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XXXIV Cycle

Compact modelling of memristive devices

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Research context and motivation

- In the last decade, the approaching limit of Moore's Law has created a great demand for innovative technologies and approaches to solve more and more complex problems. Among those approaches, Neuromorphic Computing stands as the most promising with a wide pletora of implementations (i.e. Deep Convolutional Neural Networks) already on the market and many others (i.e. Reservoir Computing) that have proven their worth from a theoretical standpoint as well as in proof of concept experiments.
- Although Neural Networks have proven their superiority in solving problems that were once thought not approachable by machines (i.e. computer vision and speech recognition), still their software implementations running on CPUs and/or GPUs are many order of magnitude power hungrier than Biological Neural Networks. On the one hand the former digital computing units, being implementations of the von Neumann architecture, spend a lot of power on transferring data back and forward between the memory site and the computation site, on the other hand Biological Neural Networks process information in situ thus achieving real low power performance. Lots of research has gone in the direction of using CMOS-based ASICs to implement in situ digital accelerators for Machine Learning.
- CMOS implementations of accelerators for the most widely used Neural Networks require very large area ICs. This is because of the massive number of synapses needed in real-world Neural Networks architecture and the necessity of at least 6 transistors for each synapse. A better alternative to implement the interconnections between neurons in Neural Networks came in the late 2000's from the research of new technologies to implement multilevel memory storage devices. One of those novel technologies, the $Pt - TiO_{2-x} - Pt$ junction, was shown by the research group lead by Stanley Williams at HP, to be a physical implementation of the memristor, a fourth fundamental 2-terminal circuit element theorized by Leon Chua in the '70.
- Memristors and memristive systems are ideally, devices whose electrical conduction properties are determined by the history of voltages/currents applied at the port. In real manufactured devices this is almost never the case. Although many technologies have shown all the distinctive experimental hallmarks of the memristive behavior, nonetheless their conduction mechanism and internal memory state evolution is usually determined by various non-electrical inputs and/or states. Having good and practical models of those nonideal devices has proven to be quite challenging. Although physical models provide the best agreement with experimental data, they do it at the cost of very long simulation times.

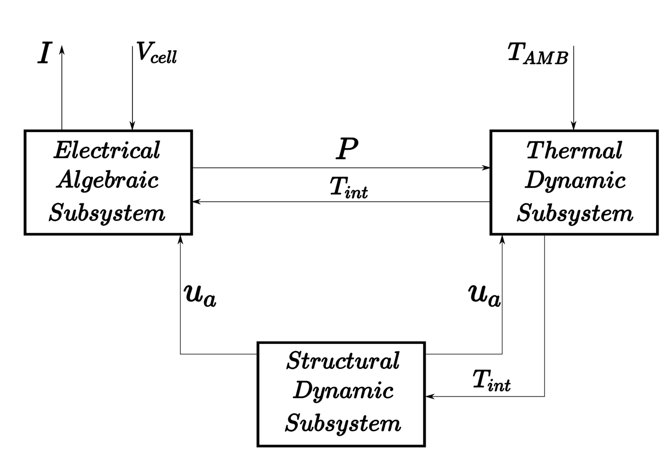
Addressed research questions/problems

- Compact physics-based models for the efficient simulation of large memristor based neural networks as simplified and accurate solutions for handling large network structures.
- Unfolding of complex dynamical behaviors in memristor based analogue oscillatory circuits.
- Novel accurate characterization techniques for memristive devices and systems.
- Topological optimization of VLSI memristor based neural network with the aim of reducing the IC surface area and number of interconnecting layers.

$$I(V,T) = Ae\frac{K\mu_0}{\sqrt{1+\left(\frac{\mu_0 V}{v_{sat}u_a}\right)^2}}\frac{\int_0^{\pi}\exp\left(-\frac{E_a(T)+\max_r \Phi(r,\theta,V)}{k_B T}\right)\sin(\theta)d\theta}{u_a}V$$

$$\Phi(r,\vartheta,V) = -e\frac{V}{u_a}r\cos(\theta) - \frac{\beta^2}{4e}\left(\frac{1}{r}+\frac{1}{s-r}\right)+\frac{\beta^2}{es}$$

