Compact modeling of hysteresis effects in ReRAM devices

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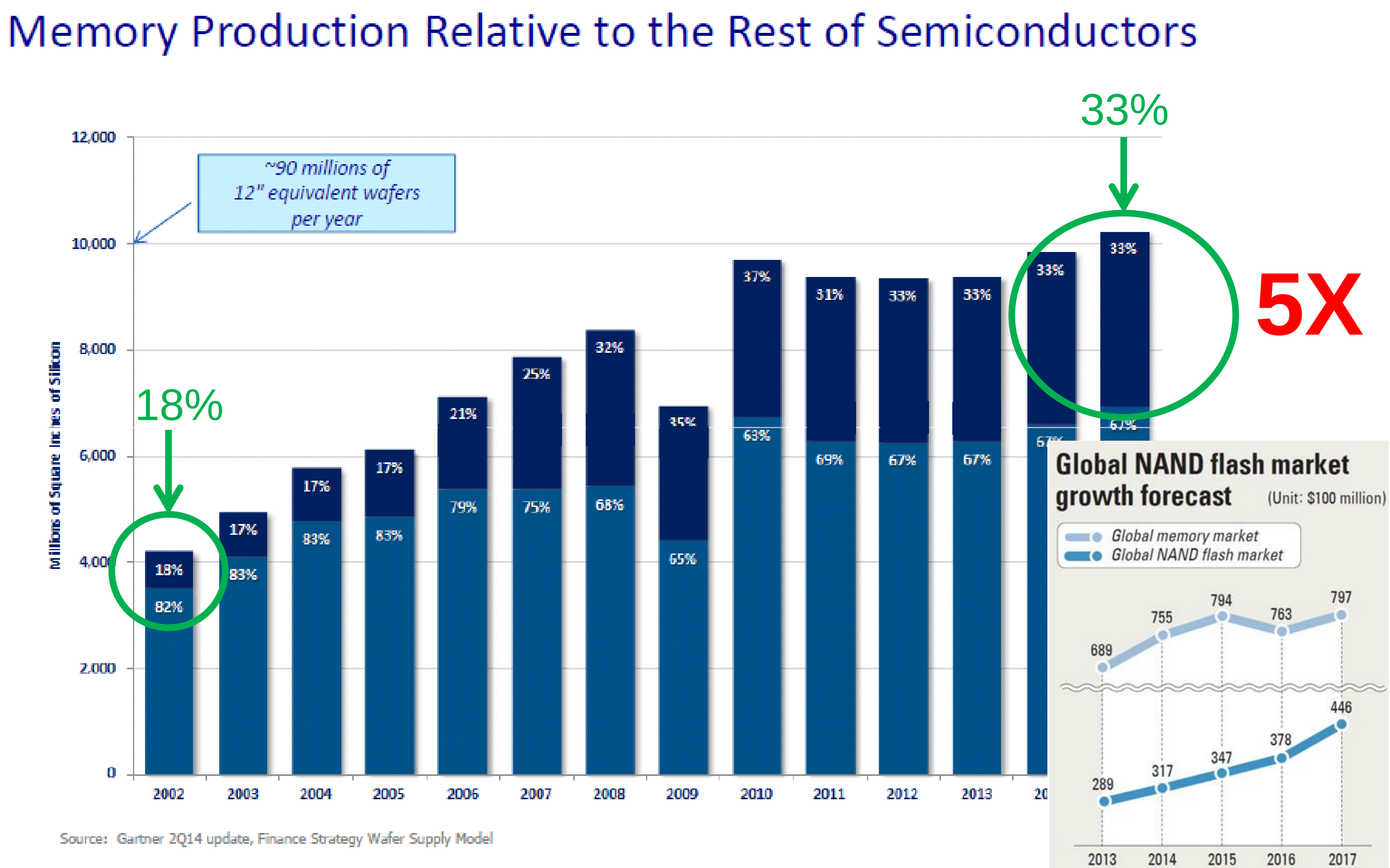
Evolution of the memory market



