Neuromorphic electronic behavior in transition metal oxide systems
From resistive switching to artificial synapses and neurons

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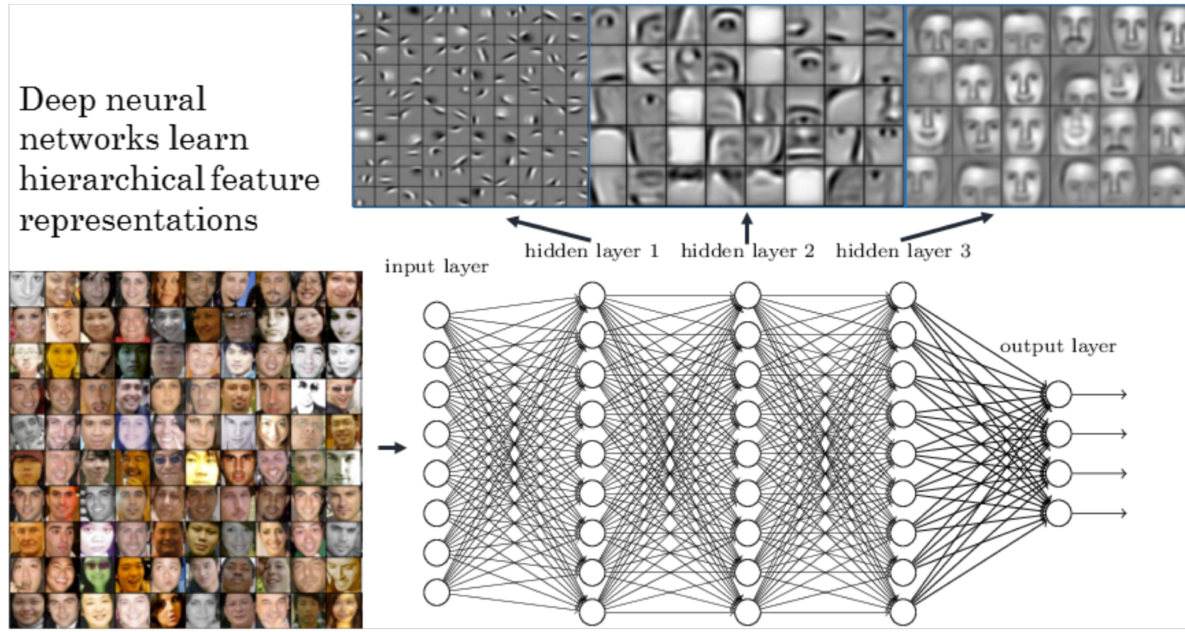
Neuromorphic circuits and computation is a very hot topic

Bio-chips (CMOS hardware)

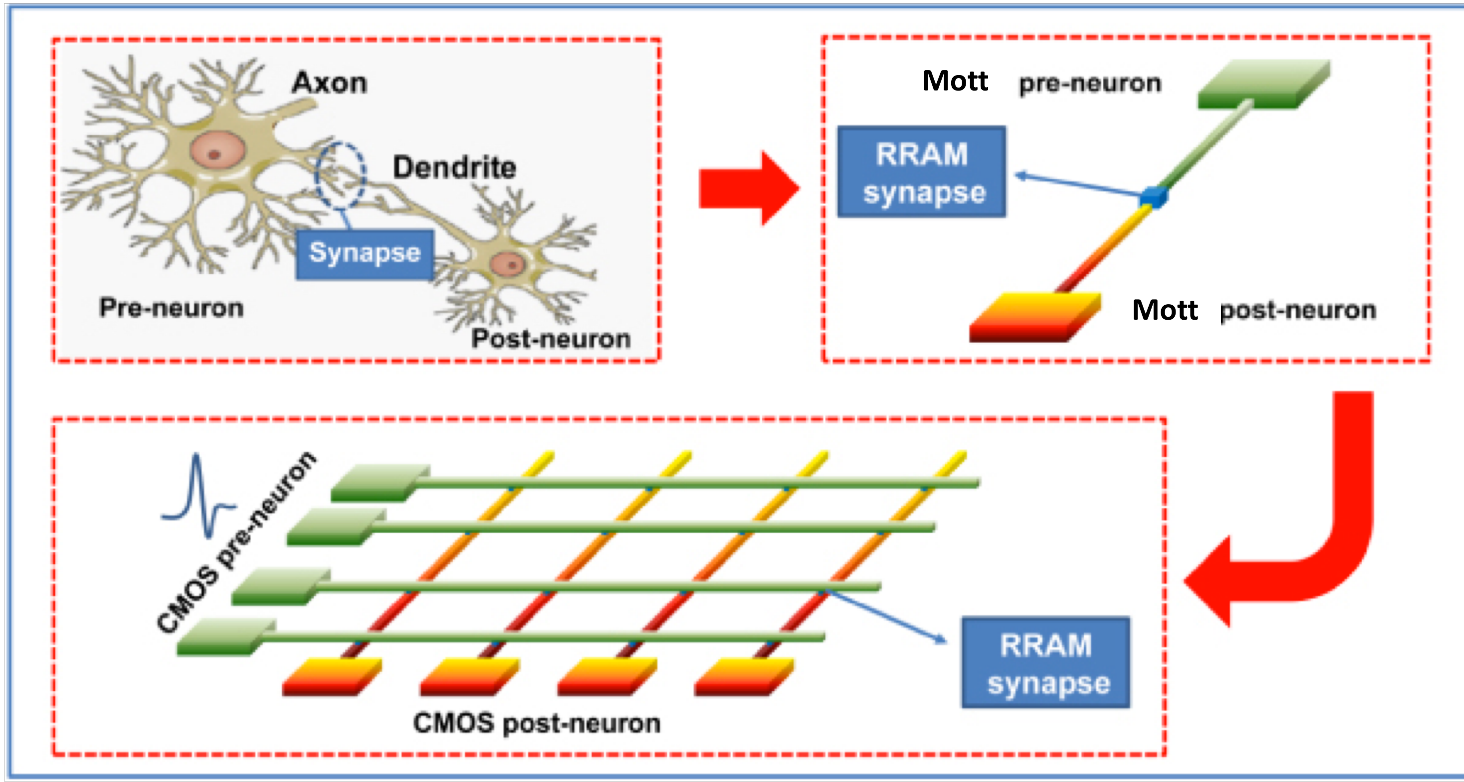
Deep Neural Networks (software)



- DARPA's Synapse Program
- EU Human Brain Project
- Facebook
- Google (DeepMind, AlphaGo)

human brain:
10^{11} neurons
10^{15} synapses

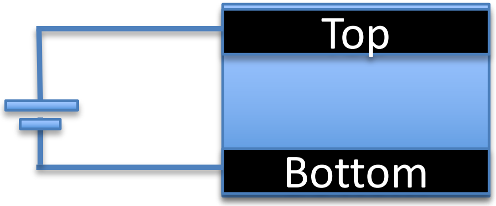
Novel electronic devices for neuromorphic systems



Park et al Nanotechnology '13

Neurons and **Synapses**:
Based on **Resistive Switching**
Great oportunity for **oxyde electronics** !

What is Resistive Switching (in TMOs) ?



It is the sudden change in *resistance* due to a strong electric stress (*V* or *I*) on a simple two-terminal device (capacitor-like)

1) The change may be permanent, ie ***non-volatile***, and ***reversible***

(Obvious) Application as electronic memory device: **RRAM** (aka: ReRAM, OxRAM, memristors)

2) The change may be non-permanent ie ***volatile***

Less obvious applications are practical realizations of:

artificial synapses (1) and ***artificial neurons*** (2)
New functionalities of TMO materials

1 - **Non-volatile** Resistive Switching

Basic concepts
Physical mechanism

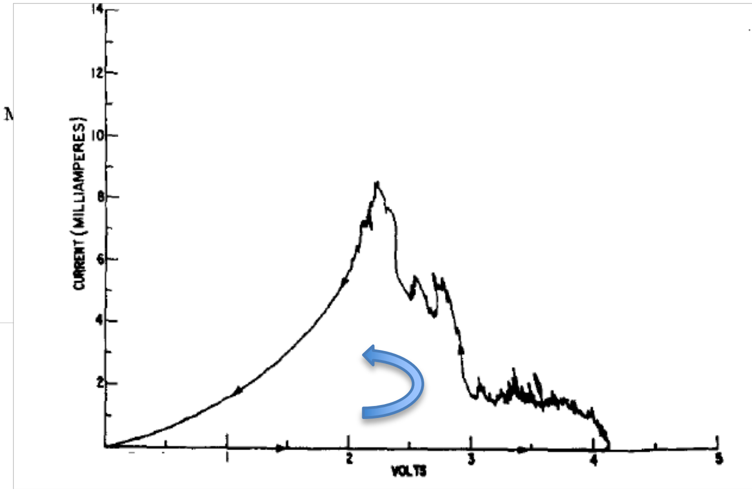
Research in “memristors” is not new

Were not « discovered » in 2008 in HP….it begun more than 60 years ago...

JOURNAL OF APPLIED PHYSICS VOLUME 33, NUMBER 9 SEPTEM

Low-Frequency Negative Resistance in Thin Anodic Oxide Films

T. W. Hickmott
General Electric Research Laboratory, Schenectady, New York
(Received February 5, 1962)



New Conduction and Reversible Memory Phenomena in Thin Insulating Films

J. G. Simmons; R. R. Verderber

Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 301, No. 1464 (Oct. 3, 1967), 77-102.

