Project Acronym: **Fun-COMP**

Project Title: **Functionally scaled computing technology:** From novel devices to non-von Neumann architectures and algorithms for a connected intelligent world

**WP2**

**Non-von Neumann computing networks**

**(WP Leader IMEC)**

# Deliverable D2.1: Report on concepts and fabrication methods for N-vN cell arrays

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[1] CO: Confidential, only for members of the Fun-COMP consortium (including the Commission Services); PU: Public.

# 1. Introduction and background

The Fun-COMP project is developing a range of new, integrated phase-change photonic devices capable of a range of computational operations, including binary and multilevel memory, arithmetic and logic processing, and brain-inspired computing. Unlike conventional (so-called von Neumann) computing devices and architectures, Fun-COMP devices are capable of carrying out processing and memory functions simultaneously. We therefore often describe Fun-COMP devices non-von Neumann (N-vN) devices. The simultaneous execution of processing and memory functions can lead to significant increases in processing speed and significant reduction in power consumption, key goals for future computing technology.

The simplest Fun-COMP device to describe is the basic N-vN unit cell, shown schematically in **Fig. 1**(a). A small patch of phase-change material (here $Ge_2Sb_2Te_5$, or GST for short) is deposited on top of a SiN (or Si) waveguide and is switched between its amorphous and crystalline phases (or, for multilevel operation, to intermediate states between fully crystalline and fully amorphous) by sending an optical ***write*** pulse (for amorphization) or an optical ***erase*** pulse (for re-crystallisation) down the waveguide. The readout of the state of the phase-change cell is carried out by injecting a low-power read pulse. Since the amorphous and crystalline phases have very different refractive indices (n and k), as shown in Fig. 1(b), there is a large contrast in the transmission through the waveguide when the phase-change cell is in different phase-states, and this provides the basis of the readout process. Thus, we can readily form a binary or multilevel memory (Fig. 1(b)), and once we have multilevel states, we can easily carry out arithmetic computations, and indeed provide synaptic and neuronal functionality needed for neuromorphic, or brain-like processing.

