Memristive Devices for Computing: Mechanisms, Applications and Challenges

J. Joshua Yang, Byung Joon Choi, Min-Xian Zhang, Antonio C. Torrezan, John Paul Strachan, R. Stanley Williams

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Abstract:

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Memristive Devices For Computing: Mechanisms, Applications And Challenges

J. Joshua Yang, Byung Joon Choi, Min-Xian Zhang, Antonio C. Torrezan, John Paul Strachan, and R. Stanley Williams
Hewlett-Packard Laboratories, 1501 Page Mill Rd., Palo Alto, CA 94304, USA

Memristive devices are two terminal electrical resistance switches that can retain a state of internal resistance based on the history of applied voltage and current. These devices can be used for computing by both storing and processing information. The switching mechanisms, applications and challenges are reviewed in this paper.

Existing technologies for the current computing system are approaching their physical limits, and novel device concepts are required as device sizes continuously decrease (1). Under these new concepts, the devices need be not only increasingly infinitesimal and simple but also increasingly capable. Memristive devices (2-6) (also called RRAM (7-13) when used for memory) seem to fulfill these goals well for the next generation computing system and have recently been recommended for additional focus in research and development by the International Technology Roadmap for Semiconductor (ITRS) in an assessment of eight memory technologies among the Emerging Research Devices (ERDs) (1). These devices with a simple structure are not only very small but also very versatile, which makes them an ideal candidate used for the next generation computing system in the post-Si era. Memristive devices are electrical resistance switches that can retain a state of internal resistance based on the history of applied voltage and current (2, 6). They can be used store and process information, and offer several key performance characteristics that exceed conventional integrated circuit technology (14).

An important class of these devices is two-terminal resistance switches based on ionic motion, which are built from a simple conductor/insulator/conductor thin-film stack. The switching mechanisms (15-19) are still a controversial topic currently under active research. Different switching mechanisms likely apply to different material systems and device stacks. Generally speaking, electrical switching is a result of ionic motion driven by both electric field and joule heating via drift, electromigration, Fick diffusion or thermophoresis (14). A family of nanodevices with a rich set of electrical properties can be obtained with the crosspoint device structure based on these switching mechanisms (20).

These crosspoint devices are usually used in a crossbar array for real applications. The potential applications range from memory to logic and from digital circuits to analog circuits. Non-volatile (>years) (21), fast (<100ps) (22) and low-energy (<pJ) (23) (17) switching has been demonstrated. Functioning devices have also been obtained at 10nm scale (24). Therefore, memristive device has the potential to be a universal memory. In addition, there are other promising applications, including Boolean logic operations via material implication (25), neuromorphic computing (26, 27), and a variety of CMOS/memristor hybrid circuits (28, 29).

In spite of the promising scalability, fast switching speed, low energy, long retention, large ON/OFF ratio, multilevel cell operation, non-destructive reading, simple structure, great stackability, low cost, great CMOS compatibility and manufacturability, there are

also some challenges for these devices, including switching endurance (30, 31), device yield (32), electroforming (33), device nonlinearity (34-36), variability and some issues related to integration (37, 38). Among them, the most significant two challenges are device nonlinearity and variability.

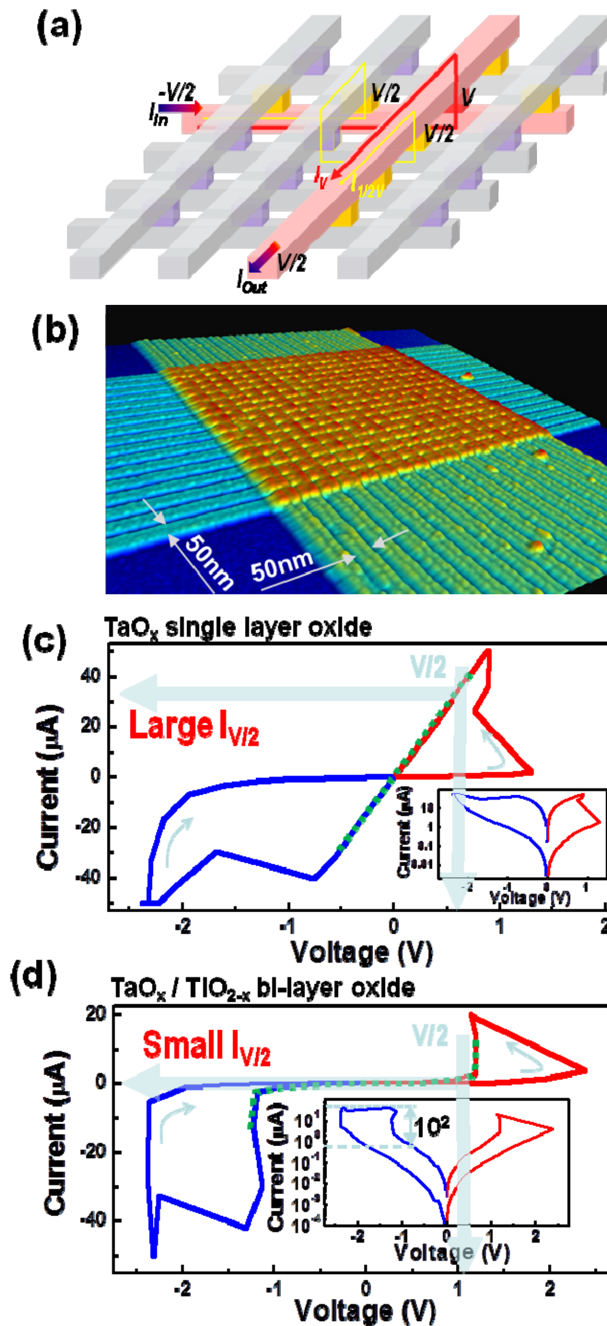

Figure 1. crossbar array and current voltage loops of nanodevices. (a) schematic illustration showing the sneak path current through the half-selected memristors (b) atomic force microscopy image of a crossbar array with 50 nm half-pitch fabricated by nanoimprint lithography. (c) switching loop from a Pt / TaO_x / Ta 50 nm × 50 crosspoint device, showing linear current-voltage curve in the ON state. (d) switching loop from a Pt / TaO_x / TiO_{2-x} / Pt 50 nm × 50 nm crosspoint device, showing nonlinear current-voltage curve in the ON state. Reprinted with permission from ref 34. Copyright 2012, American Institute of Physics.