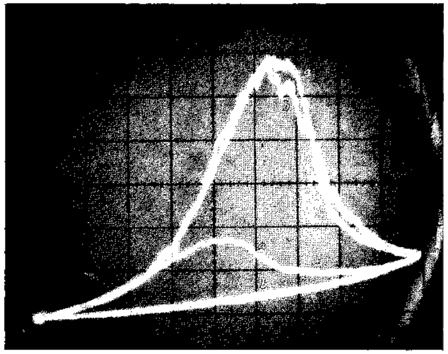


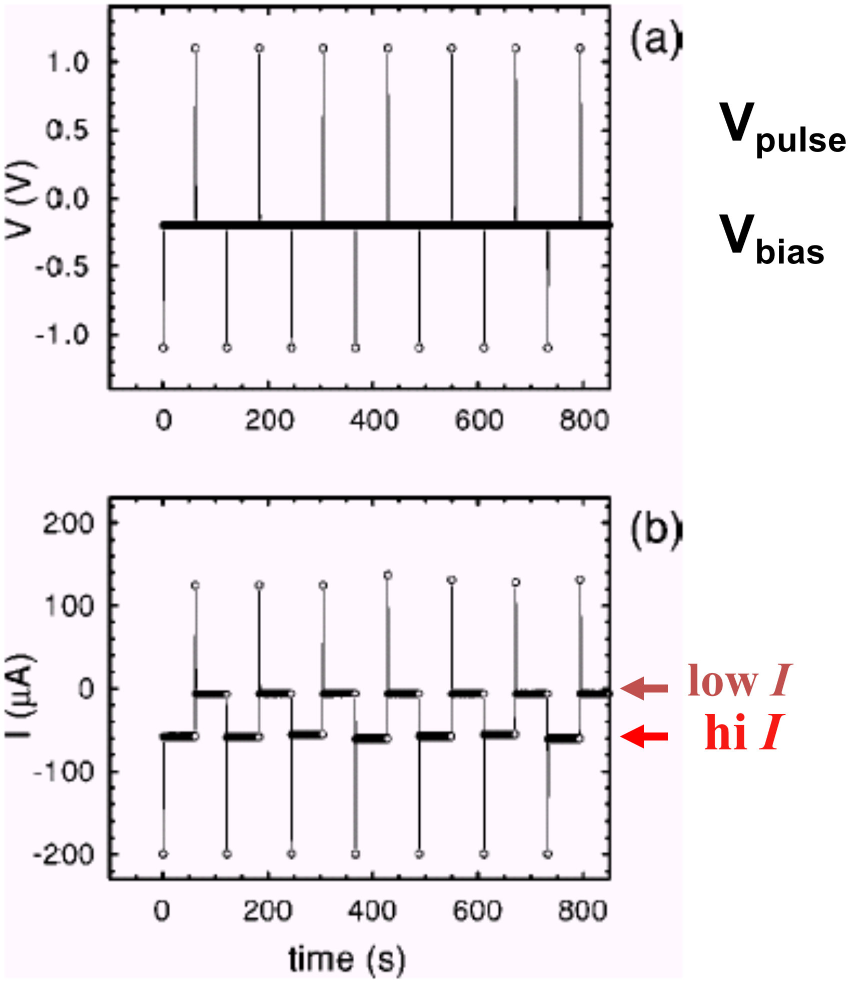
Figure 10. Photograph of X–Y oscilloscope V–I trace for a complete voltage cycle between en 0 and 9 V at (a) 300 °K and (b) 77 °K. Scales are x = 1 V/div, y = 10 mA/div.

Volume 21, Number 20 PHYSICAL REVIEW LETTERS 11 November 1968

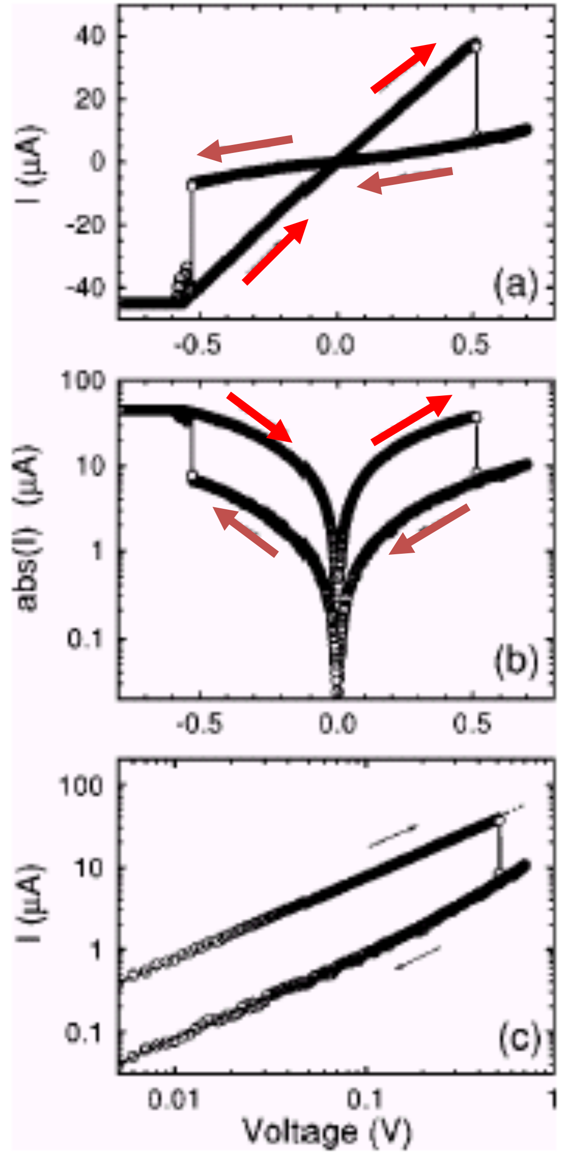
REVERSIBLE ELECTRICAL SWITCHING PHENOMENA IN DISORDERED STRUCTURES

Stanford R. Ovshinsky
Energy Conversion Devices, Inc., Troy, Michigan
(Received 23 August 1968)

switching

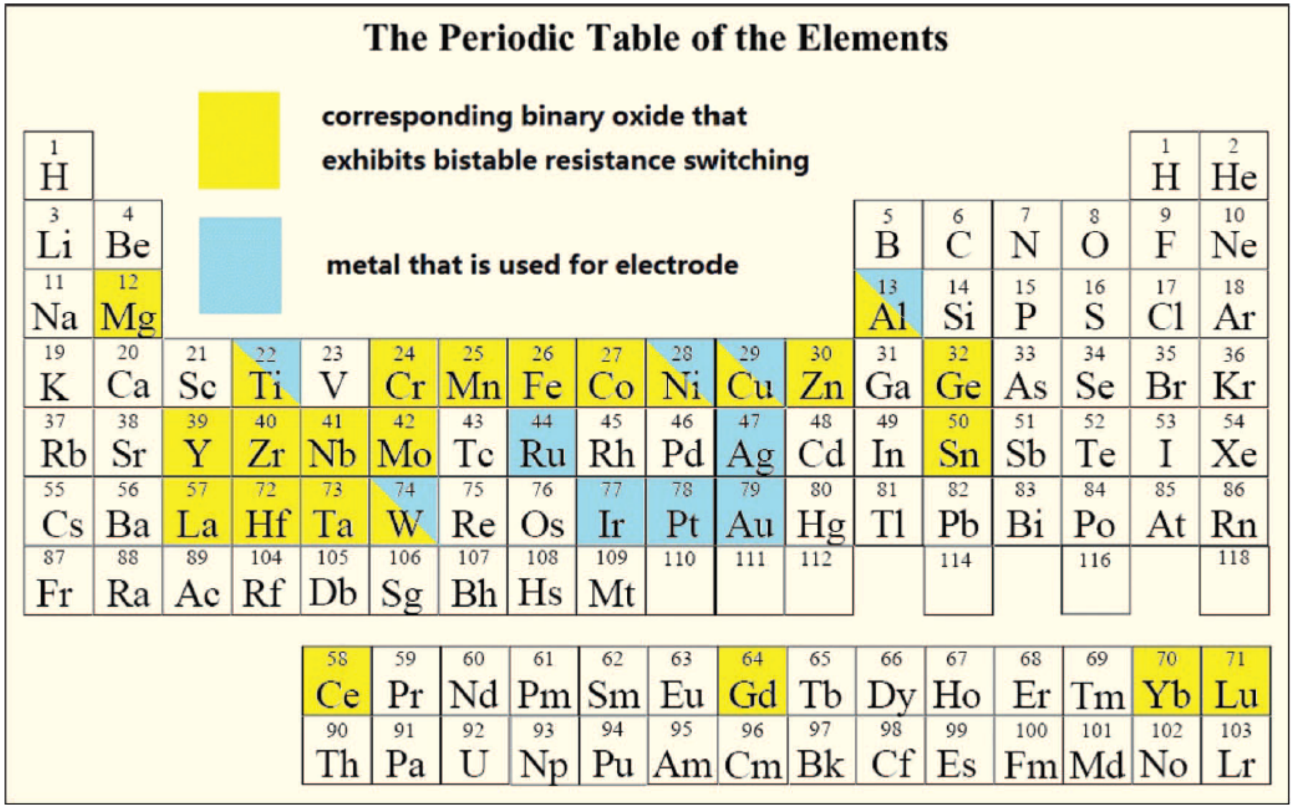


hysteresis (*I-V*)