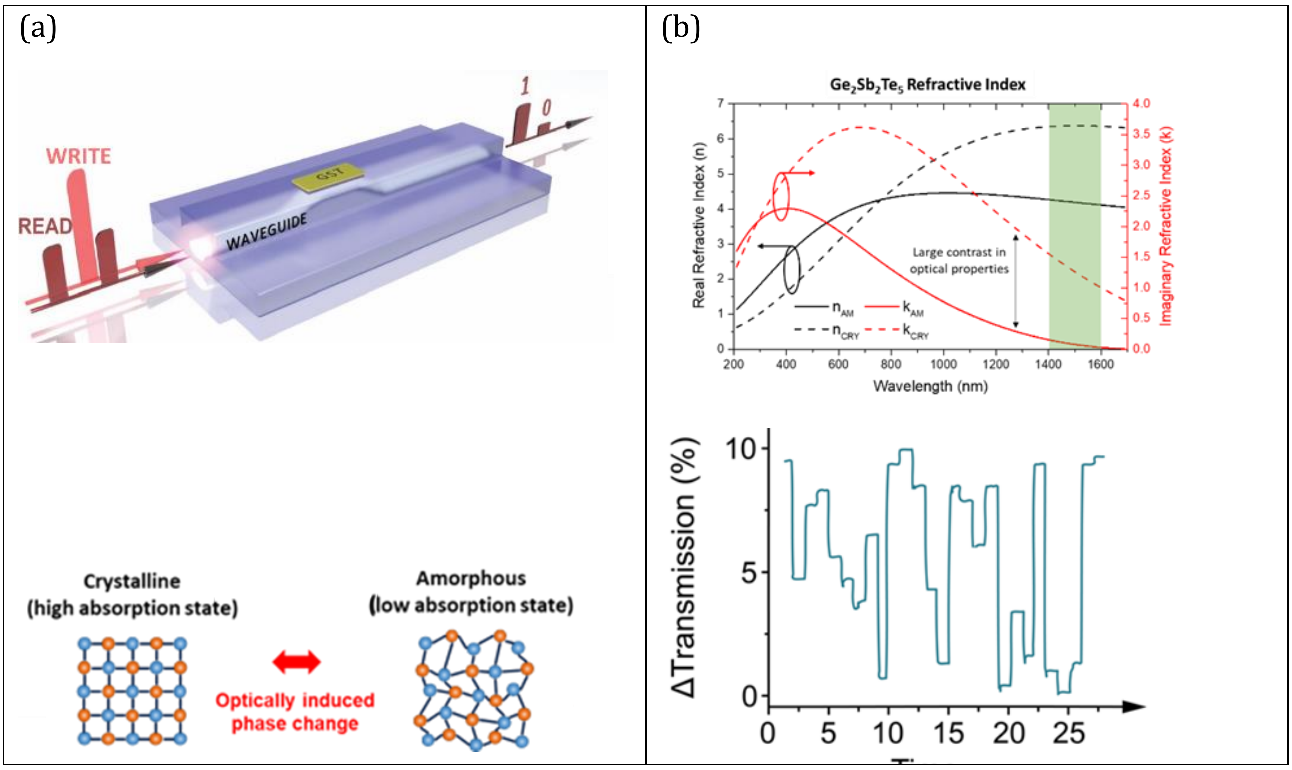


**Fig 1:** (a) Schematic of the basic integrated phase-change photonic N-vN cell and operation as a binary memory. (b) Refractive index (n and k) of the archetypal phase-change material GST in crystalline and amorphous states (top) and experimental switching of the cell into multilevel states. For a video showing the operation of this type of basic N-vN cell, please see the Fun-COMP website at https://fun-comp.org/description/

The second major Fun-COMP device is what we call the 'extended N-vN cell'; this consists of a microring type resonator, as shown in **Fig. 2**(a). These devices can be efficiently coupled to broadband waveguides, and provide sharp resonances when optical resonance conditions are fulfilled (see Fig. 2(b)). These kind of devices have lots of useful applications when embedded in systems. They can, for example, be used to transfer multiple signals, each carried on a different wavelength, to a common bus waveguide (a process known as wavelength division multiplexing – WDM). If we also add a 'patch' of phase-change material to the microring resonator, we can deliver memories that use WDM to increase storage capacity. We can even make photonic mimics of brain-like spiking neurons!

