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The Mysterious Memristor

By **Sally Adee**

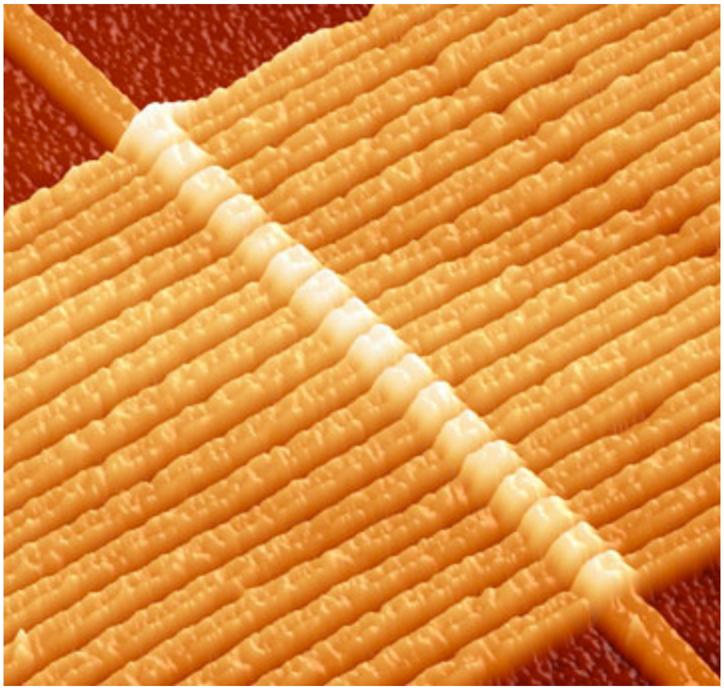

PHOTO: R. STANLEY WILLIAMS

1 May 2008—Anyone familiar with electronics knows the trinity of fundamental components: the resistor, the capacitor, and the inductor. In 1971, a University of California, Berkeley, engineer predicted that there should be a fourth element: a memory resistor, or memristor. But no one knew how to build one. Now, 37 years later, electronics have finally gotten small enough to reveal the secrets of that fourth element. The memristor, Hewlett-Packard researchers revealed today in the journal *Nature*, had been hiding in plain sight all along—within the electrical characteristics of certain nanoscale devices. They think the new element could pave the way for applications both near- and far-term, from nonvolatile RAM to realistic neural networks.

The memristor's story starts nearly four decades ago with a flash of insight by IEEE Fellow and nonlinear-circuit-theory pioneer Leon Chua. Examining the relationships between charge and flux in resistors, capacitors, and inductors in a 1971 paper, Chua postulated the existence of a fourth element called the memory resistor. Such a device, he figured, would provide a similar relationship between magnetic flux and charge that a resistor gives between voltage and current. In practice, that would mean it acted like a resistor whose value could vary according to the current passing through it and which would remember that value even after the current disappeared.

But the hypothetical device was mostly written off as a mathematical dalliance. Thirty years later, HP senior fellow Stanley Williams and his group were working on molecular electronics when they started to notice strange behavior in their devices. "They were doing really funky things, and we couldn't figure out what [was going on]," Williams says. Then his HP collaborator Greg Snider rediscovered Chua's work from 1971. "He said, 'Hey guys, I don't know what we've got, but this is what we *want*,' " Williams remembers. Williams spent several years reading and rereading Chua's papers. "It was several years of scratching my head and thinking about it." Then Williams realized their molecular devices were really memristors. "It just hit me between the eyes."

The reason that the memristor is radically different from the other fundamental circuit elements is that, unlike them, it carries a memory of its past. When you turn off the voltage to the circuit, the memristor still remembers how much was applied before and for how long. That's an effect that can't be duplicated by any circuit combination of resistors, capacitors, and inductors, which is why the memristor qualifies as a fundamental circuit element.

The classic analogy for a resistor is a pipe through which water (electricity) runs. The width of the pipe is analogous to the resistance of the flow of current—the narrower the pipe, the greater the resistance. Normal resistors have an unchanging pipe size. A memristor, on the other hand, changes with the amount of water that gets pushed through. If you push water through the pipe in one direction, the pipe gets larger (less resistive). If you push the water in the other direction, the pipe gets smaller (more resistive). And the memristor remembers. When the water flow is turned off, the pipe size does not change.

Such a mechanism could technically be replicated using transistors and capacitors, but, Williams says, "it takes a lot of transistors and capacitors to do the job of a single memristor."

The memristor's memory has consequences: the reason computers have to be rebooted every time they are turned on is that their logic circuits are incapable of holding their bits after the power is shut off. But because a memristor can remember voltages, a memristor-driven computer would arguably never need a reboot. "You could leave all your Word files and spreadsheets open, turn off your computer, and go get a cup of coffee or go on vacation for two weeks," says Williams. "When you come back, you turn on your computer and everything is instantly on the screen exactly the way you left it."

Chua deduced the existence of memristors from the mathematical relationships between the circuit elements. The four circuit quantities (charge, current, voltage, and magnetic flux) can be related to each other in six ways. Two quantities are covered by basic physical laws, and three are covered by known circuit elements (resistor, capacitor, and inductor), says Columbia University electrical engineering professor David Vallancourt. That leaves one possible relation unaccounted for. Based on this realization, Chua proposed the memristor purely for the mathematical aesthetics of it, as a class of circuit element based on a relationship between charge and flux.

