An artificial neuron founded on resistive switching of Mott insulators

*Coline Adda[a,b], Julien Tranchant[a], Pablo Stoliar[b], Benoit Corraze[a], Etienne Janod[a], Ralph Gay[b], Roger Llopis[b], Marie-Paule Besland[a], Luis E. Hueso[b,c] and Laurent Cario[a]**

[a] Institut des Matériaux Jean Rouxel (IMN), Université de Nantes, CNRS, 2 rue de la Houssinière, 44322 Nantes, France
[b] CIC nanoGUNE,*Tolosa Hiribidea 76,* 20018 San Sebastian, Spain
[c] IKERBASQUE, Basque Foundation for Science, 48011 Bilbao , Spain
E-mail: Laurent.Cario@cnrs-imn.fr

***Abstract*— Narrow-gap Mott insulators exhibit under electric field a resistive switching related to the formation of a conducting filamentary path made of metastable metallic domains. When this effect is non-volatile it can be used to build up a new type of Resistive Random Access Memory called Mott memory. But we show here that when the resistive switching remains volatile it is of great interest for neuromorphic applications different than artificial synapses implemented by the so-called Memristors. Specifically, we show that under electric field the dynamics of the creation and destruction of the metastable metallic domains implement the three basic functions Leaky Integrate and Fire of artificial neurons. The central result of the present work is therefore to demonstrate that a simple two terminal device made of Mott insulator can be considered as an analogue of an artificial Leaky Integrate and Fire neuron.**

***Index :* Mott Insulators – Resistive Switching – Neuromorphic applications - Leaky-Integrate-and-Fire – artificial neuron**

I. INTRODUCTION

Resistive switching driven by electric field was reported in numerous Mott Insulators [1,2,3]. This transition is due to the unique ability of the Mott material to locally commute thanks to an electronic avalanche breakdown between a stable insulator state and a metastable conductive state. [4,5] The conductive state is characterized by metallic filamentary structures bridging the electrodes. [6] These structures may be either stable over a long period of time (~ years) which means resistive switching is non-volatile or they may relax rapidly in time (~ ms) leading to a volatile effect. The non-volatile resistive switching was extensively studied owing to its interest to build up a Resistive Random Access Memory (ReRAM) [7] or the so-called memristor, that could be used to build up artificial synapses in neuromorphic applications. Conversely, dynamics of relaxation of the metastable conductive state leading to a volatile transition was so far very little studied.

We present here a comprehensive study of the dynamic of the volatile resistive transition. We show that a narrow gap Mott insulator behaves, under a train of electric field pulses, as a leaky integrator of the metallic phase. As a consequence a simple two terminal device made of a Mott insulator can be considered as an analogue of an artificial Leaky Integrate and Fire (LIF) neuron [8].

II. DYNAMICS OF THE VOLATILE RESISTIVE SWITCHING IN MOTT INSULATORS

The GaM_4Q_8 (M= V, Nb, Ta, Mo; Q=S, Se) compounds used for this study have been shown to be canonical Mott insulators sharing the same lacunar spinel structure but with narrow gaps depending on their chemistry and ranging from 0.1 to 0.4 eV [9,10]. Figure 1 displays a volatile resistive switching observed at 78 K on a $GaTa_4Se_8$ sample which is