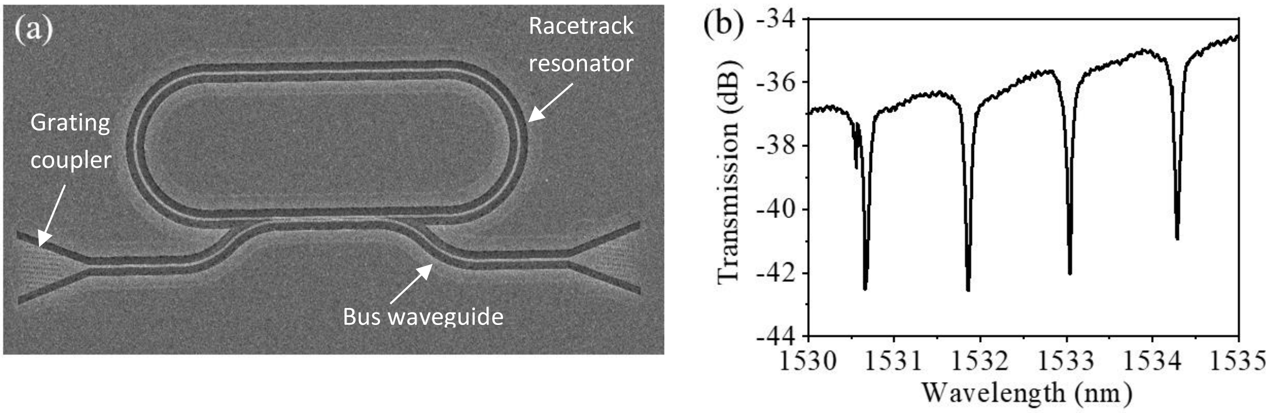


**Fig. 2.** (a) Top-view SEM image of a fabricated racetrack resonator, side coupled with a bus waveguide. The focusing grating couplers are used for light coupling with optical fibres. (b) Measured transmission spectrum of the entire device.

An optical microscope image of Fun-COMP devices integrated into a small system to deliver several brain-like spiking neurons is shown in **Fig. 3.** Each line in the image represents one single neuron with four input ports, and one tunable microring resonator with crossed waveguide on the right side for spike generation. These devices were fabricated in the labs of the Fun-COMP partners at the Universities of Muenster and Oxford, using electron beam lithography. The spiking resonator is equipped with a nanoscale phase-change 'patch' element, which is fabricated via sputter deposition and lift-off processing. The input ring resonators multiplex weighted optical driving signals onto the waveguide leading to the spiking neuron, thus superimposing on the input waveguide to the neuron the summed, weighted contributions from the all the pre-neuron (plastic) synapses (which are themselves implemented with phase-change cells of the type shown in Fig. 1 and deposited on the input waveguide to the ring resonators).

Different wavelengths are selected as inputs by varying the radius of the ring resonators. This geometric modification shifts the resonance wavelength of each ring resonator to a desired spectral position. In the telecommunication wavelength range a near-linear relationship between the ring radius and the resonance wavelength exists, and thus allows for convenient selection of the resonance wavelength. Because the fabrication approach is fully scalable, a large number of resonators can thus be realized in each device to embed WDM capability.

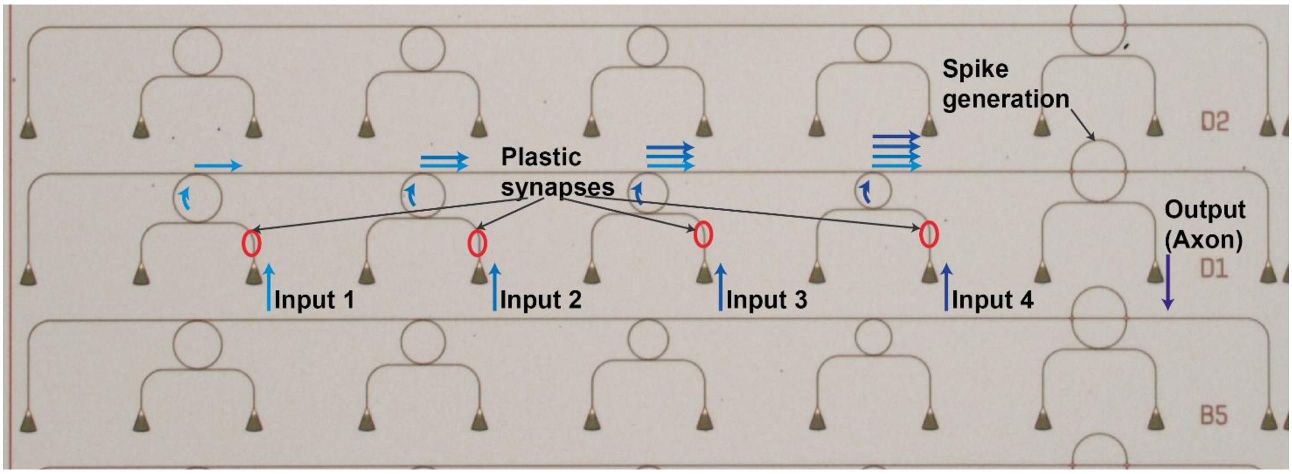


**Fig. 3.** (a) Optical micrograph of an artificial photonic spiking neuron employing WDM capability. Four ring resonators are used to multiplex optical input signals 1-4 onto a common waveguide leading to a tunable WDM ring resonator which provides spiking capability. The tunable resonator is fabricated with a crossing waveguide and uses an evanescently coupled phase-change cell for non-volatile reconfigurability.