Cr-doped SrZrO

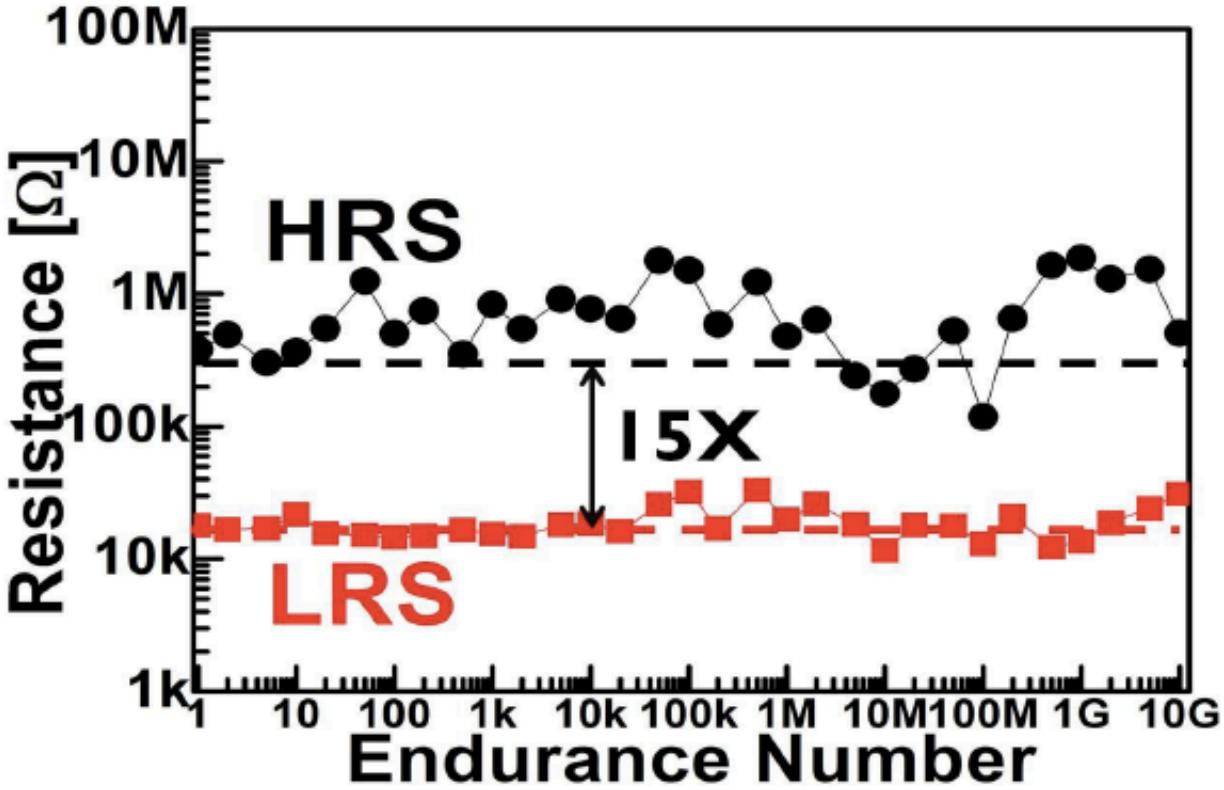
IBM group APL'00



Astonishingly universal!

Wong et al IEEE 2012

Fast commutation speed   nsec

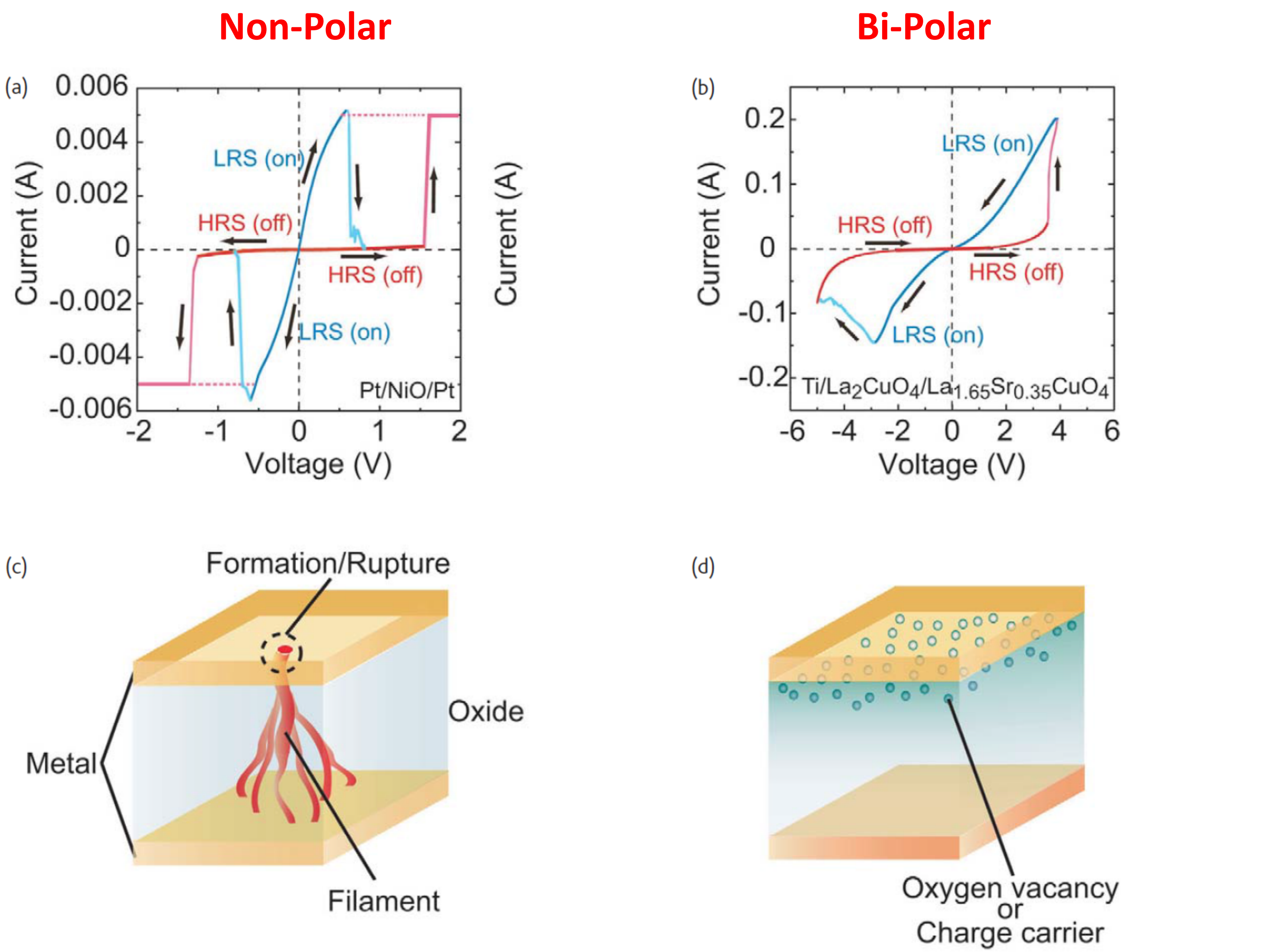


By balancing the SET pulse WL=1V, BL=1.8V, 5ns and RESET pulse WL =3V, SL=1.8V, 10ns, 10^{10} pulse endurance could be achieved on 40nm Hf/HfO_2 1T1R devices.

HfO2

YY Chen et al 2012

There are two main types of Non-volatile Resistive Switching:



Mechanism is due to semipermanent structural transformations

Realize « synapses »

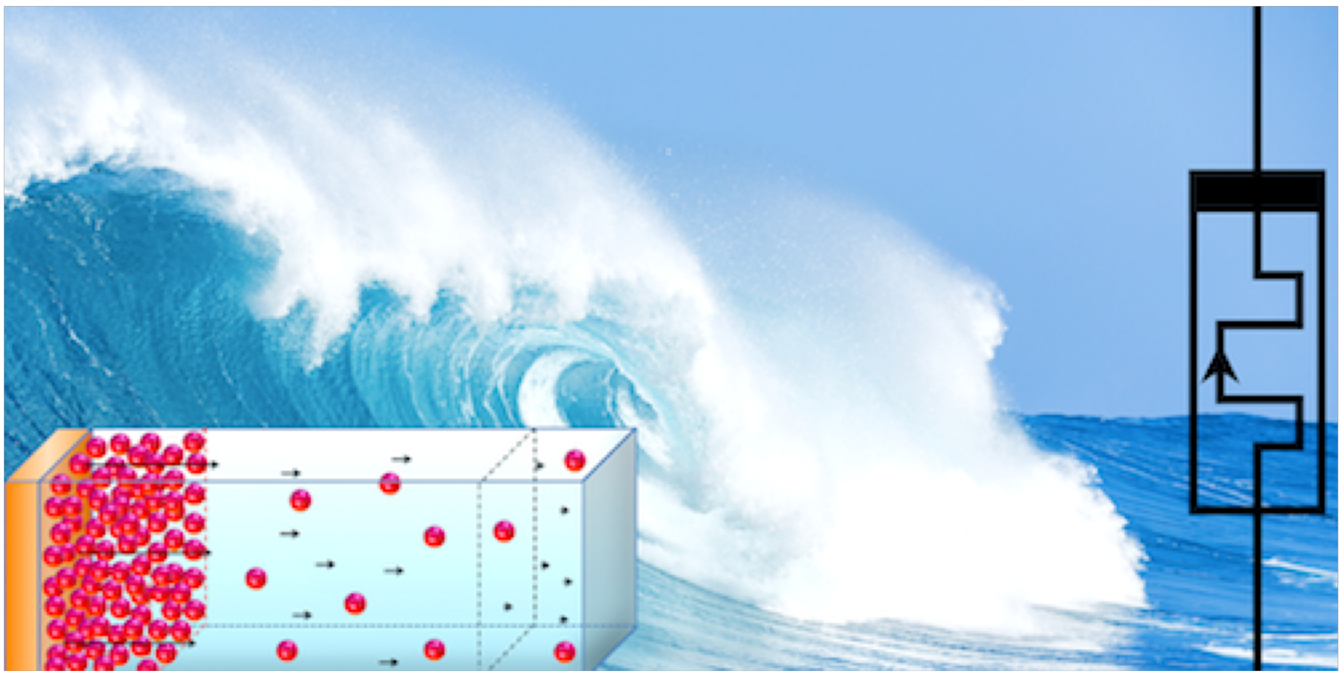
A Sawa, Mat Today (2008)