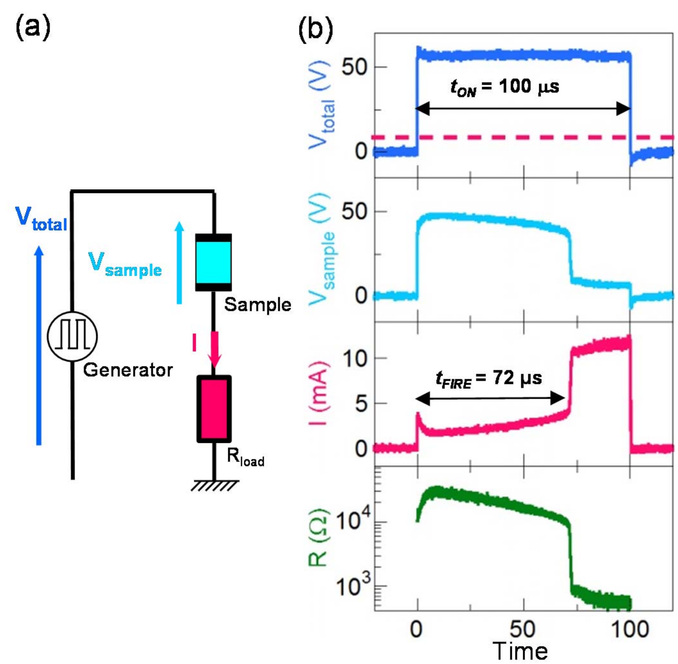

Figure 1 : Experimental setup (a) and typical volatile resistive switching obtained by applying at 78K a long single voltage pulse on this setup realized with a $GaTa_4Se_8$ crystal in series with a 5kΩ load resistor (b).

978-1-5090-3274-7/17/$31.00 ©2017 IEEE

similar to the one observed in other GaM_4Q_8 compounds [4,5,7].

When an electric field pulse exceeding a threshold field E_{th} of a few kV/cm is applied to these compounds, they undergo a sudden drastic decrease of their resistance related to the creation of a filamentary conducting path bridging the electrodes [2,3,5]. The electric pulse is applied to the $GaTa_4Se_8$ crystal connected in series with a load resistance as sketched Fig 1a. Fig. 1b shows the typical time evolution of the current and of the voltage on the sample during a voltage pulse exceeding the threshold voltage V_{th} (shown as a red dotted line). An abrupt drop of the voltage across the sample occurs after a (voltage dependent) delay time hereafter called t_{FIRE} and equal to 72 µs in this case. This lowering of the sample voltage is concomitant with an increase of the current intensity through the sample (called hereafter "firing" event). As a consequence, a resistive transition from a high to a low resistance state is observed (see bottom panel in Fig. 1(b)). An essential feature of this transition is that the sample returns to its original high resistance value after the end of the voltage pulse.

Fig. 2 shows the relaxation of the resistance after the end of the pulse. The relaxation involves in fact two successive processes. Initially, right after the end of the pulse, the resistance rises sharply because of the fast disappearance of the conducting path. Then, the resistance follows a long-time exponential relaxation law, associated to the progressive vanishing of the remaining non-percolating conductive domains. A satisfactory fit shown in Fig. 1(c) was obtained assuming the form:

$$R = \left(1 - e^{-t/\tau}\right) R_0 \qquad (1)$$

with R_0 denoting the resistance of the pristine sample, and τ the experimental relaxation time. From the fit we can extract τ = 628 ± 100 µs.

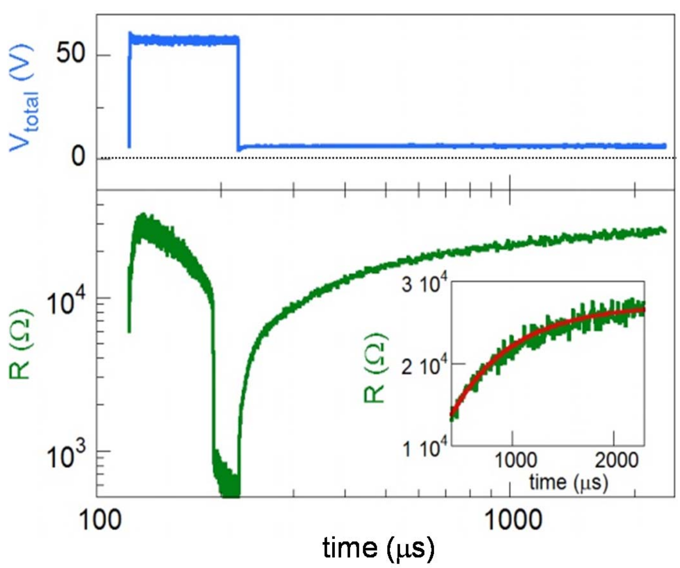

Figure 2 : Relaxation of the resistance after a pulse of 57 V inducing a resistive switching in a $GaTa_4Se_8$ crystal at 78 K. The inset shows the fit of the exponential relaxation obtained with Eq. (1).

