Memristor-Based Computing

Lizy K. John and Earl E. Swartzlander, Jr. University of Texas at Austin In 1971, Leon Chua presented the theoretical basis for a passive two-terminal circuit device that he called a "memristor" (a contraction of memory and resistor).¹ A memristor is a two-terminal device that behaves like a resistor, with the resistance depending on the history of the

current passing through it. Initially, the idea was an interesting concept that had not been seen in nature; but more than three decades later, in 2008, HP Labs realized memristors in nanoscale titanium dioxide cross-point switches.² Today, they are used in commercial microprocessors to provide nonvolatile memory on processor chips implemented with traditional CMOS.

One of the attractions of memristors is that they facilitate the co-mingling of memory and processing on the same chip. This is an example of the comment by Gordon Moore in his paper in *Electronics*³ in which he suggested what is now called Moore's law. He wrote, "For example, memories built of integrated electronics may be distributed throughout the machine instead of being concentrated in a central unit." Distributing the memory through the processor is a way to eliminate the von Neumann bottleneck where the memory and processor are separated by a memory bus that slows the processing and greatly increases the power consumption of the system. In many applications, memristor memory can act as a site for storing data, and memristors can perform the desired computations.

This special issue contains two department articles and four peer-reviewed papers on memristors. In the first department article, Leon Chua—the inventor of memristors—describes the history of memristors. Chua first explains the events and the thought process surrounding the invention of the memristor while he was at Purdue University in 1970. He then discusses the progress that led to the fabrication of the device in 2008. After describing the recent progress in manufacturing these devices, he closes the article by reproducing some of the historical artifacts surrounding the development of the memristor.

Next, "Not in Name Alone: A Memristive Memory Processing Unit for Real In-Memory Processing" describes a system that uses memristors to perform digital processing and memory on the same chip. It implements processing in memory, eliminating the von Neumann bottleneck that arises when the processor and memory are separate units that communicate through a memory data bus. By modifying the controller to the memristive array (and the row decoders and drivers), it is possible to do digital computations at the memory.

"Defect-Tolerant Logic Synthesis for Memristor Crossbars with Performance Evaluation" shows multiple logic-synthesis techniques to implement Boolean functions on memristor crossbar arrays. It also presents a defect model and a defect-tolerant design strategy for memristive arrays.

"Enabling Full Associativity with Memristive Address Decoder" presents a memristor-based address decoder for use with a RAM. By utilizing a memristive NAND gate, an associative decoder can enable associative access at the timing and energy cost of ordinary memory. The memristor-based decoder is then utilized to implement an associative cache, a contentaddressable memory, or a virtually addressable memory.

"Newton: Gravitating Towards the Physical Limits of Crossbar Acceleration" describes an analog neural-network accelerator built using memristors. The acceleration is achieved by implementing vector multiplication on memristor crossbars, taking advantage of the memristor storage and compute abilities. The weights of the neural network are stored in the memristor cells, and the input values are fed to the crossbars. By doing the computation within the memory, the data movement in the system is drastically reduced, and the resulting system is very power- and energy-efficient.

The special issue concludes with a short department article that presents some emerging trends that might influence the future of memristors. Deji Akinwande describes some recently observed circuit effects in atomically thin materials. The recent invention of nonvolatile resistance switching in atomic sheets of transition metal-based materials⁴ points to the possibility of memristors that are just one-atom thick. Akinwande's research team has coined the term "atomristors" to refer to these devices.

ACKNOWLEDGMENTS

We thank all those who submitted manuscripts for this special issue and all those who reviewed articles, without whom there would not have been a special issue.

REFERENCES

- 1. L. Chua, "Memristor The Missing Circuit Element," *IEEE Transactions on Circuit Theory*, vol. 18, no. 5, 1971, pp. 507–519.
- D.B. Stukov et al., "The Missing Memristor Found," *Nature*, vol. 453, May 2008, pp. 80–83.
- 3. G.E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, vol. 38, no. 8, 1965, pp. 114–117.
- R. Ge et al., "Atomristor: Nonvolatile Resistance Switching in Atomic Sheets of Transition Metal Dichalcogenides," *Nano Letters*, vol. 18, no. 1, 2017, pp. 434–441.

ABOUT THE AUTHORS

Lizy K. John is the Cullen Trust for Higher Education Endowed Professor in the Electrical and Computer Engineering department at the University of Texas at Austin. She has a PhD in computer engineering from the Pennsylvania State University. Her research interests include workload characterization, performance evaluation, architectures with emerging technologies, and high-performance processor architectures for emerging workloads. She is a Fellow of the IEEE and an outstanding engineering alumnus of the Pennsylvania State University. Contact her at ljohn@ece.utexas.edu.

Earl E. Swartzlander, Jr. is a professor at the University of Texas at Austin. He has a PhD from the University of Southern California. His research interest is in the development of application-specific processors with a variety of emerging technologies. He is a Fellow of the IEEE, a distinguished engineering alumnus of Purdue University and the University of Colorado, and a member of the Golden Core of the IEEE Computer Society. Contact him at eswartzla@aol.com.