Important increase of memory market in the last years

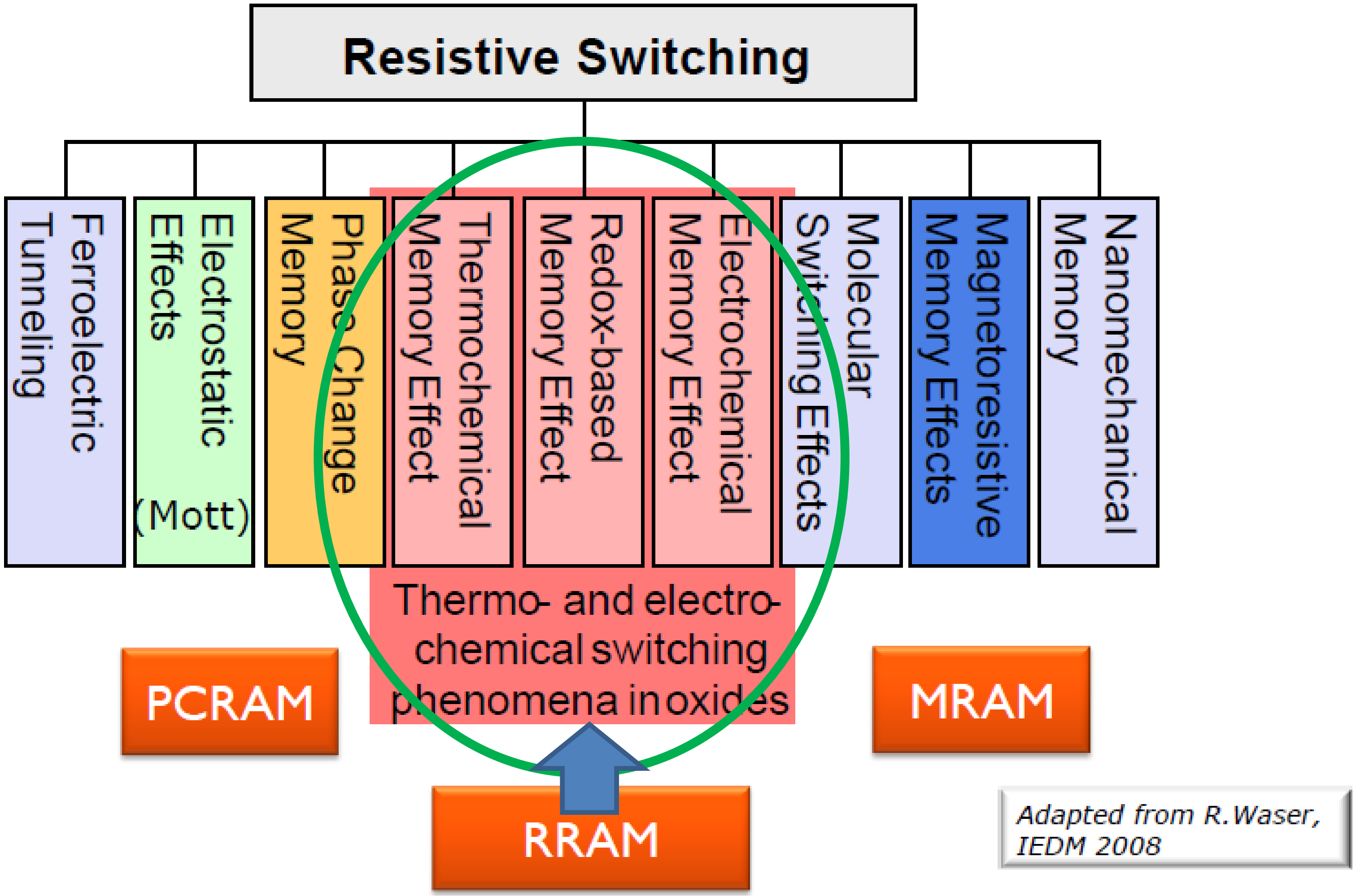
Motivation

- Increasing need of information storage systems

G.Jurczak, imec

Reaching the limits of conventional memory devices?

