the United States (*10*). Additional regulation may overburden state and local governments. Moreover, firm disclosure of HF fluids may stifle UOGD innovation (*12*).

It is not an overstatement to say that UOGD has affected all dimensions of life for those in exposed communities (*3*). Many of the impacts have lifelong consequences on individual well-being, including future health, education, and labor market outcomes. The mounting evidence on environmental impacts demonstrates a need to quantify and synthesize the associated health and socioeconomic impacts using a common metric. Benefit-cost analysis is particularly useful to facilitate a comprehensive assessment of the consequences of these innovations (*13*). This type of analysis also requires the clarification of alternative scenarios for comparison and the time frame of consideration. For example, would increasing UOGD regulation cause companies to revert to coal-based energy production (thereby exacerbating pollution) or would it instead spur the transition to a renewables-based future to aid the longer-term battle with climate change? The counterfactual scenario of comparison changes the net-benefit calculation and the optimal policy choice.

It has been more than two decades since the rapid expansion of UOGD, but we are only now beginning to grasp the full scope and extent of the costs associated with these innovations. An understanding of the environmental effects of UOGD is a necessary first step toward a comprehensive assessment of UOGD. Going forward, the mechanisms of impact and their consequences must be clarified to translate this evidence into actionable policy. ■

REFERENCES AND NOTES

1. US Geological Survey (USGS), "When did hydraulic fracturing become such a popular approach to oil and gas production?"; www.usgs.gov/faqs/when-did-hydraulic-fracturing-become-such-a-popular-approach-oil-and-gas-production?qt-news_science_products=0#qt-news_science_products.
2. K. Black, A. J. Boslett, E. L. Hill, L. Ma, S. J. McCoy, *Annu. Rev. Resour. Econ*. 10.1146/annurev-resource-110320-092648 (2021).
3. A. Bartik *et al.*, *Am. Econ. J. Appl. Econ*. **11**, 105 (2019).
4. P. Bonetti, C. Leuz, G. Michelon, *Science* **373**, 896 (2021).
5. US Environmental Protection Agency (EPA), "Hydraulic fracturing for oil and gas: Impacts from the hydraulic fracturing water cycle on drinking water resources in the United States" (Report EPA-600-R-16-236F, EPA, 2016).
6. L. Torres, O. P. Yadav, E. Khan, *Sci. Total Environ*. **539**, 478 (2016).
7. E. Hill, L. Ma, *Am. Econ. Rev*. **107**, 522 (2017).
8. A. Ebenstein, *Rev. Econ. Stat*. **94**, 186 (2012).
9. J. Currie, J. Graff Zivin, K. Meckel, M. Neidell, W. Schlenker, *Can. J. Econ.* **46**, 791 (2013).
10. D. Keiser, J. Shapiro, *J. Econ. Perspect*. **33**, 51 (2019).
11. C.B. Johnson, *ONE J*. **6**, 443 (2021).
12. T. R. Fetter *et al*., "Learning by viewing? Social learning, regulatory disclosure, and firm productivity in shale gas," Working paper 25401, National Bureau of Economic Research, Cambridge, MA, December 2018.
13. K. Arrow *et al*., *Science* **272**, 221 (1996).

10.1126/science.abk3433

OXIDE ELECTRONICS

Exploring the path of the variable resistance

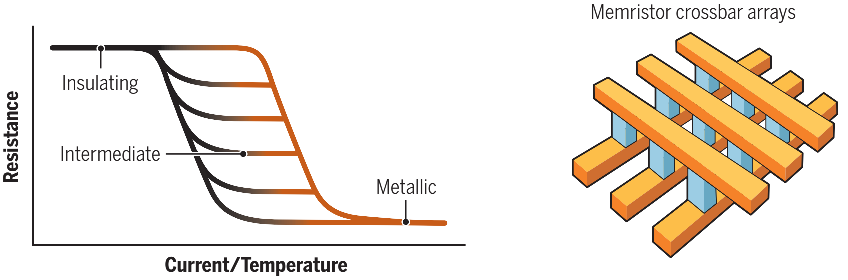
Resistive switching studies pave the way to neuromorphic information technologies

By **Hans Hilgenkamp** *and* **Xing Gao**

In handling computer hardware, the last thing anyone would like to do is expose electronic components to electrostatic discharges. Nevertheless, this is exactly an approach that researchers are taking toward faster and more energy-efficient computing. Inspired by the functions of neurons and synapses in the brain, resistive switching devices or "memristors" are being explored as building blocks for neuromorphic circuitry. In such devices, the resistance properties are durably altered by applying voltage pulses. On page 907 of this issue, del Valle *et al.* (*1*) have imaged the early stages of electric field–induced electronic breakdown and formation of a conducting filament in vanadium oxide. By doing this in a space- and time-resolved manner, the authors provide useful insight into the characteristic length and time scales involved.