$$E_a(T) = E_{a,0} - \frac{aT^2}{b+T}$$

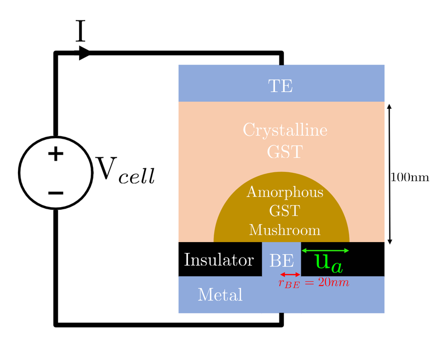


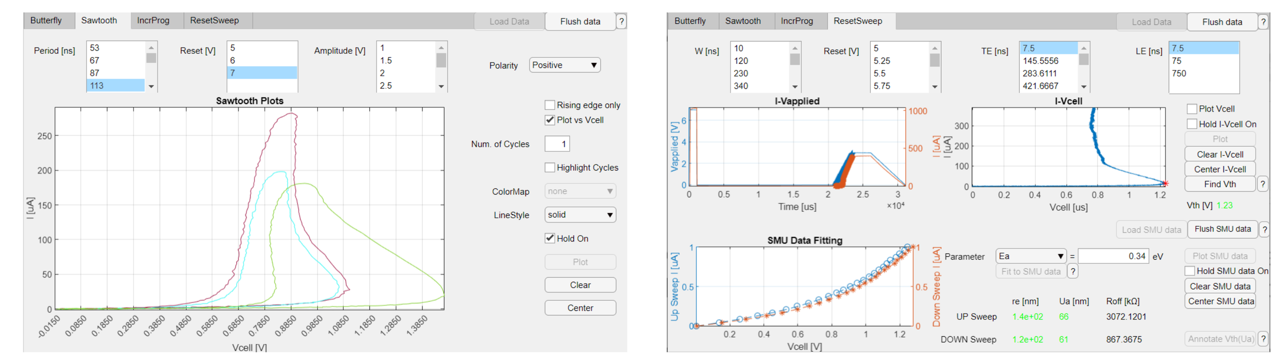
Submitted and published works

- Zoppo G., Marrone F. and Corinto F. (2019). "A Continuous-time Learning Rule for Memristor-based Recurrent Neural Networks". 26th IEEE International Conference on Electronics, Circuits and Systems, Genova (Accepted).
- Marrone F., Zoppo G., Corinto F. and Gilli M. (2019). "Second Order Memristor Models for Neuromorphic Computing". Midwest Symposium on Circuits and Systems, Dallas (USA).
- Zoppo G., Marrone F., Pittarello M., Farina M., Demarchi D., Secco J., Corinto F. and Ricci E. (2019). "Wound Viewer, a novel telemedicine method for chronic wound assessment through artificial intelligence, clinical trial and results". Journal of Wound Care. (Submitted)
- Zoppo G., Marrone F. and Corinto F. (2019). "Equilibrium Propagation for Memristor-based Recurrent Neural Networks". Emerging Technologies and Systems for Biologically plausible Implementations of Neural Functions. (Submitted)

Novel contributions

- Exhaustive dynamical characterization of nanoscale Phase Change Memory (PCM) devices carried out at IBM Research Zurich.