Classification of ReRAM or RRAM

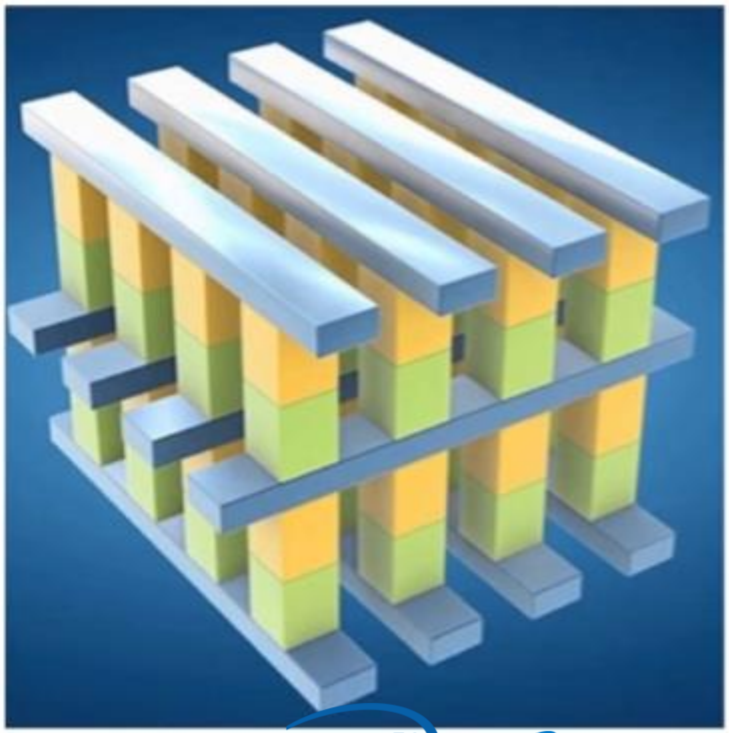


Physical mechanism: thermo- and electro-chemical phenomena

Memory application

Optane SSD: 3D-XPoint Technology

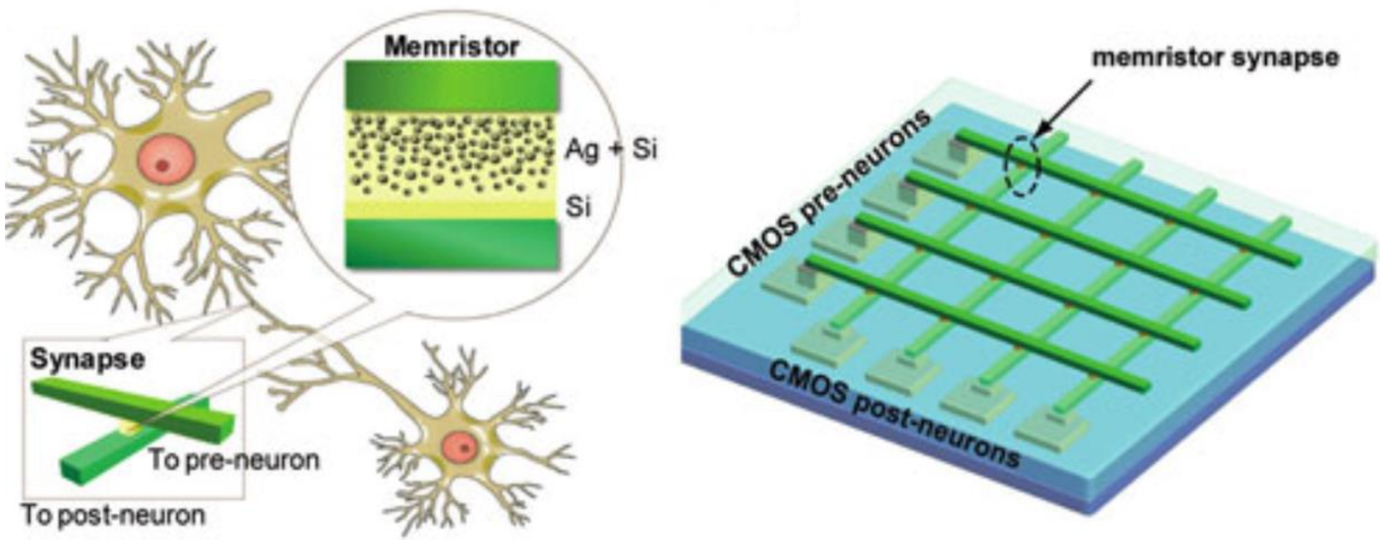
- *Selectors and memory cells are located at the intersection of perpendicular wires*
- *Each cell is individually accessed through the top and bottom wires touching each cell*
- *Cells stacked in 3D improve storage density*
- *Optane SSD 905P SSD (960GB)*