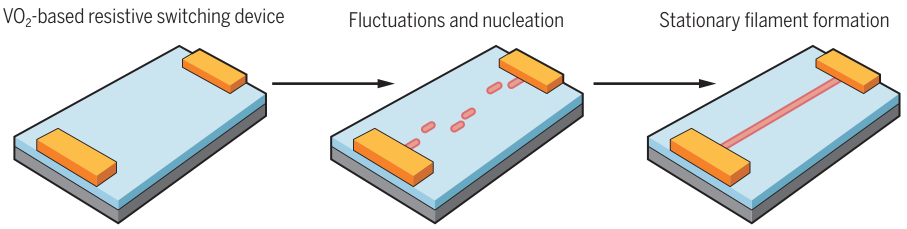
Computing systems are commonly based on the Von Neumann architecture, in which the memory is physically separated from the logic circuitry. Data are continuously shuttled between these units. This process is time consuming and presents an important cause of energy dissipation. Both aspects become very noticeable in data-intensive applications, like training deep neural networks. Neural networks are composed of layers of neuron-like devices connected through synapses. The latter comprise weight factors that are adjusted in the training process. In conventional complementary metal-oxide semiconductor (CMOS)–based technology, the weights need to be fetched, adjusted, and put back into the memory in every learning step. In an alternative and ultimately more efficient approach, the weights are embodied in the hardware it-

Moving toward neural networks



Variable electrical resistance
Vanadium dioxide (VO_2) undergoes a hysteretic insulator-to-metal transition (IMT) just above room temperature, where resistivity changes by several orders of magnitude.

Building the hardware
Creating artificial neurons can be accomplished in single memristive devices or crossbar arrays, providing a pathway for realizing functional network structures for neuromorphic computing.



Tracking the transition between states
By applying electric field pulses to the VO_2-based device, the IMT takes place through filament formation. The filament forms starting with hotspots that quickly grow and expands to a stationary state as a result of resistive heating. By tailoring current or temperature, many stable states between the insulating and metallic states can be achieved.

GRAPHIC: KELLIE HOLOSKI/*SCIENCE*

self, and training implies an alteration of the physical properties of the synapse, similar to what happens in the brain.

In a fully electronic implementation, this requires the ability to controllably adjust the electrical resistance of a material. This is achieved using the electric field–driven motion of defect states, such as oxygen vacancies and impurity atoms (*2*), which are resistive switching concepts used also in binary resistive random access memory (ReRAM). Alternatives involve thermally induced alterations of the crystallinity of the material (*3*) and organic memristors (*4*). A complication in many techniques is that they involve atomic displacements and reconfigurations, which can lead to a spread in device properties and fatigue. This problem is circumvented by exploiting tunable electronic and/or magnetic ordering phenomena. The Mott insulator VO$_2$ is an attractive example, exhibiting a hysteretic resistive transition just above room temperature (*5*). Applying electric field pulses to the material in the high-resistive state creates a metallic filament with a conductance that depends on the pulse intensity and duration. Notably, the resistance can be programmed over several orders of magnitude.

By studying thin film microdevices with various vanadium oxide stoichiometries, del Valle *et al.* found that the transition starts with resistance fluctuations and nucleation of the conducting filament in hotspots on a hundreds-of-nanoseconds time scale (see the figure). In an avalanche-like process, the filament subsequently grows, as a result of Joule heating, over a time scale of microseconds. The authors investigated the growth dynamics and the final width of the conducting filament, which depends on both the characteristics of the voltage pulse and the resistivities of the material in the insulating and conducting states. Inhomogeneities play an important role in triggering the transition and in the filament formation by focusing the current. These findings can help to optimize the switching processes—e.g., by deliberately incorporating nanoscopic elements that act as optimized hotspots.

The storing of synaptic weights in the neural network hardware is an example of the upcoming in-memory computing paradigm, which aims to circumvent the Von Neumann bottleneck. The practical implementation of this is typically in the form of cross-bar arrays (*6*), with the current lines acting as the pre- and postsynaptic connections to the neurons. The variable conductance properties of the barrier materials encode for the synaptic weight. Using this setup, Ohm's law and Kirchhoff's circuit law are used for matrix-vector multiplications, which are a key processing step in neural network operation. Also, other data-intensive applications can benefit from outsourcing data processing from the logic units to the memory—large-scale database queries being one example (*7*).