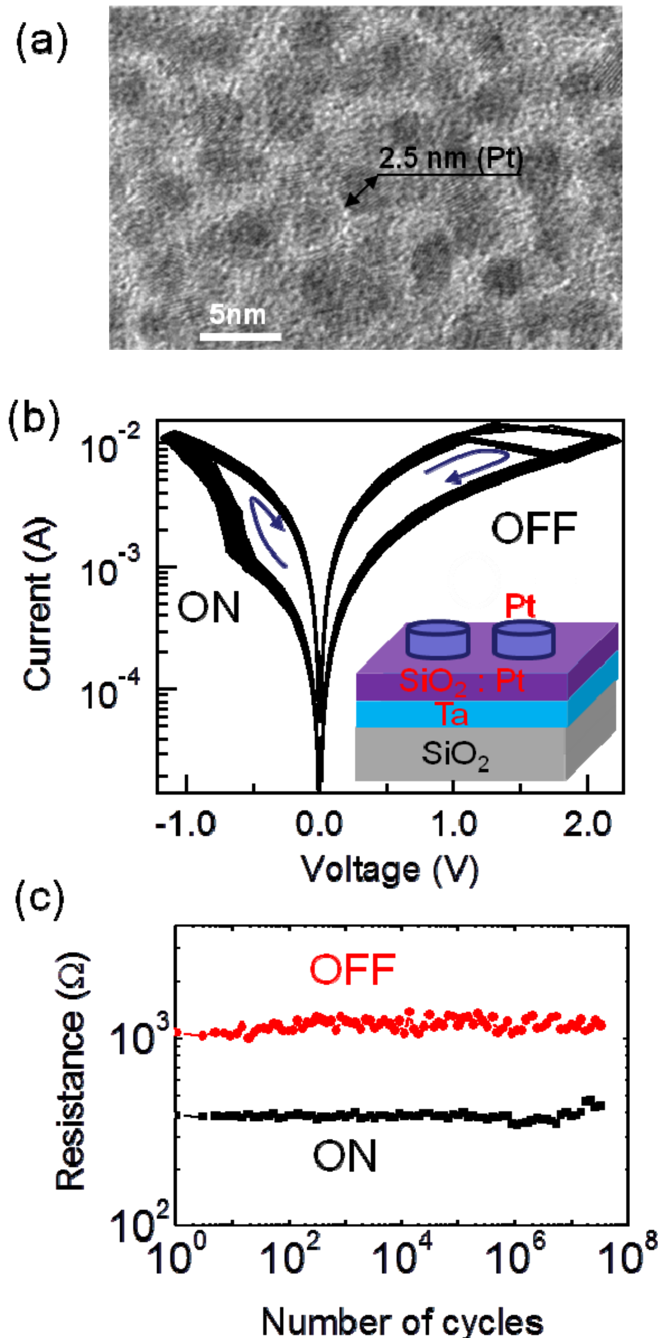

Figure 2. Memristive device using engineered switching materials. (a) plan-view TEM image of the as-prepared Pt dispersed SiO_2 film. (b) and (c) Repeatable switching of Pt dispersed SiO_2 microdevices. (b) current-voltage switching loops of 1000 consecutive test in micro-scale device (inset: schematics of device structure), (c) Endurance test using voltage pulse with 10μs width. Reprinted with permission from Ref 21. Copyright (2013) American Chemical Society.

Nonlinearity is a measure of how nonlinear the current-voltage curve is for a device in its low resistance state. Most of the memristive devices have linear or slightly nonlinear current-voltage curves, As shown in Figure 1 (c), which results in a fairly high current level at the half of the operation voltage for either write or read. This further leads to a high sneak path current in the crossbar array as schematically shown in Figure 1 (a). In

order to minimize the sneak path current, a highly nonlinear current-voltage curve is required, which can be achieved by adding a nonlinear selector to the memristor at each crosspoint. Figure 1 (d) shows a switching loop with great nonlinearity from an integrated device combined a negative differential resistance (NDR) selector with a linear memristor. The selector can also be a mixed-ionic-electronic-conductor (MIEC) (39) or a tunneling device with engineered tunnel barrier (40).

The variability includes variances from switching cycle to cycle and from device to device. The variance can be reduced by selecting a material system that has only two stable solid phases (one for conduction channel and the other for insulating matrix) at ambient temperature (30). It seems most of the variance actually stems from the somewhat random electroforming process that creates a different filament structure in each device, which can be significantly reduced by controlling the formation of conduction channel. This can be realized by, for instance, doping the switching material (e.g SiO_2) with uniformly distributed metallic nanoclusters (e.g Pt) (21). Repeatable switching is shown in Figure 2 from such a device.

In summary, while memristive devices have shown great promise for computing applications, there are still a few challenges to overcome, including mechanism understanding, device nonlinearity and variability.

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