Bit storage is based on a change of resistance

Neuromorphic application

- *Memristor devices are capable of emulating the biological synapses with properly designed CMOS neuron components*



Synaptic weight is based on a change of resistance

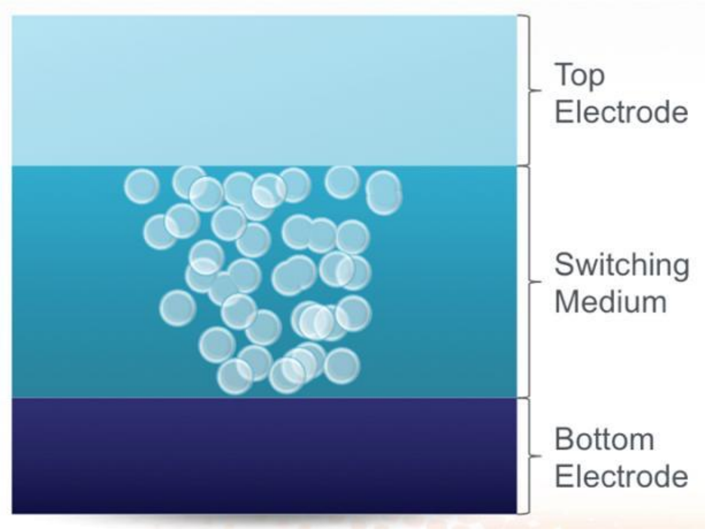
S. Jo *et al*, Nano Lett 2010

Recent announcement

July 2018

- *… to develop a switch that functions like the neuron and synapses of the human brain, based on Correlated-Electron RAM (CeRAM) technology.*
- *… to speed up neural network processing while improving power efficiency through the use of analog signal processing as compared to current digital approaches.*

This talk: filamentary-type ReRAM



- Capacitor-like structure with a conducting pathway
  - CBRAM: metal ions (usually Ag or Cu)
  - OxRAM: oxygen vacancies (usually TMO)
- Nonvolatile effect: interplay of ions and electrons
- Complex physics: relies on natural parameters

Outline

- Introduction to filamentary-type ReRAM
- Physical models and quantum limit
- The circuital approach
- Model implementation
- The problem of variability
- Final comments

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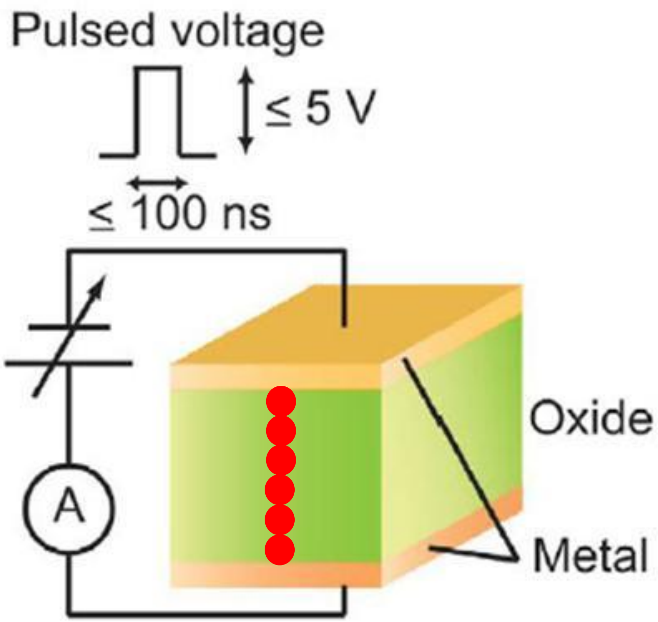
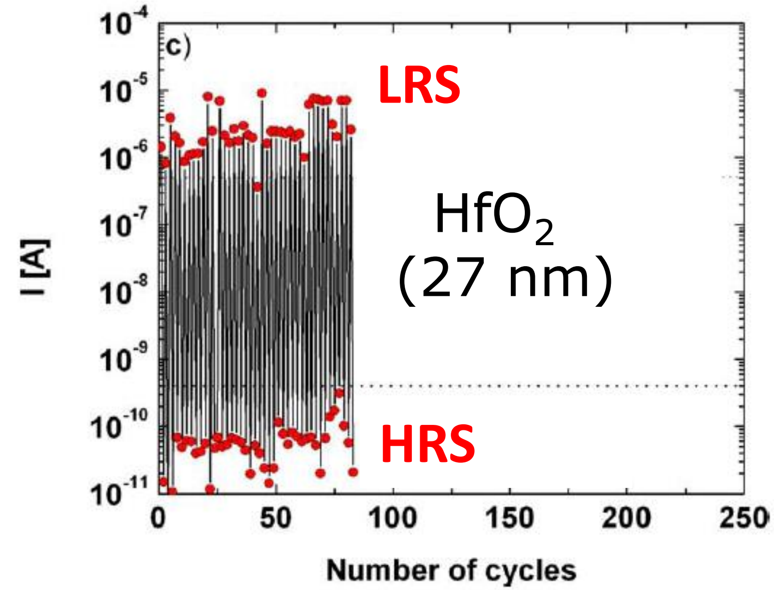
Phenomenology of filamentary-type RS