In addition to storing information, the switching of VO$_2$ when exceeding a certain threshold voltage can also be used for the realization of the artificial neurons. Using a negative differential resistance that can be invoked in the resistive transition, Yi *et al.* have even demonstrated 23 different neuronal functionalities with VO$_2$-based memristors (*8*). Spiking modes of neural network operation are facilitated by this, with further expected enhancements in energy efficiency.

The optical reflectivity modulation, as studied by del Valle *et al.*, presents a coupling between the electronic and photonic domains. This allows, for example, for the storing of synaptic weights in a photonic processor—a principle recently used in a photonic tensor core accelerator using phase change materials (*9*). Future computer systems will likely comprise a heterogeneous mix of electronic, optical, and spintronic components, and efficient coupling between these domains will then be indispensable.

The next stage in vanadium oxide memristor research will be to make the step from single resistive switching devices to functional network structures, like multilayer artificial neural networks, and to explore their operation. In this endeavor, other more exotic post–Von Neumann information processing concepts are also of interest (*10*, *11*). The space- and time-resolved optical reflectometry technique as demonstrated by del Valle *et al.* will enable current pulses and associated resistance modulations passing through such networks to be monitored without interference—tracing, so to say, the path of the variable resistance. ■

REFERENCES AND NOTES

1. J. del Valle *et al.*, *Science* **373**, 907 (2021).
2. R. Waser, R. Dittmann, G. Staikov, K. Szot, *Adv. Mater.* **21**, 2632 (2009).
3. I. Boybat *et al.*, *Nat. Commun.* **9**, 2514 (2018).
4. S. Goswami, S. Goswami, T. Venkatesan, *Appl. Phys. Rev.* **7**, 021303 (2020).
5. T. Driscoll, H.-T. Kim, B.-G. Chae, M. Di Ventra, D. N. Basov, *Appl. Phys. Lett.* **95**, 043503 (2009).
6. Q. Xia, J. J. Yang, *Nat. Mater.* **18**, 309 (2019).
7. I. Giannopoulos *et al.*, *Adv. Intell. Syst.* **2**, 2000141 (2020).
8. W. Yi *et al.*, *Nat. Commun.* **9**, 4661 (2018).
9. J. Feldmann *et al.*, *Nature* **589**, 52 (2021).
10. M. Di Ventra, F. L. Traversa, *J. Appl. Phys.* **123**, 180901 (2018).
11. M. A. Nugent, T. W. Molter, *PLOS ONE* **9**, e85175 (2014).

10.1126/science.abh2231

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INFECTIOUS DISEASES

Tracking severe malaria disease

Malaria infection prevalence predicts malaria mortality—at least for now

By **Terrie Taylor** *and* **Laurence Slutsker**

Female *Anopheles* mosquitoes transmit malaria sporozoites to humans in the context of a blood meal. In malaria-endemic areas, most of the ensuing infections are asymptomatic. Some, however, progress to an uncomplicated illness (fever, headache, body aches, and pains). Younger individuals, with less clinical immunity to malaria, are at highest risk of developing severe disease (anemia, cerebral malaria, and/or respiratory distress) and of dying (*1*). Because the relationship between malaria transmission and malaria mortality is so variable, and because both are challenging to measure, it has remained unclear whether decreases in malaria transmission, resulting from control measures, would actually decrease malaria mortality. On page 926 of this issue, Paton *et al.* (*2*) find that the higher the prevalence of malaria infection in a given community, the higher the incidence of severe malaria disease. These findings may be useful in tracking the impact of various malaria control measures over time.

Measuring malaria transmission is not straightforward. Two of the traditional metrics of exposure to malaria parasites, the entomological inoculation rate and cohort incidence studies, are expensive and difficult to measure. The entomological inoculation rate, or the number of infectious bites per person per unit time (usually per year), is the product of the human biting rate and the sporozoite rate. (Sporozoites are carried in mosquito salivary glands and are injected into skin when female *Anopheles* mosquitoes take blood meals from humans.) To estimate the human biting rate, volunteers (protected by prophylactic doses of antimalarial drugs) bare their legs and collect mosquitoes as they land. Sporozoite rates can be determined by analyzing the salivary glands of the mosquitoes. Measuring incidence rates for new malaria infections requires treating a study cohort with an effective an-

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