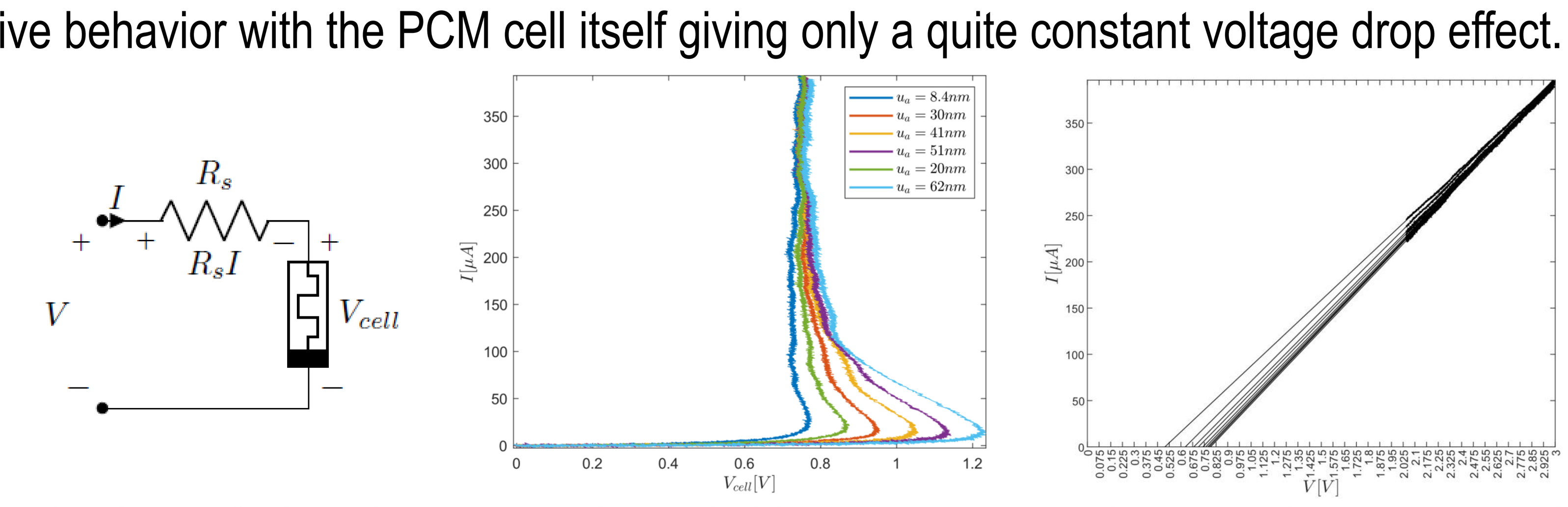




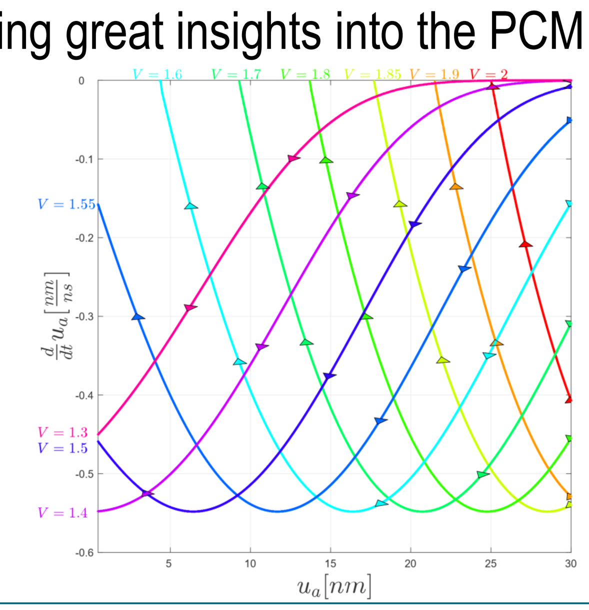
- Development of a simplified conduction model to qualitatively describe a first order PCM cell (LF approximation) and an enhanced second order model to capture the HF response.
- Study of the topological optimization of dynamical recurrent neural networks via global connections cutting using different learning rules.

Adopted methodologies

- All the interesting dynamics of PCM devices happens in the so-called above threshold regime. It is a state where the combined effect of trap-assisted electrical conduction in the amorphous phase with a relevant self heating due to Joule effect makes the conduction take place in the conduction band which is otherwise empty. The resulting conduction law is dominated mainly by the Schottky junction at the terminals and by the parastitic contact resistance.
- Manufactured PCM cells always include a series resistor either as a parastitic contact resistance or a selector device (mixed CMOS architectures) or a current compliance resistance. From the phenomenological point of view the 1-port made of an ideal PCM cell and a series resistor for high voltages (above approx. 1.5V) is heavily dominated by the resistive behavior with the PCM cell itself giving only a quite constant voltage drop effect.



- The reduction of the thermoelectric switching to an electric-only phenomenon (LF simplification) in combination with an approximated state-dependent conduction model opened the possibility of computing the PCM Dynamic Route Maps for the crystallization (SET operation) process giving great insights into the PCM first order dynamics.



Future work

- (Year 2) Compact modelling of different memristive systems and devices. Application of those developed compact models as key components to achieve programmability of simple oscillatory circuits via pulses.
- (Year 3) Application of the models developed during the previous years to simulation of large-scale neuromorphic systems for novel machine learning algorithms.

List of attended classes

- 01QORRV – Writing Scientific Papers in English (28/03, 3)
- 02IUGKG – Il metodo Monte Carlo (waiting for registration, 6)
- 01TFGKG – Oxide Electronics: from conventional to multifilamentary conduction (4/07, 4)
- 01TEVRV – Deep Learning (4/06, 6)
- 01SFURV – Programmazione scientifica avanzata in Matlab (15/05, 4)