By applying pulsed or ramped voltages, the resistance of some oxides can reversibly change between a high (HRS) and a low (LRS) state



A. Sawa, Mat Today (2008)

Formation and rupture of a filamentary path

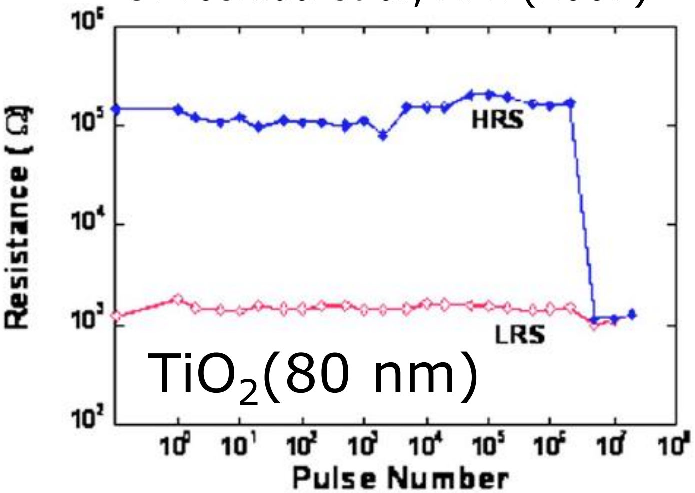


Ch. Walczyk *et al*, JAP (2009)

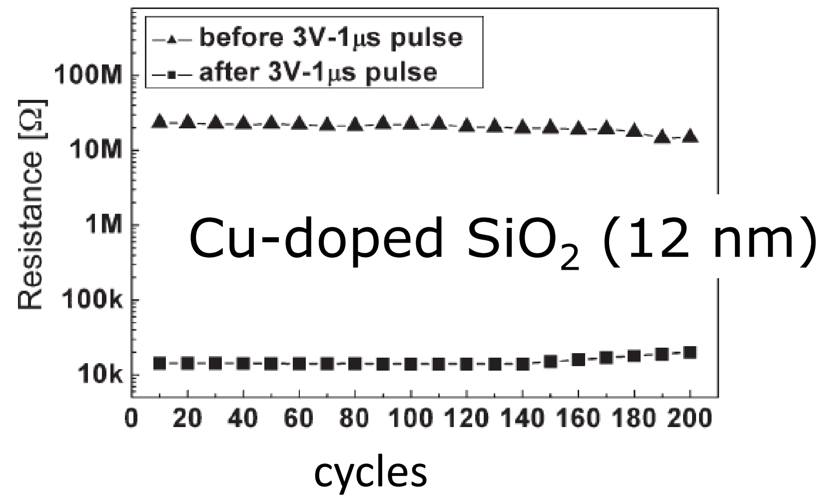
This phenomenon is the working principle of RRAMs: two stable states

