The memristor revisited

Technological innovation can require both an understanding of the past and a clear vision for the future — as the development of memristive devices illustrates.

This month marks ten years since researchers at Hewlett Packard Labs reported a memristor[1]. At first glance, their monolithic nanoscale memristive device resembles an ordinary two-terminal resistor, but closer inspection reveals something more intricate. A cross-section view shows three layers to the device: a 'storage' layer made of titanium dioxide sandwiched between two platinum electrodes. This internal storage layer can be dynamically reconfigured through electrical stimulation, and this reconfiguration creates a memory effect in which the resistance of the device depends on the history of current that has flowed through it. Crucially, this programmed state is not lost once the power supply is removed. The functionality of this passive device cannot be replicated by any combination of fundamental two-terminal circuit elements — resistors, capacitors and inductors — and it has thus been labelled the missing circuit element[2].

The history of the memristor is fascinating — and long. Writing in our Reverse Engineering column in this issue of *Nature Electronics*, Leon Chua explains how being tasked with revamping the outdated circuit analysis curriculum at Purdue University in 1964 led him to first postulate the device. It was in 1971 that Chua reported his prediction of a device that behaves like a nonlinear resistor with memory, which he then termed a memristor (a contraction of memory and resistor)[2]. Thirty-seven years later, the team from Hewlett Packard Labs, which was led by R. Stanley Williams, connected their experimental observations to Chua's theoretical prediction and the fourth fundamental circuit element was found.

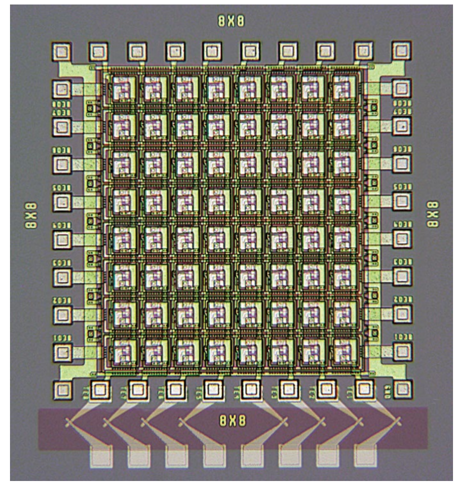
While this basic narrative — a drawn-out example of theoretical conception followed by experimental confirmation — is attractive, the history of memristive devices is more complicated. Work on non-volatile resistive switching — in other words, memristive behaviour — began in earnest as early as the 1960s[3]. And remarkably, studies of this behaviour can be traced as far back as the early 1800s[4], and thus predate both the resistor (Ohm in 1827) and the inductor (Faraday in 1831).

There can be many reasons why a nascent technology is, at first, discarded or forgotten. Timing was likely an issue for early memristive technology: the 1970s coincided with great advances in silicon technology and the digital computing revolution. And a focus on memristive technology was perhaps always unlikely as long as silicon technology continued to make significant strides.

More recently, progress in silicon technology has waned and interest in memristive technology has intensified. Writing on the future of electronics based on memristive systems, Wei Lu and colleagues have suggested that memristive technologies could help in three areas: on-chip memory and storage, in-memory computing, and biologically inspired computing[5]. Densely packed memristive devices, in the form of resistive random access memory, could, for example, be directly integrated on a processor chip. Such a configuration would improve the overall energy efficiency and speed of computation by removing the slow and energy-intensive off-chip communication between the processor and memory. In-memory computing takes the idea of reducing communication between the processor and memory to the extreme, creating systems in which there is no physical separation between computation and memory. With neuromorphic computing systems, memristive devices are designed to mimic biological synapses and neurons.

As Lu and colleagues explain, memristive devices possess many favourable properties for electronics[5]. They can be scaled down to sub-10 nm feature sizes, retain memory states for years, and switch with nanosecond timescales. Moreover, these devices can offer long write–erase endurance and can be programmed using low current levels (on the order of nanoamperes). However, the authors also concede that a single material system that combines all of the above properties remains elusive.

Crucial to the technological development of any device is an understanding of the underlying processes that govern its operation. At the device level, considerable insight into memristive switching has been obtained in recent years, largely due to the development of advanced characterization tools that can probe the processes that drive switching. In a Review Article in this issue, Yuchao Yang and Ru Huang examine the different techniques used to characterize memristive switching in oxide memristors, and based on the relative strengths and weaknesses of each approach, propose a general framework for the physical characterization of these devices.



An optical micrograph of an integrated memristive neural network, consisting of an 8 × 8 memristive synapse crossbar interfaced with eight memristive artificial neurons. Credit: Macmillan Publishers Ltd.

Studies of memristive behaviour extend back beyond the work of Williams and colleagues at Hewlett Packard Labs, and an appreciation of the past is, of course, essential in research. But what is the value of an observation (or re-observation) without a sense of its significance? The vision of Williams and colleagues, building on the imaginative insight of Chua 37 years previous, reinvigorated memristive technologies and inspired a new generation of researchers to pursue the technology. In their 2008 paper, the team at Hewlett Packard Labs suggested memristors could be used to deliver applications such as "ultradense, semi-non-volatile memories and learning networks that require synapse-like function"[1]. Today, these applications exist[5]. It is often both an understanding of the past and a clear vision for the future that drives innovation. ❐

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