III. Resistive Switching In Mott Insulators : Multi Pulse Experiments

Fig. 3 shows the response of the Mott insulator $GaTa_4Se_8$ to a train of short pulses. The duration t_{ON} and separation t_{OFF} were chosen such as $t_{ON} < t_{FIRE}$ and $t_{OFF} < \tau$. In Fig. 2(a) we used t_{ON} = 15 µs < t_{FIRE} = 72 µs (cf. Fig. 1(b)) and t_{OFF}=30µs < τ = 628 µs. In this case a resistive transition is observable during the sixth pulse (i.e. N_{FIRE} = 6). It clearly demonstrates a cumulative effect ("Integrate" first functionality). The incoming signal is indeed integrated by the system during the six pulses in order to trigger the firing event (second functionality). But we note that the applied pulse-time elapsed until the firing (~ 6 x 15=90 µs) is substantially longer than t_{FIRE} = 72 µs obtained with a single pulse. This deviation from perfect integration is of course simply due to the relaxation between pulses (i.e. during t_{OFF}). This relaxation brings a third functionality to Mott insulator, which is the *leaky* feature. As a consequence the Mott insulator appears as an imperfect integrator of the signal. Hence, at a given V_{PULSE}, raising t_{ON} or t_{OFF} should have opposite effects on the leaky integration and should lead respectively to a decrease or an increase of N_{FIRE}. This is confirmed in Figs. 3b-c where N_{FIRE} depends indeed on the values of t_{ON} and t_{OFF} used for the train of pulses.

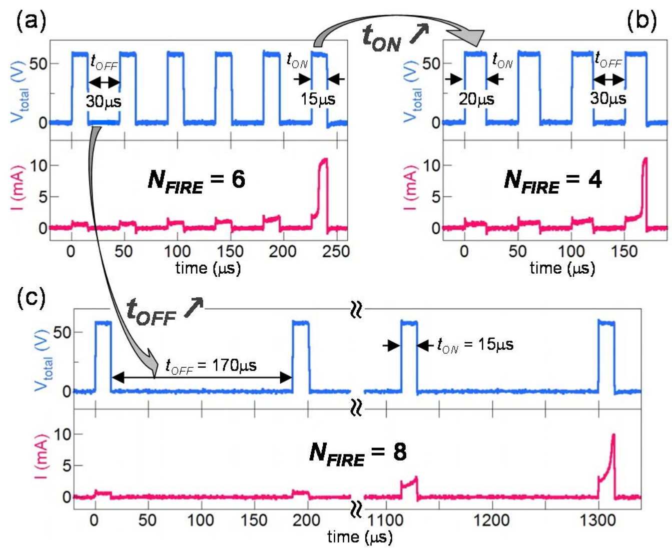

Figure 3 : Experimental resistive switching obtained by applying trains of short pulses of various t_{ON} and t_{OFF} on a $GaTa_4Se_8$ sample at 78 K. Using t_{ON} = 15 µs and t_{OFF} = 30 µs leads to N_{FIRE} =6 (a). Increasing t_{ON} to 20 µs leads to a decrease of N_{FIRE} to 4 (b). Increasing t_{OFF} to 170 µs leads to an increase of N_{FIRE} to 8 (c).

IV. Analogy With The Leaky Integrate and Fire Model For Artificial Neurons

The features just described above demonstrate that Mott Insulators implement the three functionalities "Leaky Integrate and Fire". It opens the way to the realization of an analogue to the most basic spiking artificial neuron based on the LIF model. This model aims to describe a basic function of the neuron behavior related to the accumulation of electric charge through the cellular membrane. The LIF model represents the membrane as a capacitor with a leaking resistor in parallel [11,12]. The increase in the membrane potential, resulting of synaptic processes (*i.e.* to spikes coming from other neurons) is generally modeled as current pulses that inject electrical charges into the capacitor. When the voltage reaches a given threshold the neuron fires an output electric spike.

