Memristors Ready For Prime Time

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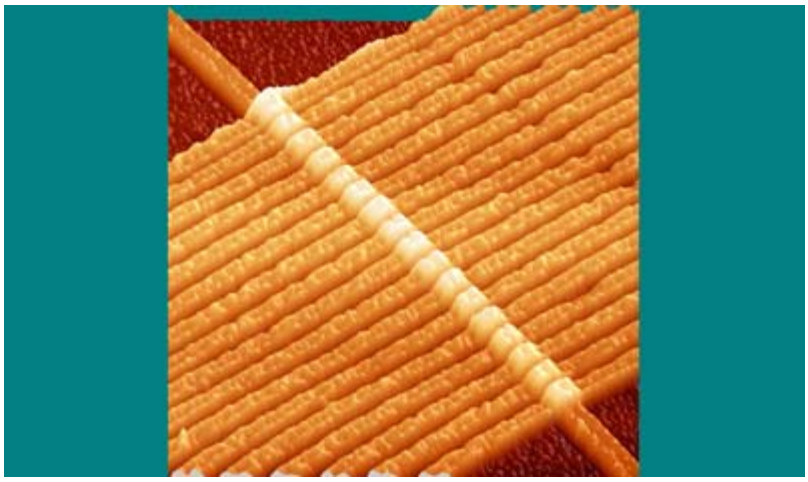
PORTLAND, Ore. — Memristors, the fourth passive circuit in electronic circuit theory, have moved a step closer to prototyping with the harnessing of a substrate material that could yield a new memory device by 2009.

In April, Hewlett Packard Laboratories researchers claimed to have "discovered" memristors, which joined resistors, capacitors and inductors as the fourth passive circuit postulated by University of California at Berkeley professor Leon Chua in a 1971 paper.

Now, HP Labs (Palo Alto, Calif.) said it has demonstrated how to control its memristor material, which changes resistance in response to current flowing through it. The advance promises to speed development of commercial prototype chips for its RRAM (resistive random-access memory) by next year.

"We now have experimental proof that our memristor behaves the way our theory predicts," said Duncan Stewart, principle investigator for memristors at HP Labs. "Plus, we have now demonstrated engineering control over the memristor device structures, which will enable us to build real chips very soon."



An atomic force microscope image shows 17 memristors sandwiched between a single bottom wire'that makes contact with one side of the device and a top wire that contacts the'opposite side.'The wires here are 50-nm wide. (Image courtesy of Jianhua Yang, HP Labs).

HP Labs' memristor is a two-terminal, two-layer semiconductor constructed from layers of titanium oxide sandwiched between two metal electrodes in a crossbar architecture. One layer of titanium oxide is doped with oxygen vacancies, making it a semiconductor; the adjacent layer is undoped, leaving it in its natural state as an insulator. By sensing the resistance between the two electrodes at the crossbar, the "on" or "off" state of the RRAM can be determined.

With one layer of titanium oxide in its natural state as an insulator, the memory switch is in its "off" state. By applying a voltage bias across the crossbar junction, oxygen vacancies drift from the doped layer of titianium dioxide to the undoped layer, causing it to begin conducting, thereby turning "on" the memory

switch. Likewise, by changing current direction, oxygen vacancies can be made to migrate back into the doped layer, thus turning the memory switch "off."

The main advantage of the memristor is that its resistance changes are nonvolatile, and remain until a reversed bias voltage is applied. That allows oxygen vacancies to migrate back into the doped layer. Switching times today are about 50 nanoseconds.

"People have been working on materials that exhibit resistance switching similar to our memristors for quite some time, but there have been a wide variety of explanations as to why they work," said Stewart. "Our demonstration puts the mechanism on very solid footing. We know just what is happening: Oxygen vacancies are changing the characteristics of the metal-oxide interface."

Still, knowing that oxygen vacancies changed the resistance of titanium oxide was not enough to exert engineering control over the material. HP researchers also needed to characterize the material with detailed measurements. They initially assumed that oxygen vacancies were affecting the bulk properties of the metal-oxide material. HP now claims that nanoscale changes at the interface between the oxide and the metal electrode, rather than the bulk characteristics of the material, affect the memristor's change in resistance.

"We have now established experimentally that oxygen vacancies are changing the metal-oxide interface's electronic barrier," said Stewart.

The researchers also claim that the memristor material works by thinning the Schottky barrier--the electronic barrier at the interface between metals and semiconductors--rather than by changing the bulk characteristics of the titanium oxide.

HP Labs devised a solution for performing a detailed characterization of the interface between each layer of a memristor: laying out its experimental device horizontally on the chip instead of vertically. "We used single-crystal titanium oxide to build the memristor into a lateral device, instead of a vertical device," said HP Labs researcher, Jianhua (Josh) Yang. "In that way, we can now test the two interfaces separately, and identify which was responsible for the memristor's behavior."

HP Labs fabricated horizontal devices in several configurations to fully characterize memristor behavior. Horizontal devices also allowed them to measure the electrical properties of each layer in different orders, thereby creating a knowledge base for building memristor-based CMOS semiconductors. "Now we know how to engineer new devices so that we get the behaviors that we want," said Yang. "For instance, if we want a positive voltage to turn the memristor off, then we want the titanium oxide layer with vacancies on the top layer. But if you want a positive voltage to turn the memristor on, then you need the layers reversed."

HP Labs is currently working on its first prototype chips to demonstrate working circuit functions that researchers expect to complete by next year. "With engineering control, we can now build a device that delivers a specific electrical performance," said Yang. "Only with engineering control do you get to a point where you can build large integrated circuits."

HP Labs' prototype chips will be for RRAMs that use its crossbar architecture. Metal lines spaced less than 50-nm apart will serve as the bottom electrodes with the top electrodes patterned from metal lines arranged perpendicular to the bottom lines into a crossbar switch. In between the metal lines, engineers plan to sandwich twin layers of titanium dioxide--one doped with oxygen vacancies and the other

undoped. Running current between two metal lines--one on the top and one on the bottom--the device will be able to address individual bit cells, changing their resistance and thus turning bits on and off.

"We are currently building real circuits, with our near- term target the nonvolatile random-access memory market where there is lots of potential," said Stewart.

HP Labs plans to unveil RRAM prototype chips based on memristors with crossbar arrays in 2009.

It will also use a similar crossbar architecture to harness precise resistance change in an analog circuit. HP Labs claims that massive memristor arrays with tunable resistance at each crossbar could enable brain-like learning. In the brain, a synapse is strengthened whenever current flows through it, similar to the way resistance is lowered by flowing current through a memristor. Such neural networks could learn to adapt by allowing current to flow in either direction as needed.

"RRAMs are our near term goal, but our second target for memristors, in the long term, is to transform computing by building adaptive control circuits that learn," said Stewart. "Analog circuits using electronic synapses will require at least five more years of research."

They estimate that it will take five years to produce the first analog memristor prototypes, with commercial applications about a decade out.