Neuromorphic computing research: Team proposes hardware that mimics the human brain

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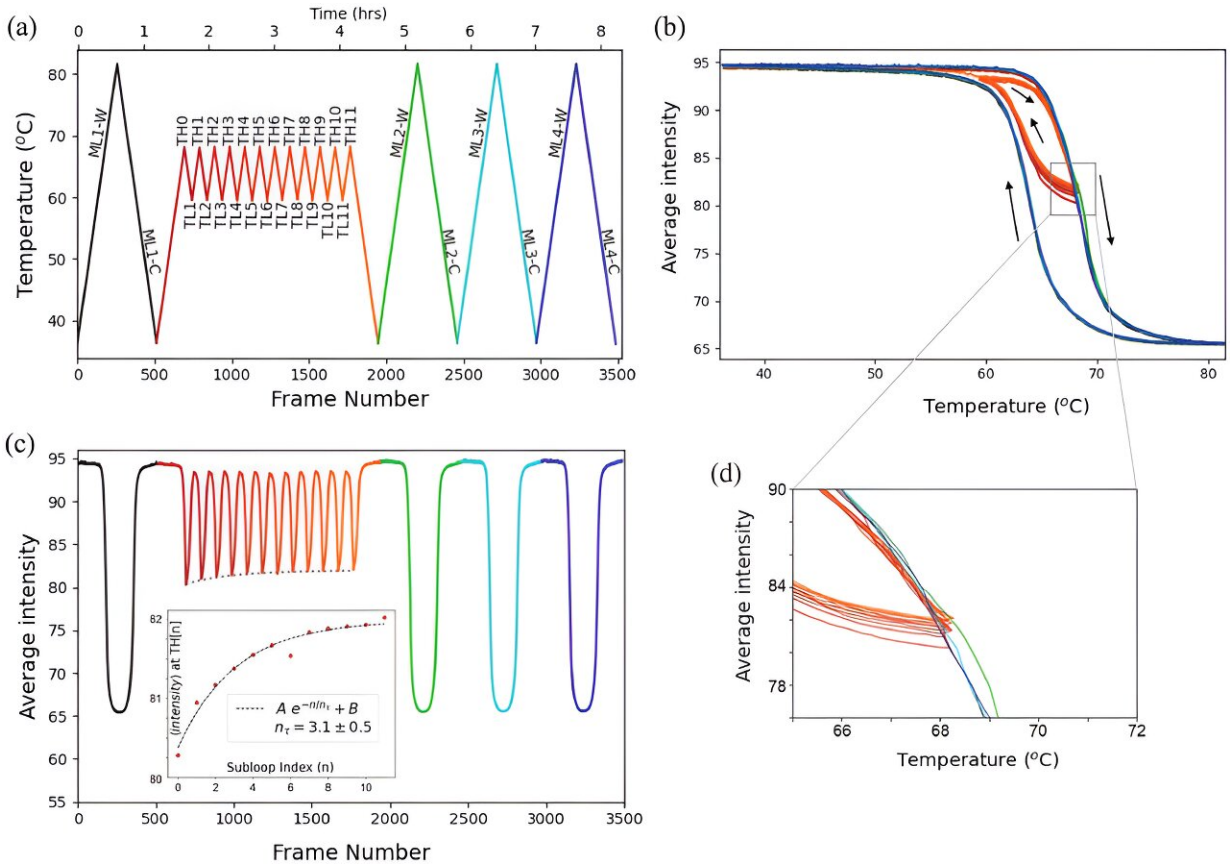

a) Ramp Reversal temperature protocol. Major loop labels are as follows: ML1-W stands for Major Loop One upon warming; ML1-C stands for Major Loop One upon cooling, and similarly for other major loops. In the subloops, temperature is varied repeatedly between a low temperature of TLn = 59.5 °C and a high temperature of THn = 68 °C, through a total of n = 11 complete subloops. Black, red/orange, green, cyan, and blue color codes denote the same

region of the hysteresis protocol in panels (a–c). b) Hysteresis curves of average intensity versus temperature throughout the Ramp Reversal protocol of panel (a). c) Average intensity versus frame number. Intensity is on a grayscale of 0 (black) to 255 (white), after accounting for illumination variation (detailed elsewhere[19]). The light gray dashed line follows the average intensity at the end of each subloop. Inset: Fit of the average intensity at the end of each subloop (i.e., at THn), versus subloop index n, to an exponential saturation. The time constant is $n\tau = 3.1 \pm 0.5$ subloops. This rise can be seen in panels (b) and (d) as the bump of the red/orange/green curves. d) Zoom showing the progressive increase after each subloop of the averaged intensity around the high temperature turning point TH = 68 °C. Credit: *Advanced Electronic Materials* (2023). DOI: 10.1002/aelm.202300085

Technology is edging closer and closer to the super-speed world of computing with artificial intelligence. But is the world equipped with the proper hardware to be able to handle the workload of new AI technological breakthroughs?