Some new theoretical insight

Shock Waves and Commutation Speed of Memristors

Shao, Tesler, Dobrosavljevic, MR; Phys. Rev. X 6, 011028 (2016)

Physics Synopsis: Waves That Shock Resistance

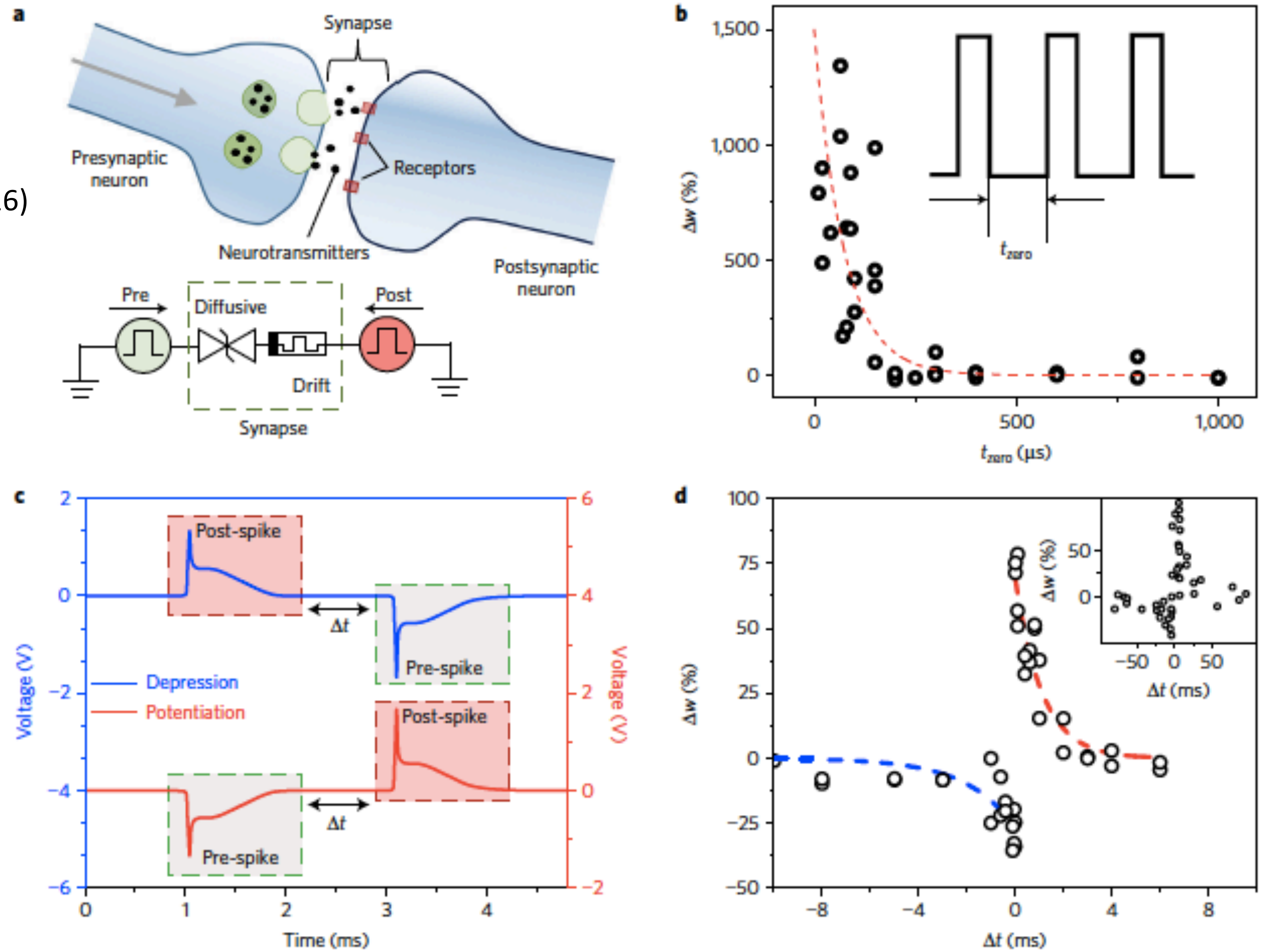


A shockwave of oxygen vcancies

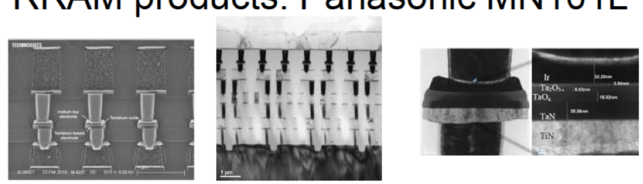
STDP

TaOx

Z. Wang Nat Mat (2016)



RRAM products: Panasonic MN101L

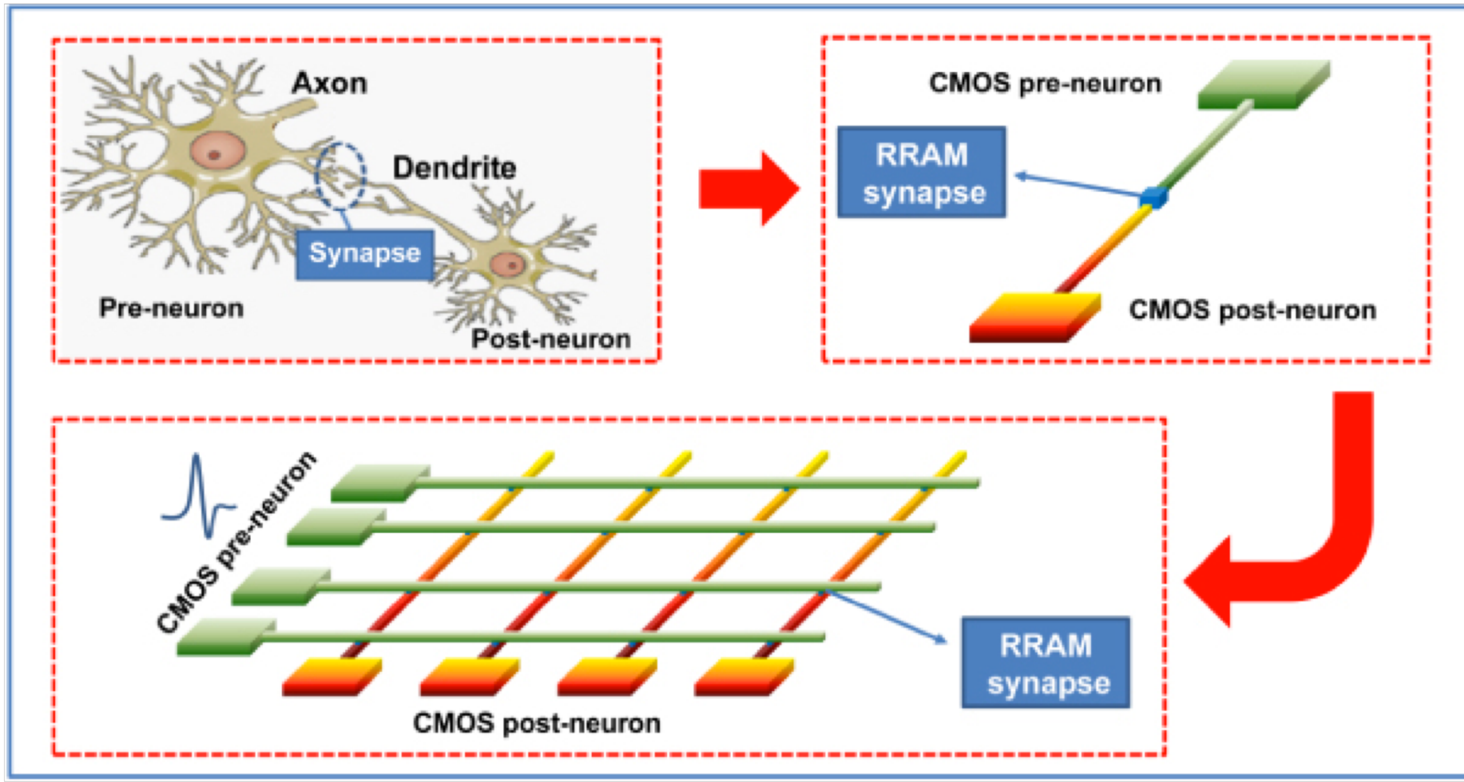


MN101L is an 8-bit microcontroller with 64kB memory

Operating T range: -40° C to +85° C

62kB of memory rated for 1e3 program cycles

2kB of memory designated for data area and rated separately for 1e5 program cycles.