Within the LIF model of an artificial neuron with one synaptic excitatory input-current, the time dependence of the voltage V across the membrane is

$$\frac{\partial}{\partial t}v=-v\frac{1}{RC}+\frac{w}{C}s(t), \tag{2}$$

with R the leaky resistance and C the capacitance of the membrane. $s(t)$ represents a train of spikes arriving to the neuron and w the synaptic weight, which we assume a constant since the LIF model does not include the behavior of synapses.

This equation can be used to predict the number of spikes (*i.e.* pulses) required to produce a firing event for a train of pulses with given parameters t_{ON} and t_{OFF} and applied voltage V/V_{th}. In this case, the expression for the required number of pulses N_{FIRE} can be obtained directly from Eq. 2.

$$N_{FIRE}=1-\frac{\ln\left[e^{t_{OFF}/\tau}-\frac{t_{FIRE}}{t_{ON}}\left(e^{t_{OFF}/\tau}-1\right)\right]}{t_{OFF}/\tau} \tag{3}$$

Interestingly Eq. 3 does not contain any free parameter as both t_{FIRE} and relaxation time τ can be obtained experimentally for a given fixed applied voltage. Equation 3 of N_{FIRE} provides therefore an easy way to compare the behavior of Mott Insulators with the LIF model used for artificial neurons. Fig. 4 show the parametric dependence of N_{FIRE} with t_{ON} and t_{OFF} measured experimentally on our Mott Insulator. For our experimental conditions, we determined τ = 628 µs and t_{FIRE} = 72 µs (cf Fig. 1). These values may be used in Eq. (3) to obtain the theoretical predictions of the LIF model. Figure 4 demonstrates a simultaneous agreement for the behavior of N_{FIRE} as a function of both t_{ON} and t_{OFF} with these predictions. These comparisons confirm therefore the equivalence between the behavior of Mott insulators and the behavior of artificial neurons based on the LIF model. This analogy was further confirmed by our modeling work that established that the

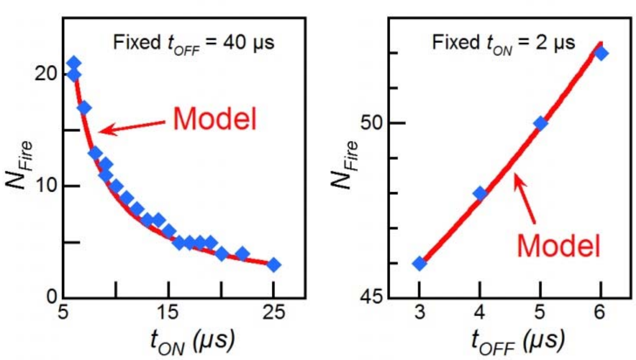

Figure 4 : Evolution of the number of pulse required to observe the firing of the Mott Neuron (N_{FIRE}) versus the pulse duration t_{ON} (a) or the separation time between the pulses (t_{OFF}) (b). The red curves correspond to the prediction obtained thanks to equation (3). They reproduces nicely the experimental dependences observed for N_{FIRE} versus t_{ON} or t_{OFF}.

transfer functions of the Mott insulator and of the LIF model are comparable. The key feature of this analogy is that the role of charge accumulation in the LIF model is played in the Mott system by the accumulation of correlated metallic sites [8].

V. Towards downscalable planar Devices

Our work provides a remarkable validation that a Mott insulator is an analogue of an artificial LIF neuron. However so far all measurements were performed on slices of crystals of thicknesses of the order of 40-80 µm that are mounted in capacitance geometry. In order to go towards devices easier to downscale, the realization of planar devices was engaged. A thin slice of GaV_4S_8 crystal of about ≈15µm was therefore cleaved by hand and subsequently pasted on a glass substrate. The crystal was then embedded in a PMMA resin with only the central rectangular part left free for the deposition of the electrodes. The TiN electrodes were then deposited by Electron Beam Lithography using PMMA resist (950K). Figure 5 shows a picture of the device where the 40µm wide TiN electrodes are separated by a gap of 10 µm.

