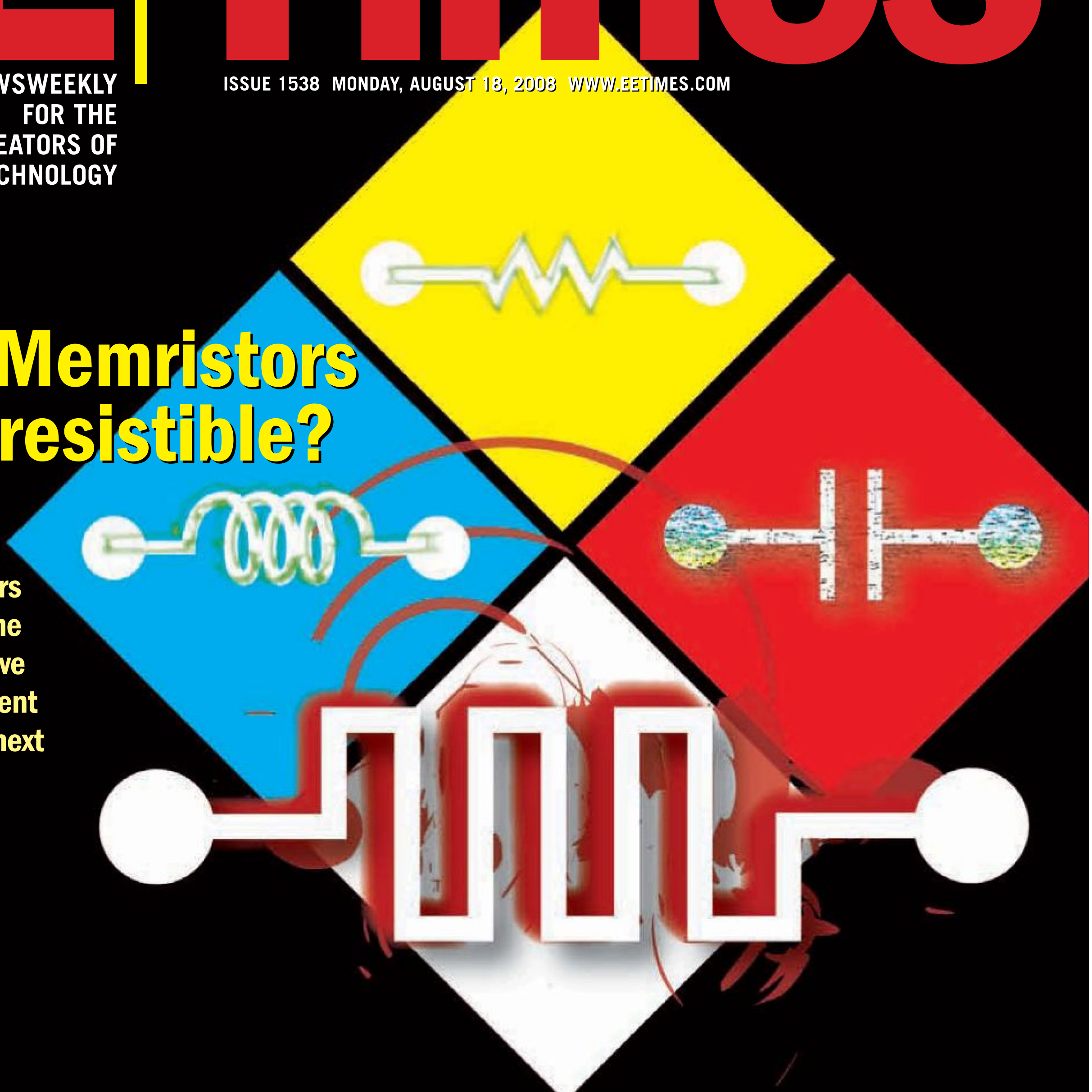
United Business Media

MEMS' Olympic moment 22

EE Times

THE NEWSWEEKLY FOR THE CREATORS OF TECHNOLOGY

ISSUE 1538 MONDAY, AUGUST 18, 2008 WWW.EETIMES.COM



Will Memristors be irresistible?