## 2. Fabrication in Silicon Photonics

The Fun-COMP devices shown in section 1 above were fabricated in silicon nitride using electron-beam lithography at the research laboratories of the Universities of Muenster and Oxford. For the fabrication of larger-scale systems and for compatibility with commercial-type integrated photonics 'foundries', we are also in Fun-COMP using silicon photonics technology. This is basically the same technology that is used for the fabrication of silicon electronic chips that you find in your laptop or your smartphone, but with an important twist: in Silicon Photonic chips, the information is no longer carried by electrical signals like voltages and currents, but rather by pulses of light. Since the scientific name for the smallest unit of light is a photon, this explains the name "photonics".

The nice thing about Silicon Photonics is that it can piggyback on the billions and trillions of dollars that have been invested in Silicon Electronics over the past half-century. We do not need to buy new equipment or develop fundamentally new processes, but we can simply leverage what is already there. This is an important advantage in terms of cost.

Another advantage related to cost is that these technologies can fabricate hundreds of chips on a single wafer in one go, see **Fig. 4**, with each of these chips containing hundreds or thousands of the basic Fun-COMP devices shown in section 1 above. This means we are working with a technology that lends itself to mass-fabrication, and these economies of scale will help with further reducing the costs.

Within Fun-COMP, the silicon photonics systems are fabricated at the partner IMEC, and a photo of a typical clean room used for such fabrication is shown in **Fig. 5**.

To give a bit more detail on how these chips are made, first the general layout of the chips is designed to be printed on a transparent glass slide, a so-called mask. In **Fig. 6**, each line is a "waveguide", essentially a wire for light, so that this light can be brought to many different places on the chip, to be processed e.g. in Fun-COMP's computing elements. The next step is to take a bare Silicon wafer and coat it with a thin light-sensitive layer. UV light is then projected through the mask, into this light-sensitive layer. The dark lines on the mask will shield certain regions of the wafer, and the chemical difference between exposed and unexposed areas allows one to print the structures of the mask on the surface of the wafer.

A final step is an etching procedure, to transfer this surface pattern inside the actual silicon layer. This creates the network of waveguides, resulting in the silicon photonic chips.