"The brain-inspired codes of the AI revolution are largely being run on conventional silicon computer architectures, which were not designed for it," explains Erica Carlson, 150th Anniversary Professor of Physics and Astronomy at Purdue University.

In a joint effort among physicists from Purdue University, University of California San Diego (USCD) and École Supérieure de Physique et de Chimie Industrielles (ESPCI) in Paris, France, the researchers believe they may have discovered a way to rework the hardware by mimicking the synapses of the human brain. They have published their findings, "Spatially Distributed Ramp Reversal Memory in VO_2," in *Advanced Electronic Materials*.

New paradigms in hardware will be necessary to handle the complexity

of tomorrow's computational advances. According to Carlson, lead theoretical scientist of this research, "neuromorphic architectures hold promise for lower energy consumption processors, enhanced computation, fundamentally different computational modes, native learning and enhanced pattern recognition."

Neuromorphic architecture basically boils down to computer chips mimicking brain behavior. Neurons are cells in the brain that transmit information. Neurons have small gaps at their ends that allow signals to pass from one neuron to the next which are called synapses. In biological brains, these synapses encode memory. This team of scientists concludes that vanadium oxides show tremendous promise for neuromorphic computing because they can be used to make both artificial neurons and synapses.

"The dissonance between hardware and software is the origin of the enormously high energy cost of training, for example, large language models like ChatGPT," explains Carlson. "By contrast, neuromorphic architectures hold promise for lower energy consumption by mimicking the basic components of a brain: neurons and synapses. Whereas silicon is good at memory storage, the material does not easily lend itself to neuron-like behavior.

"Ultimately, to provide efficient, feasible neuromorphic hardware solutions requires research into materials with radically different behavior from silicon—ones that can naturally mimic synapses and neurons. Unfortunately, the competing design needs of artificial synapses and neurons mean that most materials that make good synaptors fail as neuristors, and vice versa. Only a handful of materials, most of them quantum materials, have the demonstrated ability to do both."

The team relied on a recently discovered type of non-volatile memory which is driven by repeated partial temperature cycling through the

insulator-to-metal transition. This memory was discovered in vanadium oxides.

Alexandre Zimmers, lead experimental scientist from Sorbonne University and École Supérieure de Physique et de Chimie Industrielles, Paris, explains, "Only a few quantum materials are good candidates for future neuromorphic devices, i.e., mimicking artificial synapses and neurons. For the first time, in one of them, vanadium dioxide, we can see optically what is changing in the material as it operates as an artificial synapse. We find that memory accumulates throughout the entirety of the sample, opening new opportunities on how and where to control this property."

"The microscopic videos show that surprisingly, the repeated advance and retreat of metal and insulator domains causes memory to be accumulated throughout the entirety of the sample, rather than only at the boundaries of domains," explains Carlson. "The memory appears as shifts in the local temperature at which the material transitions from insulator to metal upon heating, or from metal to insulator upon cooling. We propose that these changes in the local transition temperature accumulate due to the preferential diffusion of point defects into the metallic domains that are interwoven through the insulator as the material is cycled partway through the transition."

Now that the team has established that vanadium oxides are possible candidates for future neuromorphic devices, they plan to move forward in the next phase of their research.

"Now that we have established a way to see inside this neuromorphic material, we can locally tweak and observe the effects of, for example, ion bombardment on the material's surface," explains Zimmers. "This could allow us to guide the electrical current through specific regions in the sample where the memory effect is at its maximum. This has the

potential to significantly enhance the synaptic behavior of this neuromorphic material."

More information: Sayan Basak et al, Spatially Distributed Ramp Reversal Memory in VO2, *Advanced Electronic Materials* (2023). DOI: 10.1002/aelm.202300085

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