Transistors, capacitors and inductors were. Can the fourth passive circuit element launch the next revolution?

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Circuit redux

Will memristors prove irresistible?

By R. Colin Johnson

THE TRANSISTOR WAS INVENTED in 1925 but lay dormant until finding a corporate champion in Bell Labs during the 1950s. Now another groundbreaking electronic circuit may be poised for the same kind of success after languishing as an academic curiosity for more than three decades.

Hewlett-Packard Labs is attempting to catapult the memristor, the fourth passive circuit element after resistors, capacitors and inductors, into the electronics mainstream. Invented in 1971, this "memory resistor" represents a potential revolution in electronic-circuit theory akin to the invention of the transistor — and perhaps its time has finally come. But as with that earlier device, it will take a killer application to get it off the ground.

Where the hearing aid played that role for the transistor, Hewlett-Packard Labs (Palo Alto, Calif.) hopes resistive random-access memories (RRAMs) will open the floodgates for the memristor. HP Labs is promising prototypes of these ultradense memory cells next year.

"I'd say memristors give HP a chance to become the dominant leader in memory technology in 10 years," said Martin Reynolds, vice president of Gartner Inc. (Stamford, Conn.). "We have seen HP reinvent itself a number of times in the past, and this is a technology that could really drive that kind of change in the company again."

However, the clock is ticking. Last year, HP's crossbar switches — the building blocks of a new memory type the company is developing — were more than 20 times denser than flash memories, giving HP breathing room to perfect its RRAMs. But in less than a year, flash memories have upped their density fourfold to eightfold by going to 2- and 3-bit-per-cell configurations, respectively.

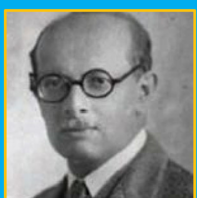
That unforeseen leap has narrowed HP's advantage. RRAMs now claim just three times the density of flash, evoking memories of the same scenario that has doomed other next-generation memory technologies.

"When HP started work on the crossbar several years ago, they were 40 or 50 times denser than flash," said Reynolds. "But now they are only about three times denser than flash." To stay ahead, he said, HP will have to figure out how to boost the memristor's current density of 100 Gbits/cm2 "to a terabit in a square centimeter."

Regardless of whether HP's RRAMs become

Transistor milestones

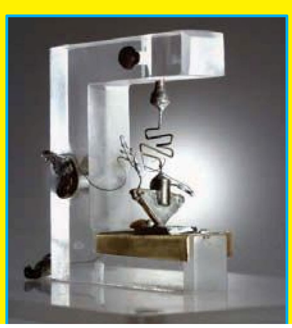
1925
Julius Edgar Lilienfeld (physicist, University of Leipzig) files first transistor patent on a metal epitaxial semiconductor field-effect transistor (MESFET, US patent 1745175), but never builds one.