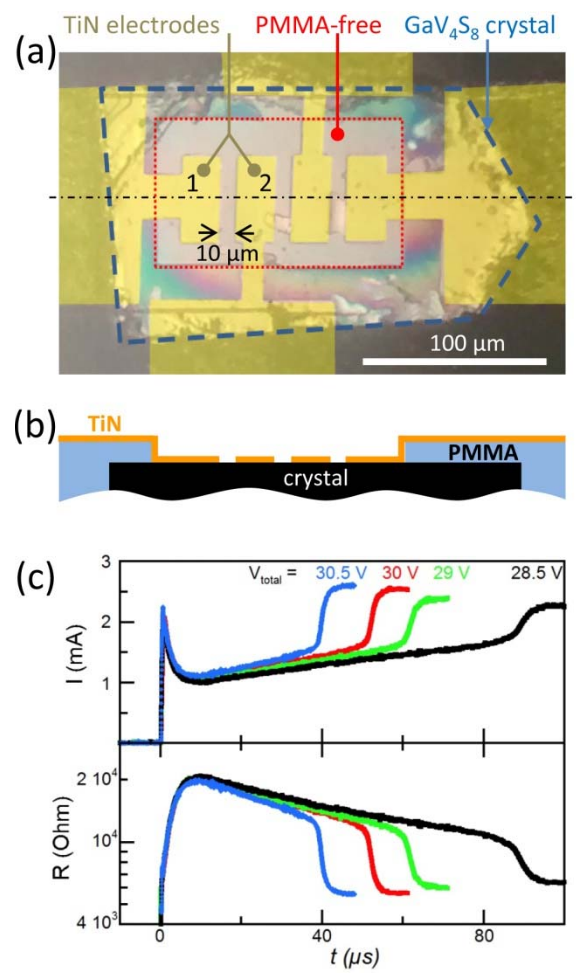

Figure 5 : (a) top view of the planar device realized with the Mott insulator GaV_4S_8. (b) Device schematic cross-sectional view along the dash-dotted line drawn in (a). (c) Resistive switching with different t_{FIRE} observed on this planar device with various pulse voltages applied on the device in series with a 5 kΩ load resistor. The signal measured during the first 10 µs is altered by an RC effect due to residual capacitances within the circuit.

Figure 5c shows the results of the application of single pulses of increasing voltage between electrodes 1 and 2 of this planar device. These experiments demonstrate the possibility to induce volatile resistive switchings with variable t_{FIRE} depending on the voltage applied on the setup. This result strongly suggests that the Leaky Integrate and Fire behavior could be achieved on planar devices with much smaller dimensions. This is therefore a first step towards the realization of artificial Neuron devices made with Mott insulators thin films.

VI. Conclusion

We have demonstrated that resistive switching in Mott insulator compounds fulfills all three basic functions of Leaky, Integrate and Fire neurons. It opens the way to the realization of artificial neuron made with Mott insulators. First results obtained on a simple two-terminal planar device show that the resistive switching is observed for inter-electrodes distances as small as 10 µm. This is a first step towards the realization of dense spiking neuromorphic networks made with Mott Insulators.

Acknowledgment

The authors thank the “Région Pays de la Loire” for funding the present work in the framework of the “pari scientifique Neuro-Mott”. P.S. acknowledges the support of the Spanish Ministry of Economy through the Ramón y Cajal (RYC-2012-01031).

References

[1] E. Janod, J. Tranchant, B. Corraze, M. Querré, P. Stoliar, M. Rozenberg, T. Cren, D. Roditchev, V.T. Phuoc, M.-P. Besland, and L. Cario, « Resistive Switching in Mott Insulators and Correlated Systems », *Adv. Funct. Mater.*, vol. 25, nº 40, p. 6287-6305, oct. 2015.