Cycling experiments in MIM structures

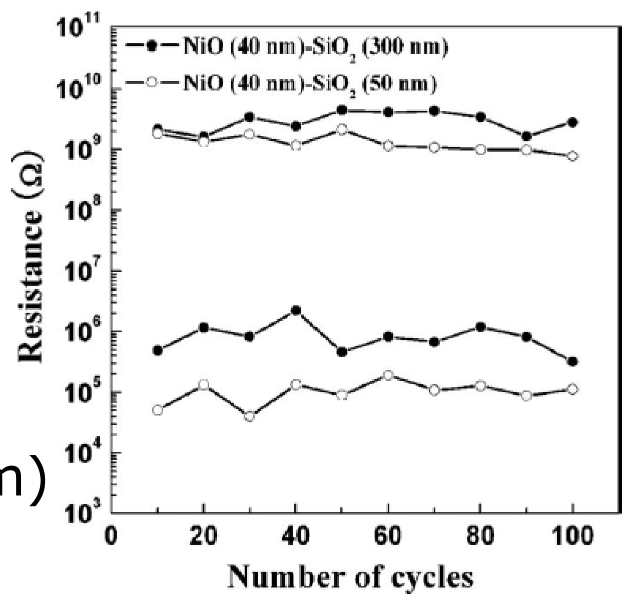
C. Yoshida *et al*, APL (2007)



C. Schindler *et al*, IEEE TED (2007)



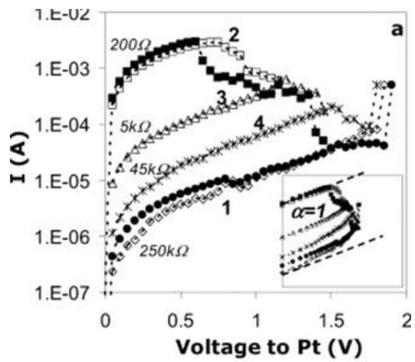
J. Choi *et al*
APL (2009)

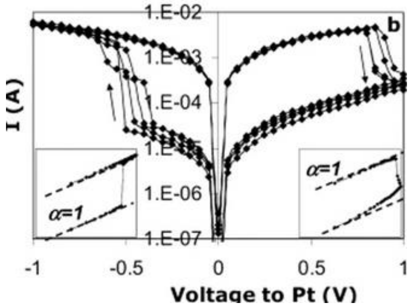


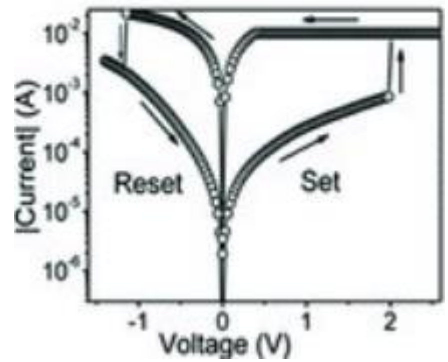
NiO(40 nm)
/SiO_2(50-300 nm)

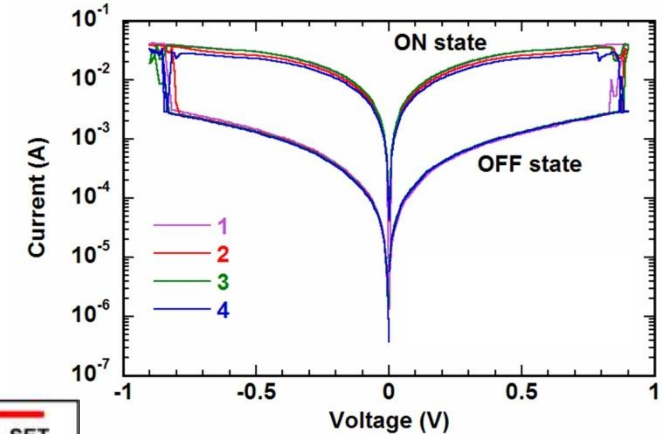
The switching property is observed in a wide variety of dielectric stacks

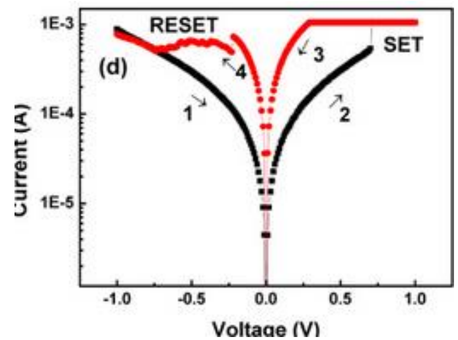
… exhibiting a wide variety of *hysteretic* I-V curves