Axon
Dendrite
Synapse
Pre-neuron
Post-neuron
CMOS pre-neuron
RRAM synapse
CMOS post-neuron
CMOS pre-neuron
RRAM synapse
CMOS post-neuron

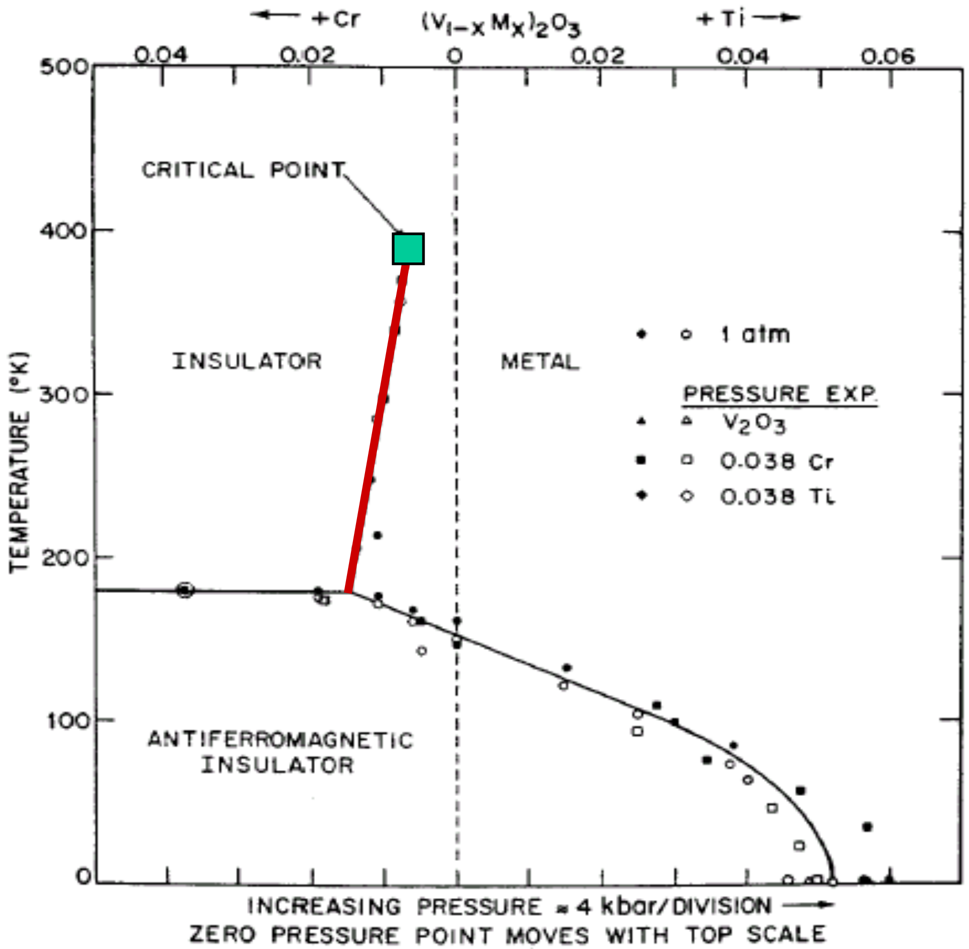
Strong correlation effects?

