabricated neurons (B5, D1 and D2), showing four input ports. The four small ring resonators on the left are used to couple light of different wavelengths from the inputs to a single waveguide, which then leads to the PCM cell at the crossing point with the large ring. The triangular structures on the bottom are grating couplers used to couple light onto and off the chip. Reproduced with permissions from [5].

taking into consideration the full computing infrastructure i.e., in terms of photonics, but also communication interfaces and processor operation. Such an analysis can provide an accurate description of the trade-offs that shall be considered for these memories with respect to more standard electronic ones

and novel insights in terms of optimal designs.

CURRENT CHALLENGES

Although thin-film PCMs have been successfully applied to several applications, there are still some challenges that are limiting their ubiquitous adoption in photonics.

One of the limiting factors concerns their current absence from the offer *e.g.*, in multi-project-wafer (MPW) runs, of photonic platforms openly available to the scientific community. This is mainly due to their current level of maturity for integration in CMOS-compatible platforms, but also their only recent adoption in several applications.

A device-level challenge with multiple consequences in terms of applications concerns limited resolution in terms of data encoding *i.e.*, the number of bits that can be encoded in standalone PCM patches is still very limited and, while for certain applications this might not be a major concern, for others that involve photonic memories or neuromorphic computing, this can be a strong constraint for their adoption over more mature technologies, especially when looking at the bit resolution/area metric.

Lastly, from a system-level perspective, a major challenge consists of addressing these devices when write/read operations are carried out in the optical regime. The scaling of optical interconnects for device-dense applications *e.g.*, for photonic memories, is not simple due to the size of the photonic components that are involved. In the future, a 3D integration of multiple guiding layers could be foreseen for this technology to enable higher component

densities with different wavelengths of operation to optimize writing and reading operations.

CONCLUSIONS

To conclude, we discussed about how PCMs can be integrated in Silicon photonic platforms and what are their key properties for photonic applications. In particular, Se-based PCM thin films are promising for reconfigurable photonics applications with ultra-low on-chip losses. For telecom wavelength applications, these alloys have a figure of merit that exceeds that of GST225, currently the standard PCM for non-volatile reconfigurable photonics, by 550%. Then, we proposed a platform for their integration and addressed relevant devices and applications that can benefit from PCMs unique properties. Finally, we underlined some of the main challenges that currently prevent their widespread adoption in the field. ●

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LIDT > 100 J/cm², absorption
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LIDT 0.6 J/cm², AR @ 343 nm
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