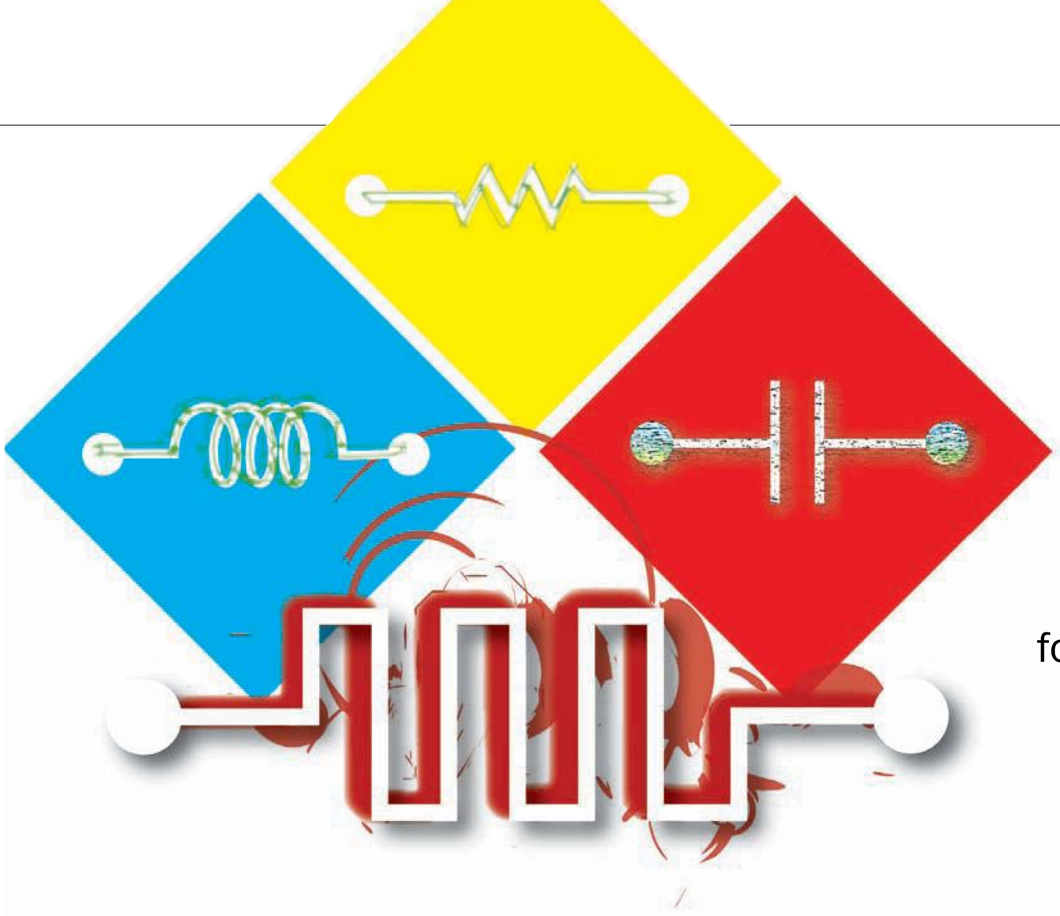
1928
Lilienfeld files patent on a thin-film metal oxide semiconductor FET (MOSFET, US patent 1900018), but never builds one.

1934
Oskar Heil (physicist, University of Göttingen, Germany) patents the FET in Germany (GB patent 439457), but never builds one.

1945
Bell Labs forms Solid State Physics Group led by physicist William Shockley to develop an alternative to vacuum tube amplifiers.



1948
John Bardeen (physicist, Bell Labs) awarded US patent 2524035 for building a working point-contact FET.
William Shockley awarded US patent 2569347 for what becomes the modern junction FET.



Hearing aids did the trick for transistors. What killer app will take memristors into the mainstream?

the killer application, the memristor could turn out to be as important a development as the transistor itself. And as with the transistor, applications may take a while to accumulate.

"The memristor's history is similar to that of the transistor, which was invented 35 years before its first major application," said Wolfgang Porod, an EE professor at Notre Dame University. Created in the 1920s by physicist Julius Edgar Lilienfeld, the device was not developed to its full potential until it came to the attention of Bell Labs researchers William Bradford Shockley, John Bardeen and Walter Houser Brattain, who were awarded the 1956 Nobel Prize for their pioneering work.

The first application, Porod said, was in-ear hearing aids, where "its small size justified its higher cost in those days compared with vacuum tubes." Transistor radios soon followed.

In just the same way, HP sees RRAMs as only the beginning for the memristor. HP Labs foresees its use in neural networks that 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 Duncan Stewart, principal investigator for memristors at HP Labs.

Using a crossbar architecture similar to that of the RRAM to harness precise resistance changes in an analog circuit, HP Labs claims that massive memristor arrays with tunable resistance at each crossbar could enable brainlike learning. In the brain, a synapse is strengthened whenever current flows through it, in much the same way as flowing current through a memristor lowers resistance.

"Analog circuits using electronic synaps-

↑ 1956
Shockley, Bardeen and Walter Brattain (physicist, Bell Labs) share Nobel Prize for world's first working transistors.