2 – Volatile Resistive Switching
in 3-dimensional **Mott** insulators

May realize neurons

The classic example: Mott transition in V_2O_3

T



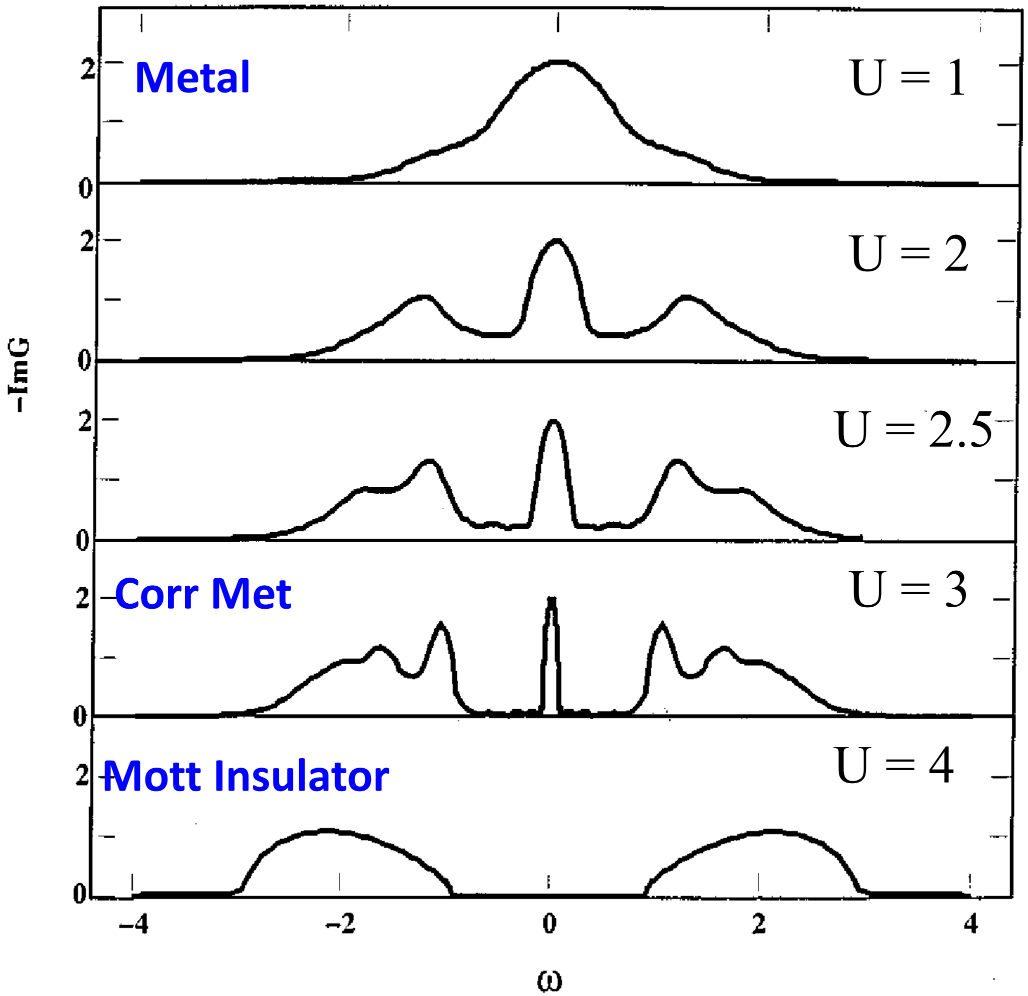
pressure or chemical substitution

McWhan et al PRB ’71 ‘73

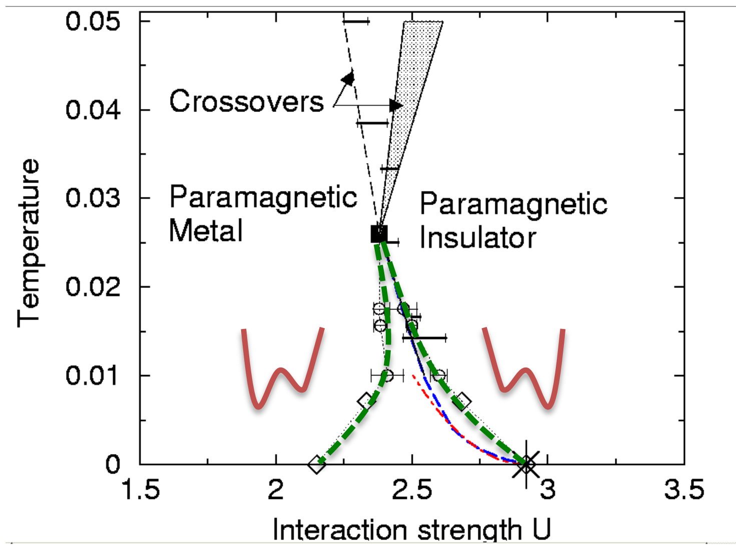
DMFT of the Mott – Hubbard transition

Georges, Kotliar, Krauth & MR, RMP '96

Georges, Kotliar PRB '92
Zhang, MR, Kotliar PRL '92



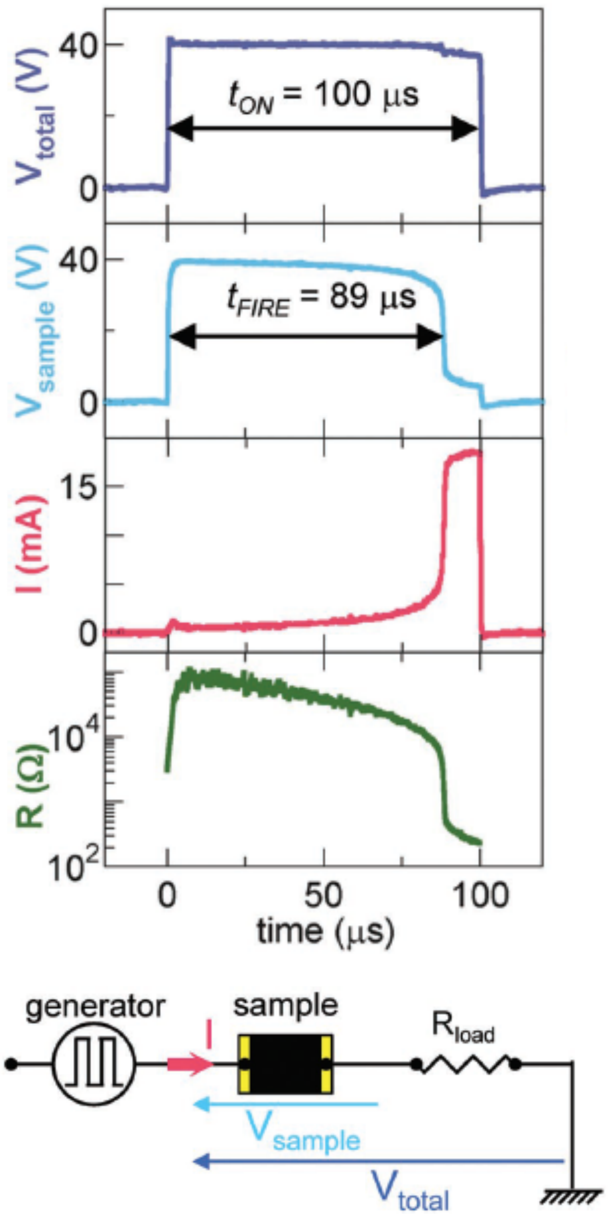
Coexistance region: 2 solutions



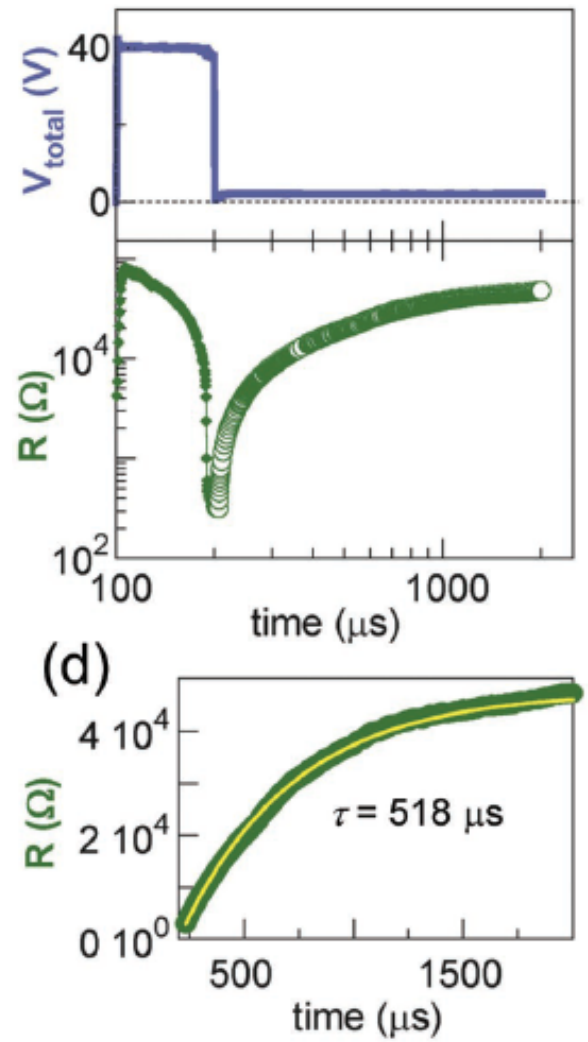
Mott physics + electronics
« Mottronics »

Applying strong E-fields to
Mott systems

Volatile RS in 3D Mott insulators



Stoliar et al Adv Func Mat 2016

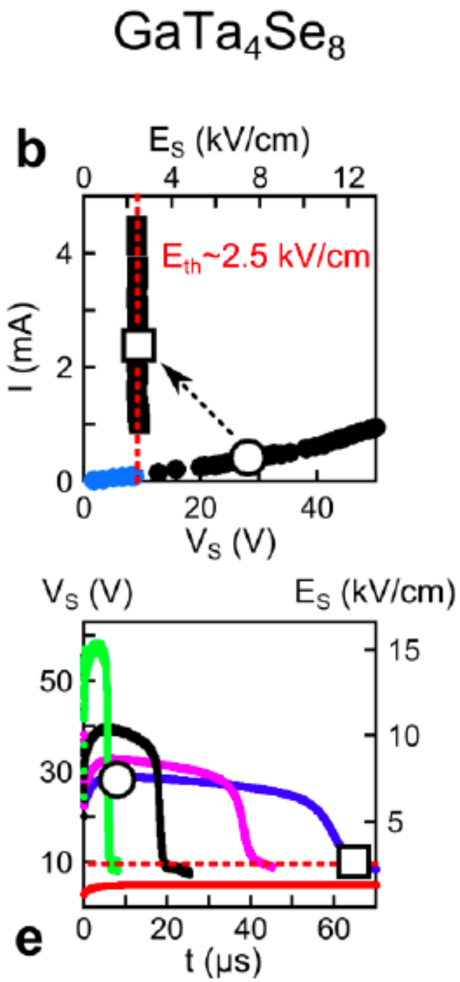


Perfectly reproducible!!

GaTa4Se8 single x-tal @ 74K

A. Camjayi, et al PRL 2014

Volatile RS in 3D Mott insulators

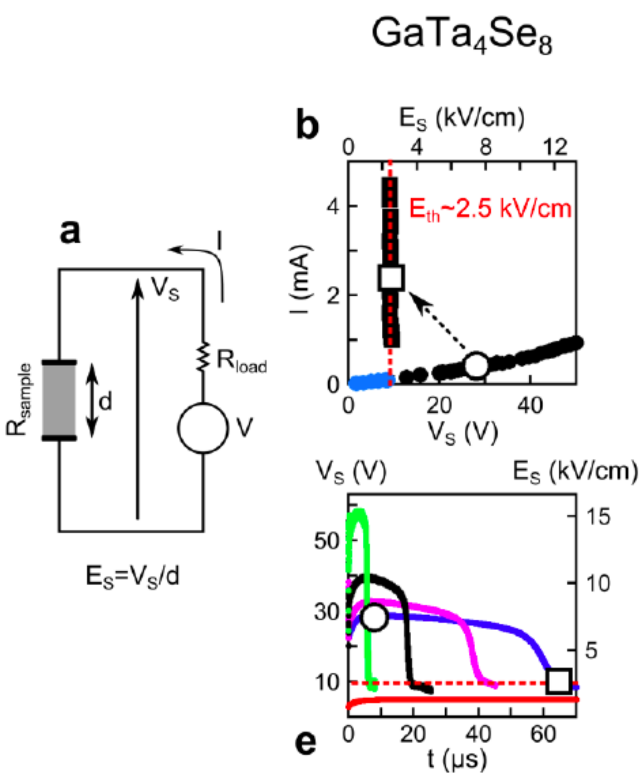


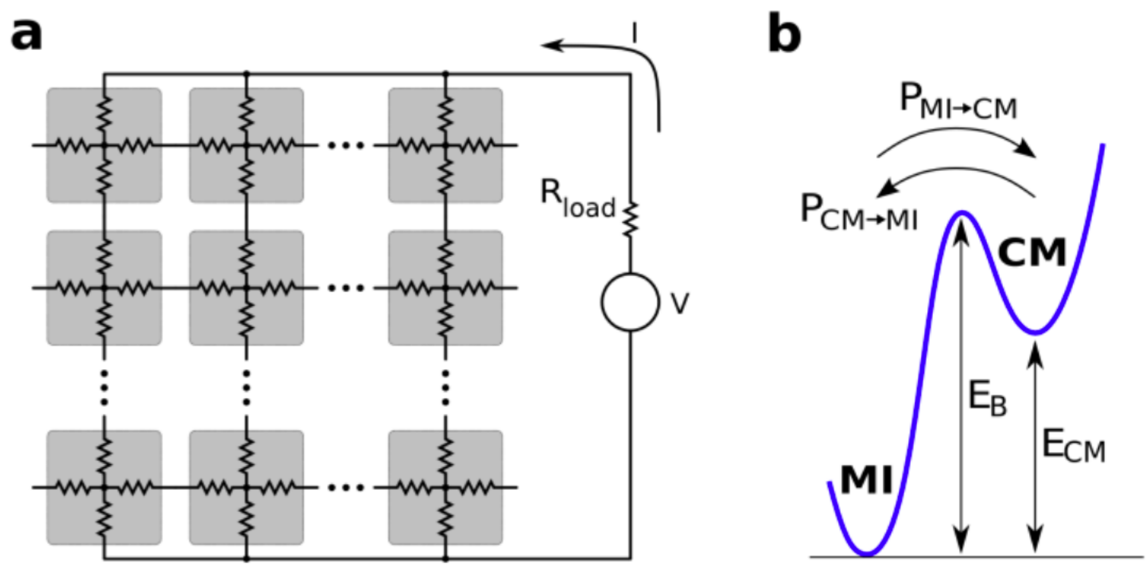
P. Stoliar et al Adv. Mater. (2013)

Model of the Mott resistive transition

(with inspiration from DMFT)

P. Stoliar et al Adv. Mater. (2013)





Two states: MI – Mott insulator

CM – Correlated metal

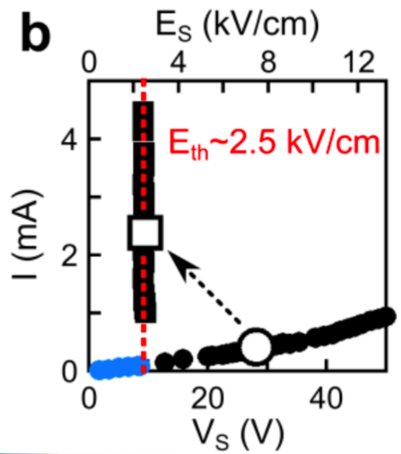
$R_{MI} >> R_{CM}$

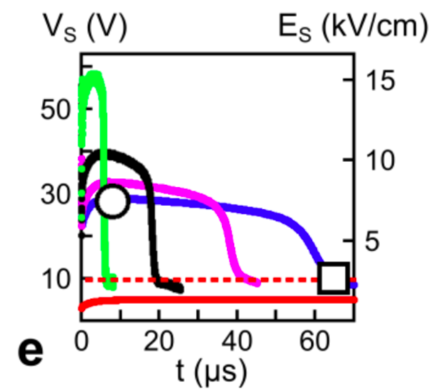
$P_{\text{MI->CM}}$ and $P_{\text{CM->MI}}$ are transition probabilities

$$P_{\text{MI}\to\text{CM}} = \nu e^{-(E_B - q\Delta V)/kT} \qquad P_{\text{CM}\to\text{MI}} = \nu e^{-(E_B - E_{CM})/kT}$$

