Probabilistic modeling of resistive switching in emerging ReRAM cells

Y. V. Pershin and V. A. Slipko*
Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA
*Institute of Physics, Opole University, Opole 45-052, Poland
e-mail: pershin@physics.sc.edu

In this workshop contribution, we present a new model developed to simulate the resistive switching process in resistance-switching random access memory (ReRAM) devices such as electrochemical metallization (ECM) cells. Fig. 1 shows that in ECM cells, under appropriate bias, a conductive metallic filament is formed out of the top electrode (TE) atoms in the insulating layer. Such filament can be dissolved using the voltage of opposite polarity. ECM cells are considered as a promising candidate for the next generation of non-volatile memory, as well as in-memory computing and neuromorphic architectures thanks to their ability to store and process the information on the same physical platform.

The cycle-to-cycle variability is a well-known general property of ECM cells that is not taken into account by standard models. Fundamentally, it originates from the randomness of thermally-assisted atomic rearrangement processes. Quite recently, we demonstrated [1] that the master equation may tremendously simplify the modeling of binary and multi-state ReRAM cells compared to Monte-Carlo simulations (Fig. 2). One of the advantages is that the master equation can be used to find many device/circuit characteristics in a single computation without the need for averaging (see, e.g., Fig. 3).

The main assumption of our new model [2] is that the resistance switching occurs via random markovian jumps in the *continuous* space (CS) of an internal state variable x (see Fig. 1, bottom). The statistical description of a cell is based on the state probability distribution function $p(x,t)$ whose evolution is governed by

$$\frac{\partial p(x,t)}{\partial t} = \int_a^b \gamma(x',x,V(x'))p(x',t)\mathrm{d}x' - p(x,t)\int_a^b \gamma(x,x',V(x))\mathrm{d}x'. \qquad (1)$$

Here, $\gamma(y,z,V(y))$ is the voltage-dependent transition rate density from internal state y to z, and $V(y)$ is the voltage across the device in state y. Eq. (1) is supplemented by statistically averaged Ohm's law

$$\langle I\rangle = \left\langle \frac{V}{R(x,V)} \right\rangle \equiv \bar{R}^{-1}(V)\cdot V, \qquad (2)$$

where $\langle I\rangle$ is the mean current, V is the voltage across the device, $R(x,V)$ is the state- and voltage-depend resistance.

Figs. 4-6 present examples of simulations based on the above model with resistance used as the internal state variable. Both the responses to ac-voltage (Figs. 4, 5) and step-like voltage (Fig. 6) demonstrate good agreement with experimental behavior of ECM cells. The suggested approach can be extended to more complex cases such as the description of electronic circuits with several cells.

Overall, our modeling approach is unique and fundamentally different from traditional (deterministic) models of ReRAM cells. In essence, it provides a straightforward way to simulate the response of ReRAM cells *on average*. As such, we expect that this work will contribute to the accelerated development of future information processing and storage devices. Moreover, it may find applications in other fields.

REFERENCES

[1] V. J. Dowling, V. A. Slipko, and Y. V. Pershin, "Probabilistic memristive networks: Application of a master equation to networks of binary ReRAM cells," *Chaos, Solitons & Fractals*, vol. 142, p. 110385, 2021.

[2] V. A. Slipko and Y. V. Pershin, "A probabilistic model of resistance jumps in memristive devices," *arXiv preprint arXiv:2302.03079 (submitted for publication)*, 2023.

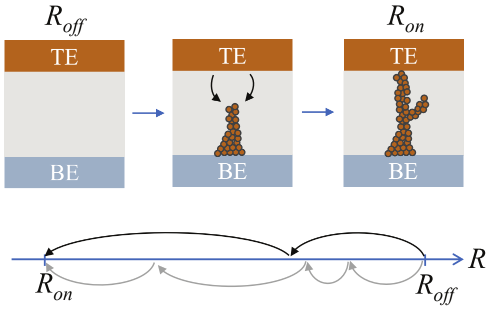

Fig. 1. Schematics of the transition from high- to low-resistance state in an ECM cell. Here, the top (TE) and bottom (BE) electrodes are separated by an insulating layer. Bottom: two different realizations of the resistance switching process.

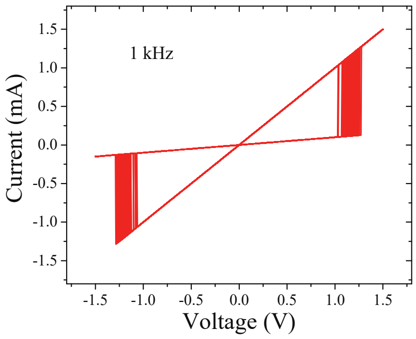

Fig. 2. Monte-Carlo simulations of a two-state resistance switching device [1].

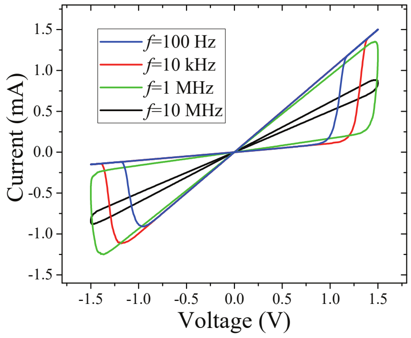

Fig. 3. Two-state model simulations [1]. $\langle I \rangle - V$ curves.

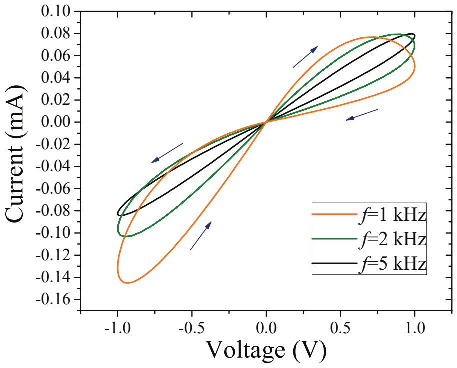

Fig. 4. CS model simulations [2]. $\langle I \rangle - V$ curves.

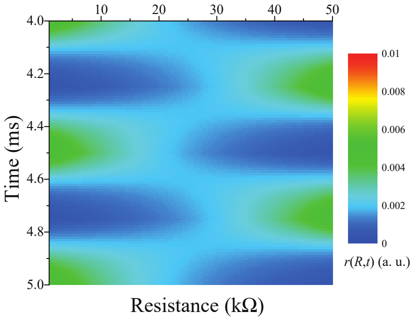

Fig. 5. CS model simulations [2]. Evolution of the resistance probability distribution function.

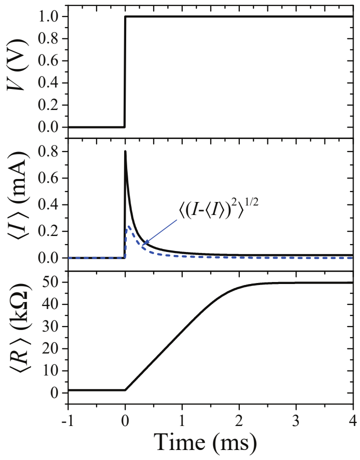

Fig. 6. CS model simulations [2]. Response to a step-like voltage.