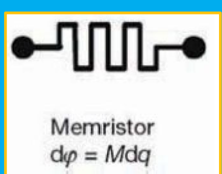
→ 1952
Sonotone introduces first commercial transistor application, the hearing aid.

→ 1953
Sony, Texas Instruments and others demo first transistor radios.

Memristor milestones

1971

Leon Chua (EE, University of California, Berkeley) publishes "Memristor — the Missing Circuit Element," (IEEE Transactions of Circuit Theory, Vol. 18, No. 5), but never builds one.



1976

Leon Chua publishes "Memristive Devices and Systems" (Proceedings of the IEEE, Vol. 64, No. 2), but ultimately builds only an emulator.

1980

Leon Chua publishes "Dynamic Nonlinear Networks: State of the Art" (IEEE Transactions on Circuits, Vol. 27, No. 11), which models all nonlinear circuit elements, including the memristor.

es will require at least five more years of research," Stewart said. HP Labs estimates that commercial applications are about a decade out.

The fundamentals

Technically, a memristor is a passive circuit element that relates flux to charge in the same way resistors relate voltage to current, capacitors relate voltage to charge and inductors relate flux to current. The fact that this fourth combination has been ignored in electronic-circuit theory was discovered by EE professor Leon Chua at the University of California, Berkeley, who wrote a seminal paper about the memristor in 1971.

"Memristors represent a fundamental change in electronic-circuit theory," said Sung-Mo Kang, chancellor of the Engineering School and an EE professor at the University of California at Merced. The most important items in electronics are the voltage, the current, the electrical charge and the flux linkage, he said. "If you consider those four variables as constitutive relations, then you get the equations that describe the resistor, inductor and capacitor."

But there is a fourth combination that everybody had overlooked, said Kang. "Chua's genius was realizing that combination defined a new passive-device type — the memristor," he said. "Chua's argument was mathematical, but what he was saying is that the memristor had just as much a fundamental right as resistors, inductors and capacitors."

Chua called his discovery a memristor because of its behavior: The device acts as a variable resistance that "remembers" how much current has flowed through it by changing the voltage across its terminals. Thus, it can serve as a memory element that can be flipped "on," with a current in one direction, and "off," with a current in the reverse direction.

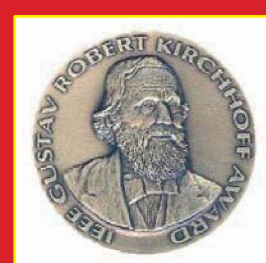
"A resistor relates voltage to current and the memristor relates flux to charge," said Notre Dame's Porod. "However, if you sum up flux over time, it becomes a voltage, and if you sum up charge over time it becomes a current. So a device that relates flux to charge, like the memristor, will over time relate voltage to current like a variable resistor that changes its value depending on how much, and in which direction, current has flowed through it."

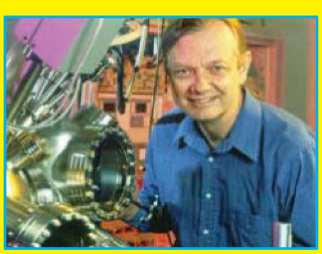
For 35 years, only Chua and a handful of his former students taught fledgling engineers about the concept of a memristor. In lab classes, using resistors, inductors, capacitors and transistors, Chua had circuit boards built that emulated a memristor. He also wrote many papers providing detailed characterizations for EEs — effectively telling them how to recognize a memristor when they saw one.

Nevertheless, the idea remained an academic matter for 35 years, until HP chemist Stanley Williams (now a senior fellow) realized he had discovered an electronic-circuit element that exhibited the behavior Chua described.

"The fingerprint by which EEs can recognize a memristive circuit element is by its voltage-current relationship," Chua said. He described that relationship as "a hysteresis loop that goes through the origin — what I call a pinched hysteresis loop."

Many such pinched hysteresis loops have cropped up in the literature on nanoelectronics over the past 15 years, said Chua, "but these devices have been incorrectly identified by the authors of these papers." It took Williams' multidisciplinary team of physicists, chemists, mathematicians and EEs at





1995

HP Labs forms "Quantum Structures Research Initiative" led by chemist Stanley Williams to develop molecular-scale alternative to transistor-based switches.