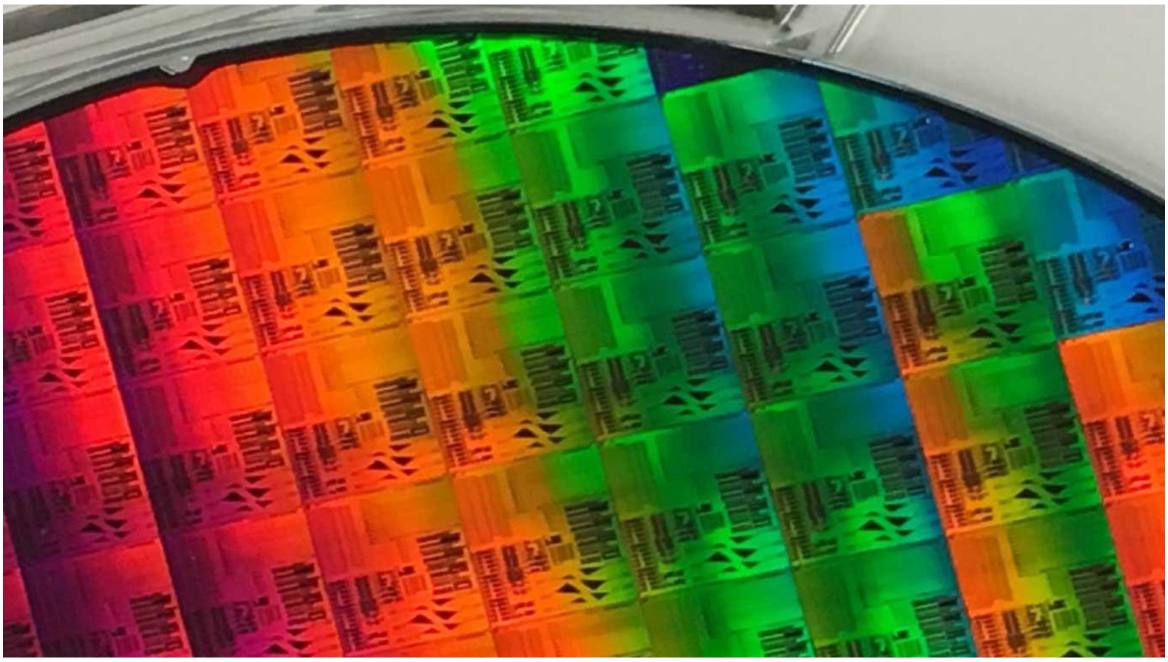

**Fig. 4.** A silicon photonics wafer, containing hundreds of different chips


**Fig. 5**. A clean room at imec, where both silicon electronic chips and silicon photonics chips are being fabricated.

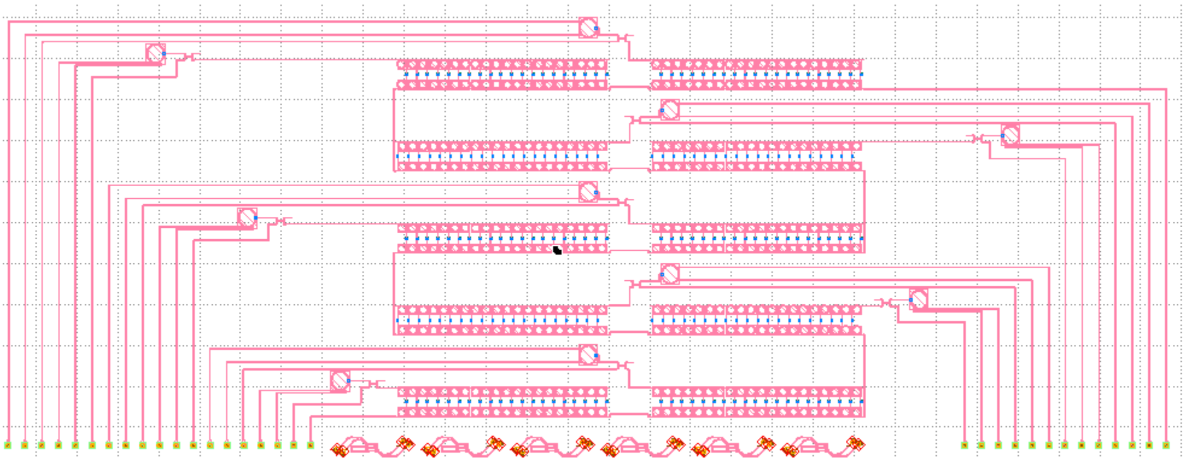

**Fig. 6.** Mask layout for one of the Fun-COMP chips

## 3. Summary

In this report we have given a brief overview of the basic Fun-COMP devices that we use for memory and computing applications. These devices – the so-called 'basic' and 'extended' non-von Neumann cells – provide us with a remarkable range of functionality, including non-volatile binary and multilevel memory, synaptic and neuronal mimicks – along with the ability to combine multiple signals (carried on different wavelengths) together in a simple and efficient way. By combining these devices into large-scale systems, we can develop all-optical computers and memories that can offer distinct advantages over electronic systems in terms of speed of operation and power consumption.