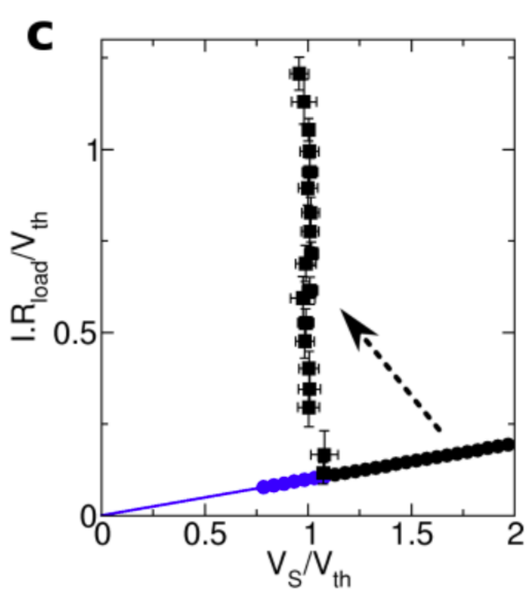
Model results: Threshold Mott resistive transition

Experiment

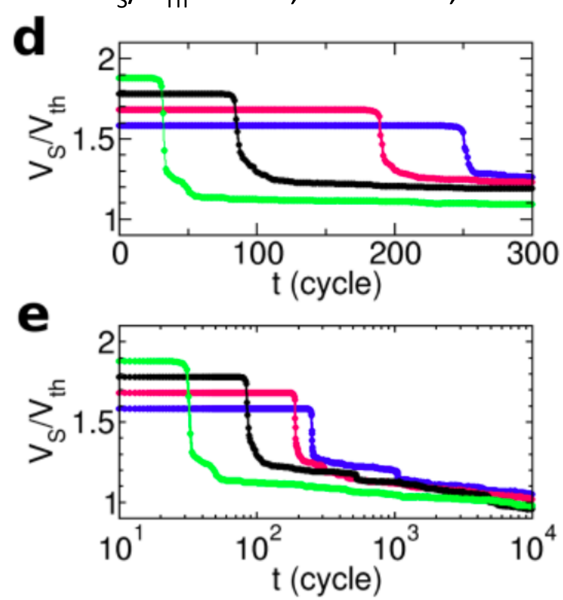




Theory



V_S/V_{Th} = 1.74, 1.84 1.95, 2.06

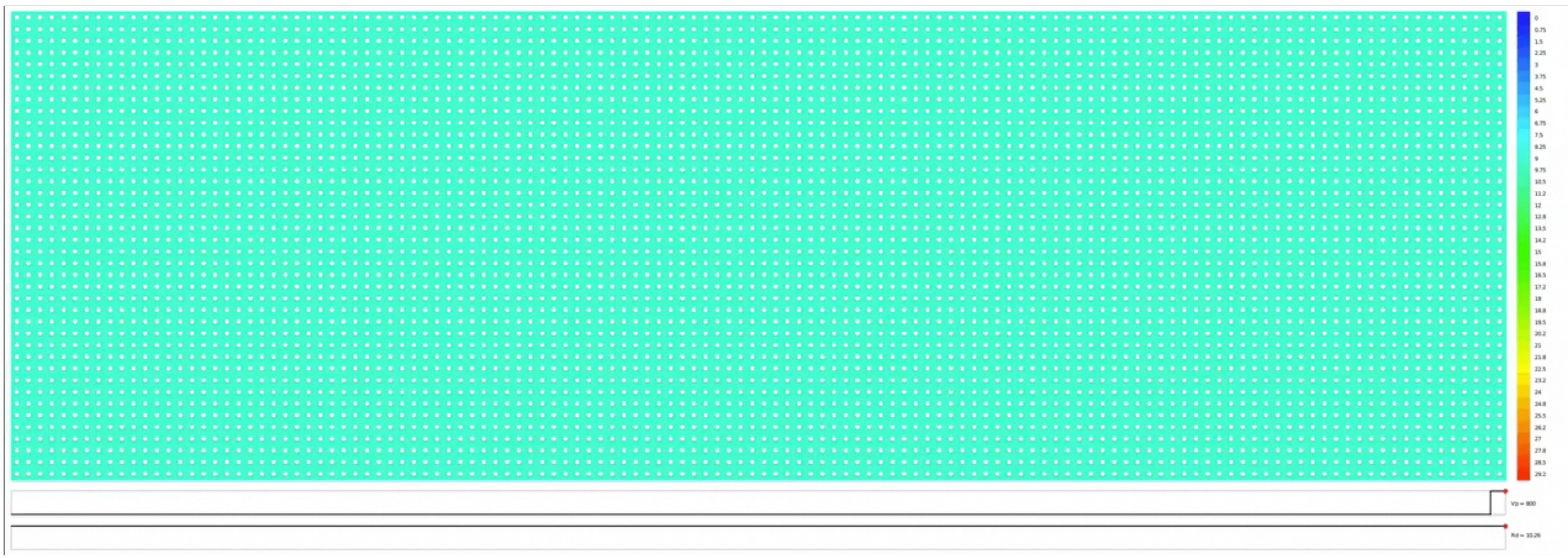


How the transition evolves in time?

V(T)

Top electrode

Low E



Hi E

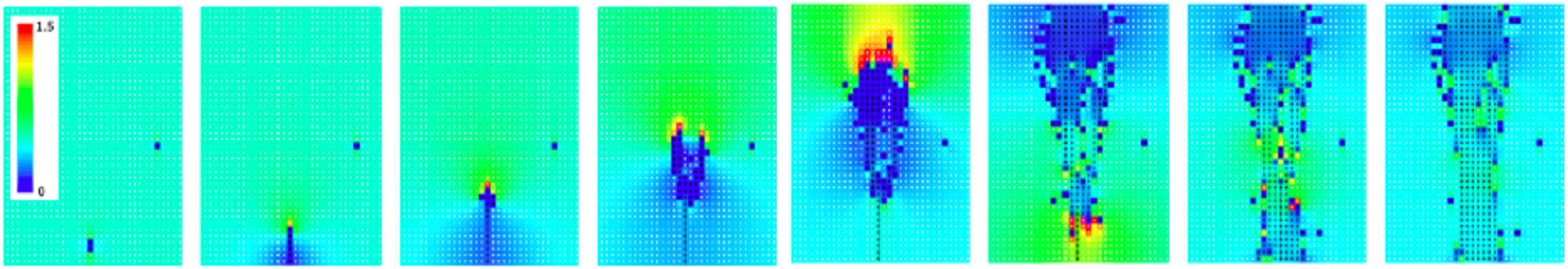
Bottom electrode

GND

Each pixel is a cell of the resistor network model

Color intensity indicates the local ΔV drops (ie local E)

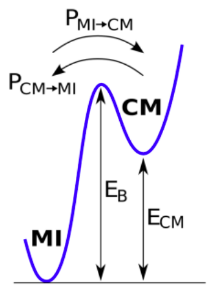
How the transition evolves in time?
(snapshots)



time →

Model validation

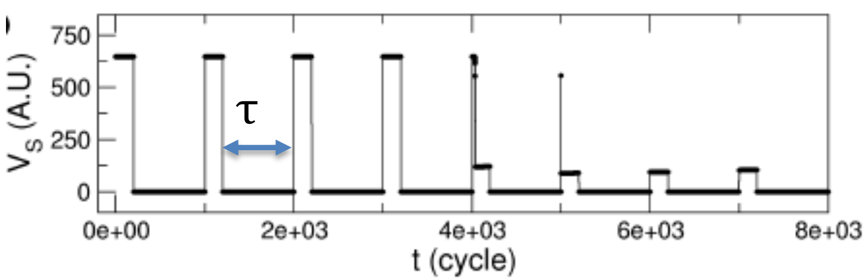
P. Stoliar,MR, et al., Adv. Mat. (2013)