2002

Leon Chua publishes "Nonlinear Circuit Foundation for Nanodevices" (Proceedings of IEEE, Vol 91, No. 11), which positions memristors within his nonlinear circuit theory.

2005

Leon Chua receives IEEE Gustav Robert Kirchhoff Award, which recognizes him as the father of both nonlinear circuit theory and cellular neural networks.

2006

HP's Stanley Williams files US patent application for the world's first working memristor.

2008

HP Labs publishes description of its memristive device based on the drift of charged dopants in a semiconductor, and proposes two applications — nonvolatile resistive random access memory (RRAM) and electronic synapses that mimic the brain's neural networks.

HP Labs to correctly identify a memristor for the first time, Chua said — namely, "the titanium-dioxide nanostructures they [HP] are using between their crossbars."

Because a memristor's resistance changes as current flows through it, HP has made the memristor the key element in its overall program to build an entirely new kind of memory using crossbar switches. By using nanoimprint lithography, HP had already perfected a method of fabricating crossing arrays of ultradense perpendicular metal lines — the crossbars. By picking one line from the top array and one line from the bottom, any bit can be directly addressed at the point where the two lines cross, enabling crossbar arrays that today pack 100 Gbits/cm2. By contrast, flash is currently at 32 Gbits/cm2.

For a while, HP was unable to find a reliable material to sandwich between the crossbars, despite several years of experimentation with all sorts of nonvolatile-memory materials. Last year HP disclosed it was experimenting with organic molecules as the memory element for its crossbars, but the organic material's sensitivity to high temperatures made HP start looking in the inorganic world for a sturdier nonvolatile option.

"The nice thing about using the memristor in a crossbar is that it is made out of relatively robust inorganic materials like titanium dioxide," said Gartner analyst Reynolds.

With memristors composed of inorganic titanium oxide, HP believes it finally has the right mix to leapfrog flash and other alternative memory technologies, such as phase-change RAM (PRAM), with its resistive random-access memories. Hynix, Intel, Samsung, STMicroelectronics and others have licensed chalcogenide-based PRAM technology from Ovonyx Inc. (Rochester Hills, Mich.).

"We now think that memristors are the best technology for our crossbar switches," said Williams.

HP has already demonstrated that it can control its memristor material by sending current through it to change the resistance at a crossbar point. By merely measuring the resistance on any element of an array, HP claims it can determine the state of the nonvolatile bits as "on" or "off." Using its engineering expertise at building crossbars with nanoimprint lithography, HP promises to speed development of a prototype chip for its RRAM.

"We have now demonstrated engineering control over the memristor device structures, which will enable us to build real chips very soon," said Stewart of HP Labs.

HP Labs' memristor is a two-terminal, two-layer semiconductor built 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 applying a voltage bias across the crossbar junction, oxygen vacancies drift from the doped 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. Switching times are about 50 nanoseconds.

What happens next

The HP researchers say 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' promised prototype RRAM will likely just demonstrate that the memory array itself can be read and written to with external circuitry. The next milestone will be fabricating a crossbar memory array on a conventional silicon chip, with the read/write and addressing circuitry in silicon and the memory array embedded into the metallization layers on top.

"All memory storage elements today use silicon transistors as the memory element," said Gartner's Reynolds. "The thing about the crossbar that I really like is that it moves the memory element out of the silicon and puts it on top." Because "relatively conventional silicon circuits" are used for control and management logic below the array, "the crossbar memory array can be much more dense than the underlying transistor technology," he added.

PRAMs likewise enable the memory element to be lifted out of the silicon and established in a separate thin film of chalcogenide. However, chalcogenide is a glass that can only be coded with two different states — amorphous and crystalline. RRAMs, by contrast, have a full range of analog resistance values available. Thus, like today's flash, they can encode multiple bits per cell.

"HP will have to demonstrate that [the RRAM] is better than chalcogenide-based technology," Reynolds said. ■