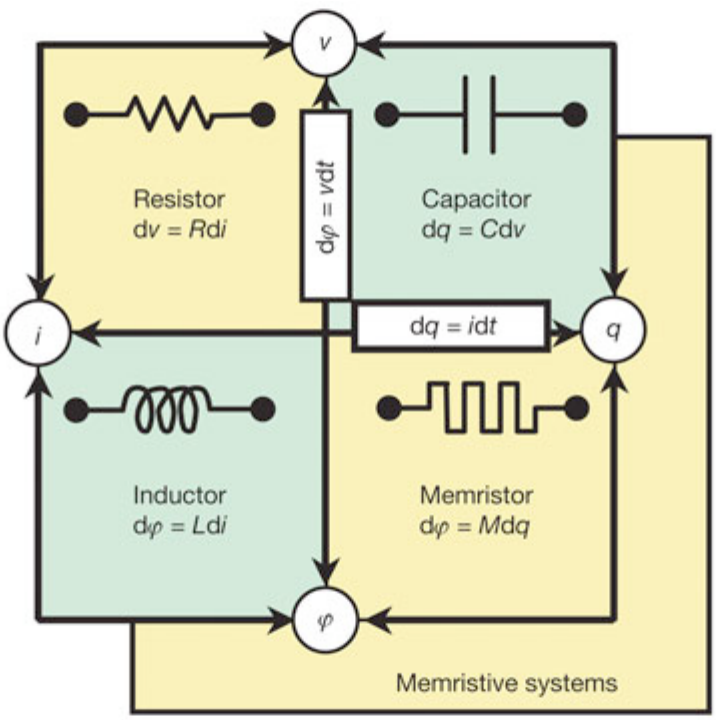

IMAGE: J. J. YANG/HP LABS

Chua calls the HP work a paradigm shift; he likens the addition of the memristor to the circuit design arsenal to adding a new element to the periodic table: for one thing, "now all the EE textbooks need to be changed," he says.

So why hadn't anyone seen memristance? Chua actually produced a memristor in the 1970s with an impractical combination of resistors, capacitors, inductors, and amplifiers as a proof of concept. But memristance as a property of a material was, until recently, too subtle to make use of. It is swamped by other effects, until you look at materials and devices that are mere nanometers in size.

No one was looking particularly hard for memristance, either. In the absence of an application, there was no need. No engineers were saying, “If we only had a memristor, we could do X,” says Vallancourt. In fact, Vallancourt, who has been teaching circuit design for years, had never heard of memristance before this week.

> *"now all the EE textbooks need to be changed" -IEEE Kirchoff Award winner Leon Chua on the discovery of the memresistor.*

But the smaller the scales of the devices scientists and engineers were working with got, the more the devices started behaving with the postulated “memristor” effect, says Chua, who is now a senior professor at Berkeley.

There had been clues to the memristor's existence all along. “People have been reporting funny current voltage characteristics in the literature for 50 years,” Williams says. “I went to these old papers and looked at the figures and said, ‘Yup, they've got memristance, and they didn't know how to interpret it.' ”

“Without Chua's circuit equations, you can't make use of this device,” says Williams. “It's such a funky thing. People were using all the wrong circuit equations. It's like taking a washing machine motor and putting it into a gasoline-powered car and wondering why it won't run.”

Williams found an ideal memristor in titanium dioxide—the stuff of white paint and sunscreen. Like silicon, titanium dioxide (TiO_2) is a semiconductor, and in its pure state it is highly resistive. However, it can be doped with other elements to make it very conductive. In TiO_2, the dopants don't stay stationary in a high electric field; they tend to drift in the direction of the current. Such mobility is poison to a transistor, but it turns out that's exactly what makes a memristor work. Putting a bias voltage across a thin film of TiO_2 semiconductor that has dopants only on one side causes them to move into the pure TiO_2 on the other side and thus lowers the resistance. Running current in the other direction will then push the dopants back into place, increasing the TiO_2's resistance.

HP Labs is now working out how to manufacture memristors from TiO_2 and other materials and figuring out the physics behind them. They also have a circuit group working out how to integrate memristors and silicon circuits on the same chip. The HP group has a hybrid silicon CMOS memristor chip “sitting on a chip tester in our lab right now,” says Williams.

The implications for circuit design may be niche at the moment. “This will require a fair amount of work to exploit,” says Columbia's Vallancourt. Applications will have to be identified in which the memristor's unique characteristics offer possibilities not covered by today's components.

Williams is in talks with several neuroscience/engineering labs that are pursuing the goal of building devices that emulate neural systems. Chua says that synapses, the connections between neurons, have some memristive behavior. Therefore, a memristor would be the ideal electronic device to emulate a synapse.

By redesigning certain types of circuits to include memristors, Williams expects to obtain the same function with fewer components, making the circuit itself less expensive and significantly decreasing its power consumption. In fact, he hopes to combine memristors with traditional circuit-design elements to produce a device that does computation in a non-Boolean fashion. “We won't claim that we're going to build a brain, but we want something that will compute like a brain,” Williams says. They think they can abstract “the whole synapse idea” to do essentially analog computation in an efficient manner. “Some things that would take a digital computer forever to do, an analog computer would just breeze through,” he says.

The HP group is also looking at developing a memristor-based nonvolatile memory. “A memory based on memristors could be 1000 times faster than magnetic disks and use much less power,” Williams says, sounding like a kid in a candy store.

Chua agrees that nonvolatile memory is the most near-term application. “I'm very happy that this is a breakthrough,” he says. “The reality is that at the nanoscale, this effect becomes dominant, and you'll find it whether you like it or not. I'm glad I can point people in the right direction.”