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PHASE-CHANGE DEVICES

Crystal-clear neuronal computing

Induced progressive crystallisation in chalcogenide-based materials can be used to closely mimic neuronal functions, opening new paths to neuromorphic computing.

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Will we ever be able to make computers work like the brain? Such a question has captivated our imagination ever since the computer's invention but, so far, computers are poor facsimiles of biological brains. Indeed, brains fuse together processing and memory tasks on an overall analogue basis, use surprisingly little energy and occupy a remarkably small volume – the human brain consuming only 10 to 20 Watts of power and occupying less than two litres of space. The question naturally arises whether progress might be made by developing simple, energy-efficient – yet effective – electronic mimics of the brain's basic building blocks, the neurons and synapses. Writing in Nature Nanotechnology,[1] Tomas Tuma and his co-workers at IBM-Research Zürich and ETH Zürich report on a nanoscale electronic phase-change device reproducing the integrate-and-fire functionality and stochastic dynamics of a biological neuron.

Ever since the pioneering work of Carver Mead on neuromorphic computing, various routes have been explored for the realisation of electronic neurons and synapses. The most conventional approaches based on silicon transistor-based circuits are relatively complex and usually include hard-to-shrink capacitors for storing the membrane potential.[2] More recently, memristors have emerged as nanoscale devices able to remember their excitation history.[3] More specifically, their electrical conductance at any time depends on the cumulative effects of past inputs – a property well-suited to the efficient implementation of electronic neurons. The working principle of a biological neuron is indeed to accumulate ('integrate') the various excitations presented to it via its dendrites and to output a spike when their aggregation reaches a certain threshold level. However, while neuromorphic applications of memristors have invariably focused on realising synaptic processes, reproducing neuron mimics is far less explored to date. Now, Tuma and colleagues use phase-change memristive devices not only to implement neuronal mimics but also to carry out neuronal computations (Fig. 1).

Phase-change materials are widely exploited – anyone who has ever used a rewritable optical disc has come across them – and they are now making inroads in the realm of electrical memories. Made from chalcogenide alloys such as $Ge_2Sb_2Te_5$, phase-change devices can be switched between purely amorphous and purely crystalline states quickly and repeatedly, using either light or electrical stimuli. Their optical and electrical properties are modified accordingly, making it possible to readily determine their state – an ideal situation for the storage of binary data.

Intermediate conditions between purely amorphous and purely crystalline states are even more interesting. Multiple inputs of proper strength can induce a controlled progressive crystallisation that eventually leads to a sudden change in device conductance and, via external circuitry, to an output (neuronal) spike. This mimics the neuronal behaviour in response to a sum of incoming postsynaptic potentials.[4]

Just one of these integrate-and-fire phase-change neurons, when combined with plastic synapses, can carry out computational tasks of surprising complexity, including the detection of temporal correlations in parallel data streams. When applied to social media and search engine data, this leads to some remarkable possibilities, such as predicting the spread of infectious disease, trends in consumer spending and even the future state of the stock market.[5] Importantly, the spiking dynamics of the phase-change neuron also exhibit an inherently stochastic nature, reflecting properties found in biological neurons. This reveals itself as variations in the spike rate and inter-spike duration, and can be exploited in probabilistic population-based neural computing.[6]

In their current embodiment, the phase-change neurons rely on external circuitry to complete their functionality and on software emulations of plastic synapses to mediate inter-neuron connections. Removing such reliance is obviously a next step, and the recent progresses in the development of phase-change synapses may offer an excellent route.[7] The endurance of phase-change devices, i.e. the number of times they can be switched before failure, will also be a concern. This might limit processor lifetimes – especially if phase-change neuromorphic systems were to operate on the nanosecond timescales of which they are capable. Another crucial issue concerns the amorphisation process, which requires heating above the melting temperature (620^0C for $Ge_2Sb_2Te_5$) and leads to a significant energy consumption for every post-spike re-setting. This can be reduced by shrinking the device – smaller devices consume less – though there may be a limit on how small we can go before losing access to multiple phase states. Recent work on non-melting phase transitions might offer a way forward on this front.[8] Finally, we might ask about the bio-fidelity of the phase-change neuron, since it certainly does not capture the full range of biological neuron traits.

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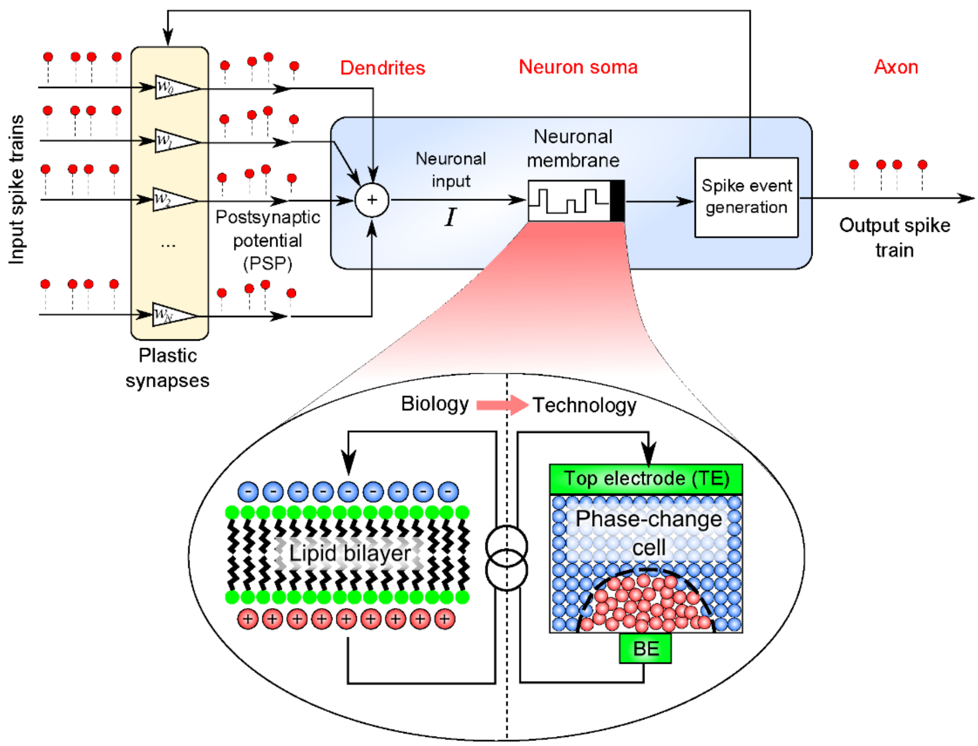

Figure 1. Schematic of the phase-change neuron proposed by Tuma and colleagues.[1] The membrane potential of a real biological neuron is mimicked by the phase configuration of a nanoscale phase-change device of the kind typically used for non-volatile memory applications. Incoming postsynaptic potentials lead to changes in the phase-change neuron's conductance, causing the neuron to spike in turn with the aid of external circuitry.