

Spiking Neurons Demystified by a Dynamical Model of Mott Memristors

Léopold Van Brandt, Noémie Bidoul, Thomas Ratier, Jean-Charles Delvenne, Denis Flandre
ICTEAM Institute, UCLouvain, Louvain-la-Neuve, Belgium
t.leopold.vanbrandt@uclouvain.be

I. INTRODUCTION

Bio-inspired sensory neurons implemented with phase-change materials [1] like Vanadium dioxide (VO_2) [4] are able to encode the perceived information into spikes in the time domain. Since they fully operate in the analog world and do not require digital conversions and memories, exceptional energy efficiency is promised for these systems compared to ultra-low-voltage CMOS architectures [1].

At UCLouvain, VO_2 memristors exhibiting reversible Metal-Insulator Transitions (MIT) have been micro-fabricated [4]. The experimental static characteristics of one typical device are shown in Figure 1(a) in two different configurations: voltage- or current-controlled, respectively. A circuit made of a VO_2 memristor (Figure 1(b)) driven by an appropriate current source (e.g. a MOS transistor,) can leverage the MIT to produce continuous voltage spikes on the output capacitor shaped by a charge/discharge process

(Figure 1(c)). Such experimentally evidenced spiking or oscillating behaviour still awaits insightful mathematical model and quantitative predictions from the theory of nonlinear dynamical systems.

II. NONLINEAR DYNAMICAL MODEL OF MOTT MEMRISTORS

A insightful toy model of Mott memristors capable of reproducing the experimental static characteristics such as those reported in Figure 1(a) has been proposed in the pioneer modelling work of [2], more deeply exploited by [3]. The memristor is regarded as a nonlinear dynamical system with internal state u , describing the metallic phase fraction, and input v or i , respectively in voltage- and current-controlled mode. Consistently with Chua's formulation, the dynamics of the memristor is then shown to be governed by two coupled nonlinear equations (we here limit to the current-controlled mode):

$$v = f(u, i) = R(u)i \quad (1)$$

$$\frac{du}{dt} = g(u, i) \quad (2)$$

where $g(u, i)$ is a strongly nonlinear function absorbing all the electrothermal phenomena inherent to the device.

As we will present, the state model (1) and (2) can be harnessed to discuss the stability of the steady states of the memristor system. In particular, we will mathematically show that, in current-controlled mode, such device exhibits the so-called *negative differential resistance* behaviour (Figure 1(a)), all the steady states being stable, while this region is unstable and hence cannot be observed in voltage-controlled mode. We will then provide an oscillation criterion for the neuron of Figure 1(b), thought as a Van Der Pol relaxation oscillator. Future work also includes fine investigation and analysis of the *stochastic bursting* regime, offering more sparsity and promising lower energy consumption.

REFERENCES

- [1] R. Carboni and D. Ielmini in *Advanced Electronic Materials* 2019, 5(9), 1900198.
- [2] M.D. Pickett *et al.* in *Nanotechnology* 2012, 23(21), 215202.
- [3] S.A. Sarles *et al.* in *Applied Physics Letters* 2021, 118(22).
- [4] N. Bidoul *et al.* *Proc. of IEEE ESSDERC* 2023.

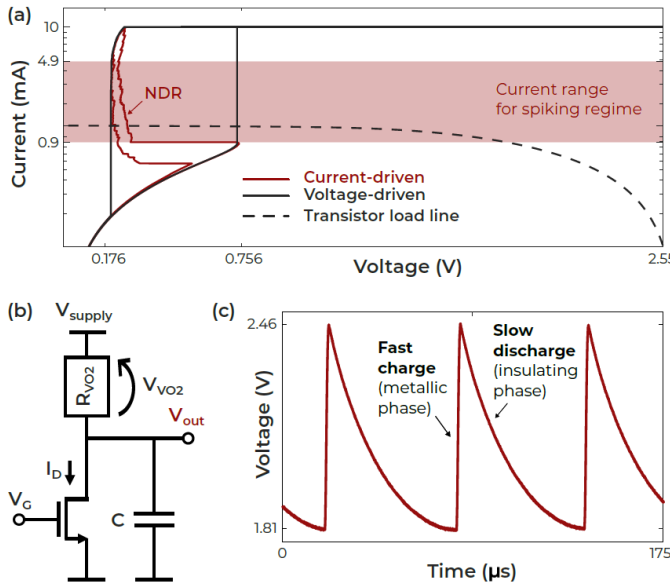


Figure 1. (a) Static characteristics of a micro-fabricated VO_2 memristor in both voltage- and current-controlled mode. (b) Schematic of the spiking sensory neuron. (c) Experimentally measured spikes when the neuron operates as a relaxation oscillator, suggesting that the studied system has a closed orbit that is a limit cycle. Reproduced from [4].