[2] F. Pan, S. Gao, C. Chen, C. Song, et F. Zeng, « Recent progress in resistive random access memories: Materials, switching mechanisms, and performance », *Materials Science and Engineering: R: Reports*, vol. 83, p. 1-59, sept. 2014.

[3] D. S. Jeong *et al.*, « Emerging memories: resistive switching mechanisms and current status », *Reports on Progress in Physics*, vol. 75, nº 7, p. 076502, juill. 2012.

[4] V. Guiot, L. Cario, E. Janod, B. Corraze, V. Ta Phuoc, M. Rozenberg, P. Stoliar, T. Cren, and D. Roditchev, « Avalanche breakdown in $GaTa_4Se_{8-x}Te_x$ narrow-gap Mott insulators », *Nat Commun*, vol. 4, p. 1722, avr. 2013.

[5] P. Stoliar, L. Cario, E. Janod, B. Corraze, C. Guillot-Deudon *et al.*, Universal electric-field-driven resistive transition in narrow-gap Mott insulators. *Adv. Mater.* **25**, 3222-3226 (2013).

[6] C. Vaju, L. Cario, B. Corraze, E. Janod, V. Dubost, T. Cren, D. Roditchev, D. Braithwaite, and O. Chauvet, « Electric-Pulse-driven Electronic Phase Separation, Insulator–Metal Transition, and Possible Superconductivity in a Mott Insulator », *Advanced Materials*, vol. 20, nº 14, p. 2760–2765, 2008.

[7] (a) L. Cario, C. Vaju, B. Corraze, V. Guiot, and E. Janod, « Electric-Field-Induced Resistive Switching in a Family of Mott Insulators: Towards a New Class of RRAM Memories », *Advanced Materials*, vol. 22, nº 45, p. 5193–5197, 2010; (b) J. Tranchant, E. Janod, L. Cario, B. Corraze, E. Souchier, J.-L. Leclercq, P. Cremillieu, P. Moreau and M.-P. Besland, « Electrical characterizations on RRAM devices based on GaV_4S_8 thin layers », *Thin Solid Films,* vol. 533, p. 61, 2013; (c) J. Tranchant, E. Janod, B. Corraze, P. Stoliar, M. Rozenberg, M.-P. Besland and L Cario, « Control of resistive switching in AM_4Q_8 narrow gap Mott insulators: A first step towards neuromorphic applications » Phys. Status Solidi A, vol. 212, n°2, p. 239, 2015

[8] P. Stoliar, J. Tranchant, B. Corraze, E. Janod, M.-P. Besland F. Tesler, M. Rozenberg, and L. Cario., A Leaky-Integrate-and-Fire neuron analogue realized with a Mott insulator *Adv. Funct. Mater.*, DOI: 10.1002/adfm.201604740, janv. 2017.

[9] V. Ta Phuoc, C. Vaju, B. Corraze, R. Sopracase, A. Perucchi, C. Marini, P. Postorino, M. Chligui, S. Lupi, E. Janod, and L. Cario, « Optical Conductivity Measurements of $GaTa_4Se_8$ Under High Pressure: Evidence of a Bandwidth-Controlled Insulator-to-Metal Mott Transition », *Phys. Rev. Lett.*, vol. 110, nº 3, p. 037401, janv. 2013.

[10] A. Camjayi, C. Acha, R. Weht, M.G. Rodríguez, B. Corraze, E. Janod, L. Cario, and M.J. Rozenberg, « First-Order Insulator-to-Metal Mott Transition in the Paramagnetic 3D System $GaTa_4Se_8$ », *Physical Review Letters*, vol. 113, nº 8, p. 086404, août 2014.

[11] L. Lapicque, « Recherches quantitatives sur l’excitation électrique des nerfs traitée comme une polarisation », *J Physiol Pathol Générale*, vol. 9, p. 567–578, 1907.

[12] N. Brunel et M. C. W. Rossum, « Quantitative investigations of electrical nerve excitation treated as polarization: Louis Lapicque 1907 · Translated by », *Biological Cybernetics*, vol. 97, nº 5-6, p. 341-349, nov. 2007.