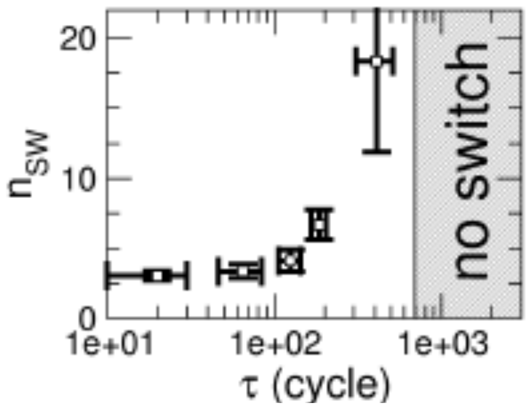


Transition rates imply the existence of a relaxation time scale t_{relax}

Short pulses (< t_{delay}) are sent at intervals $\tau < t_{relax}$

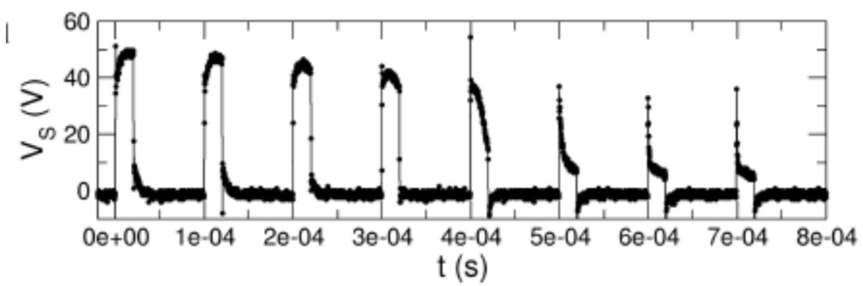
Model prediction

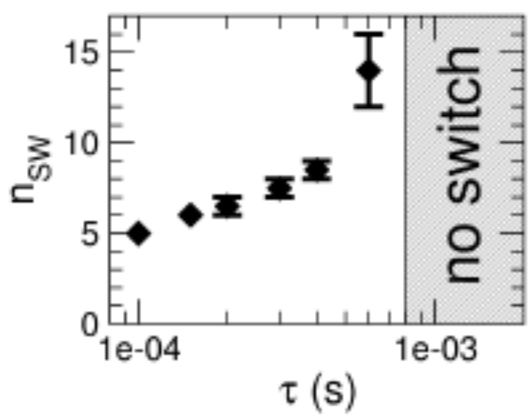




Transition after 5 pulses

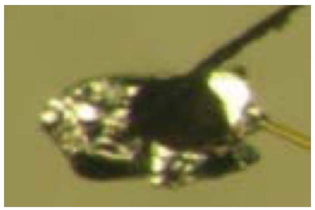
Experiment

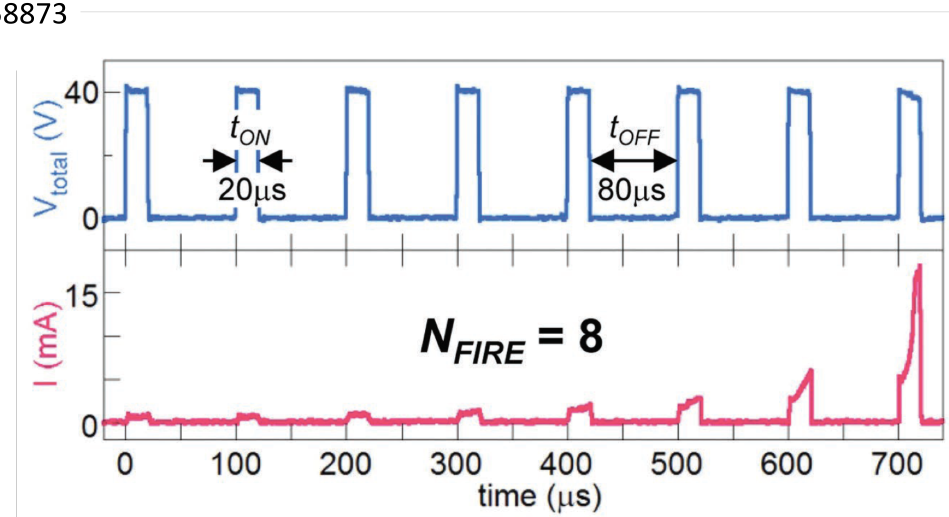


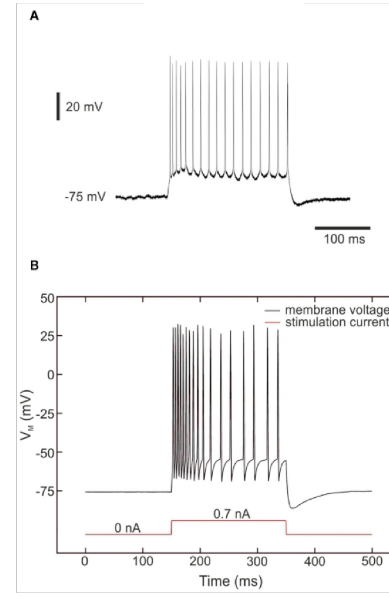


A Leaky-Integrate-and-Fire Neuron Analogue realized with a Mott insulator

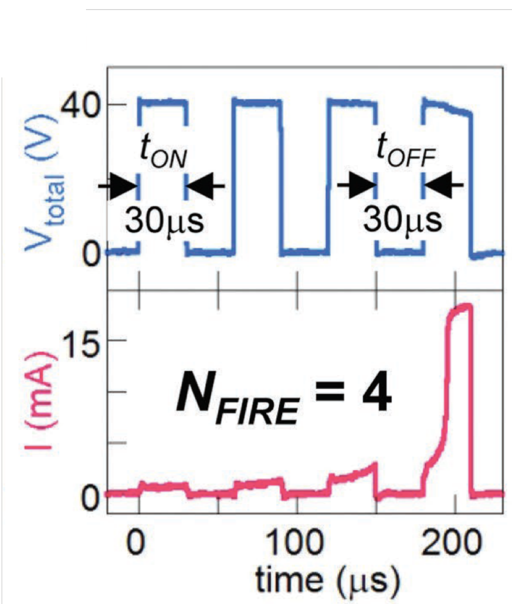
P. Stoliar, MR, et al Adv Funct Mat (2017)
US Patent n° PCT/EP2015/058873



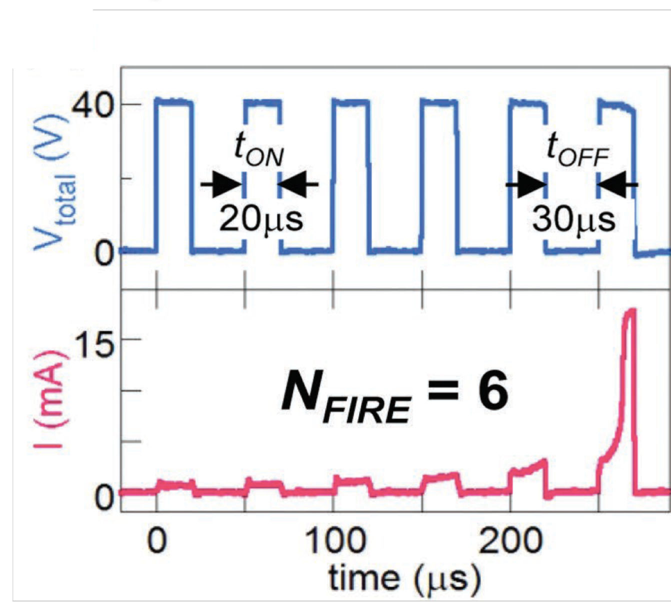


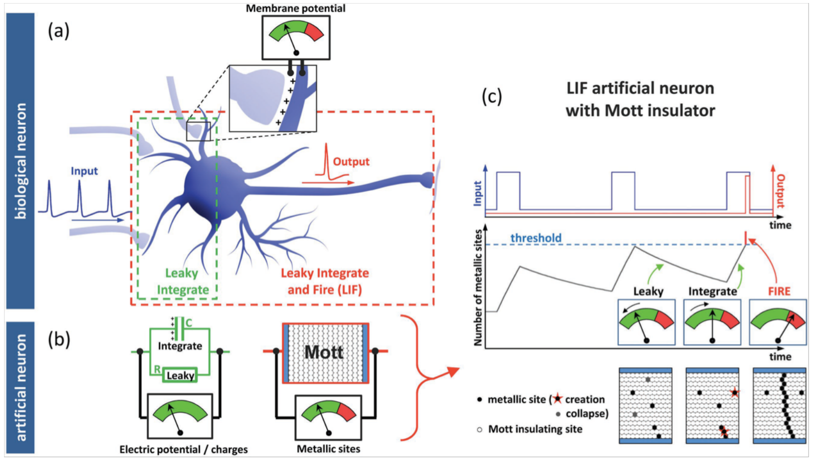


higher frequency



higher strength





	LIF model	Mott LIF neuron
Integrated variable	Membrane potential v	Fraction metallic regions n_{CM}
Model	$\frac{\partial}{\partial t}v = -v\frac{1}{RC} + \frac{w}{C}s(t)$	$\frac{\partial}{\partial t}n_{\text{CM}} = -n_{\text{CM}}P_{\text{CM}\rightarrow\text{MI}} + Ap(t)$
Input variable	Dirac delta function	Voltage pulse
Output variable	Not defined	Current pulse
Leaking time constant	RC	$1/P_{\text{CM}\rightarrow\text{MI}}$
Synaptic input	$s = \sum_i \delta(t - t_i)$	$p = \sum_i [H(t - t_i) - H(t - t_i - t_{\text{ON}})]$
Spike contribution	w/C	At_{ON}
Number of pulses for FIRE	$N_{\text{FIRE}} = \text{ceiling}\left(1 - \frac{\ln\left[e^{t_{\text{OFF}}/\tau} - \frac{t_{\text{FIRE}}}{t_{\text{ON}}}\left(e^{t_{\text{OFF}}/\tau} - 1\right)\right]}{t_{\text{OFF}}/\tau}\right)$	

Summary

- We now have artificial synapses and neurons made of simple 2 terminal oxide devices whose physics is based on the physical phenomenon of resistive switching
- Mott insulators (with small gap) can realize LIF-neurons
- Theoretical modeling may provide useful guidance for experiments
- The way is open for neuromorphic aplications

Collaboration with the group at IMN (Nantes),
P. Stoliar (AIST Japan)

Volatile Resistive Switching in Mott insulators:

V. Guiot et al, Nat Comm (2013)
P. Stoliar et al., Adv. Mat. (2013)
A. Camjayi et al., Phys Rev Lett (2014)
P. Stoliar et al., Phys. Rev. B (2014).
E. Janod et al Adv Func Mat (2016) **Review**
P. Stoliar et al. Adv Func Mat (2017)
P. Diener et al. Phys. Rev. Lett. (2018)

Job opportunity

Postdoc position is available

marcelo.rozenberg@u-psud.fr

Funded by DOE – US

New 4-year project with the group of Ivan Schuller at U. California (San Diego)

Recent work

On recovery from the E-MIT

Tesler et al. *Phys. Rev. Applied* **10**, 054001 (2018). Editor's suggestion

J. Del Valle et al. *Nature* (in press)