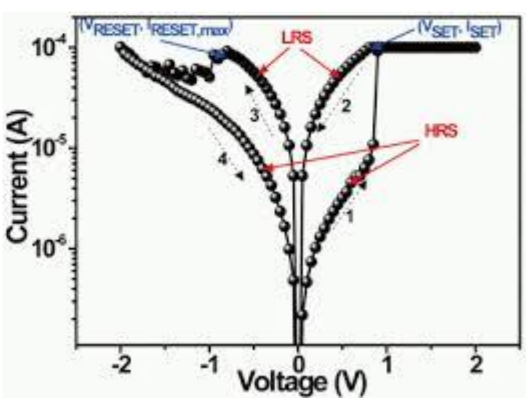


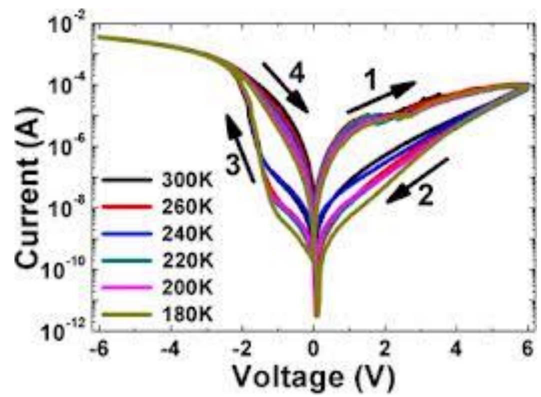


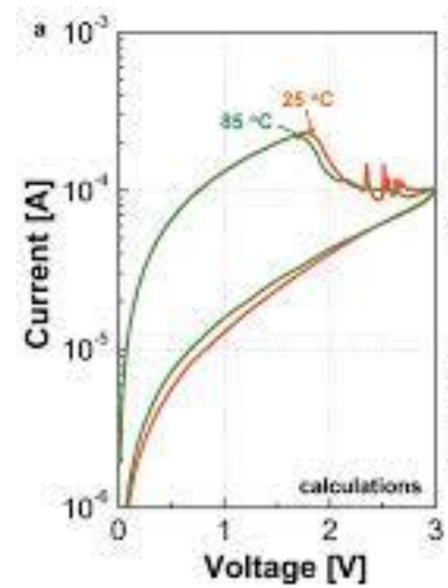












RS phenomenon observed in many material systems

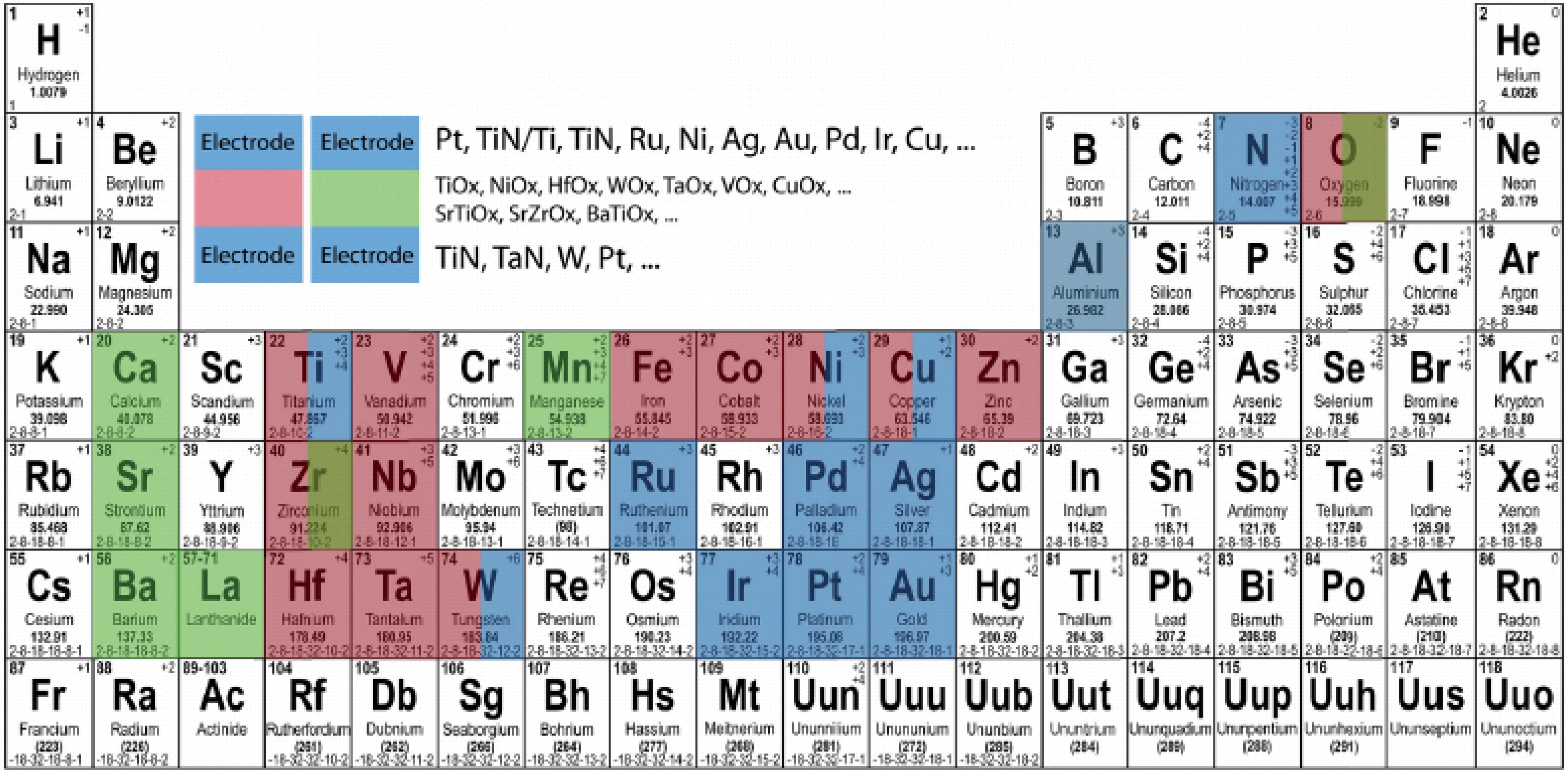
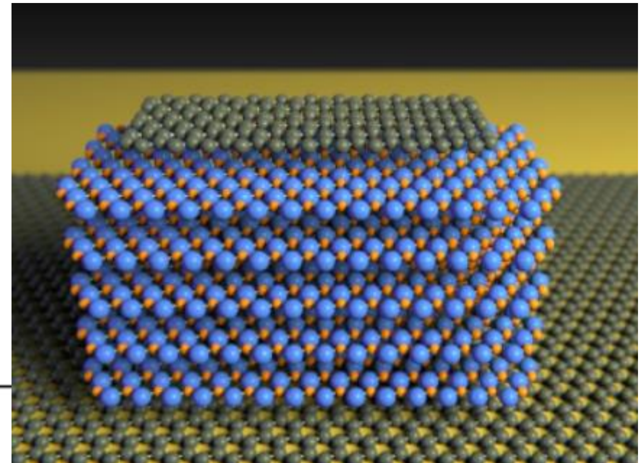


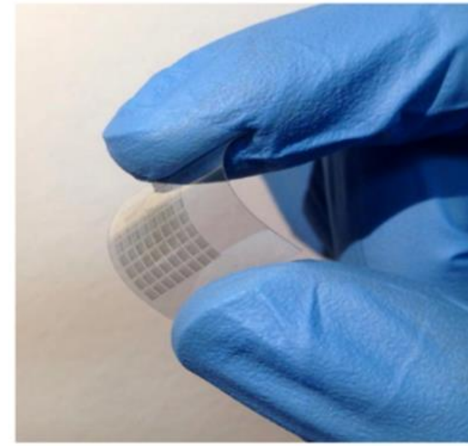
Figure 46: The periodic table, showing the materials for the top and bottom electrodes as well as the transition metal-oxide materials used in ReRAM structures. The elements in blue are the candidates for the electrodes. The red and green elements are binary oxides and the ternary oxides (perovskite type) respectively (reprinted with permission from [60]).

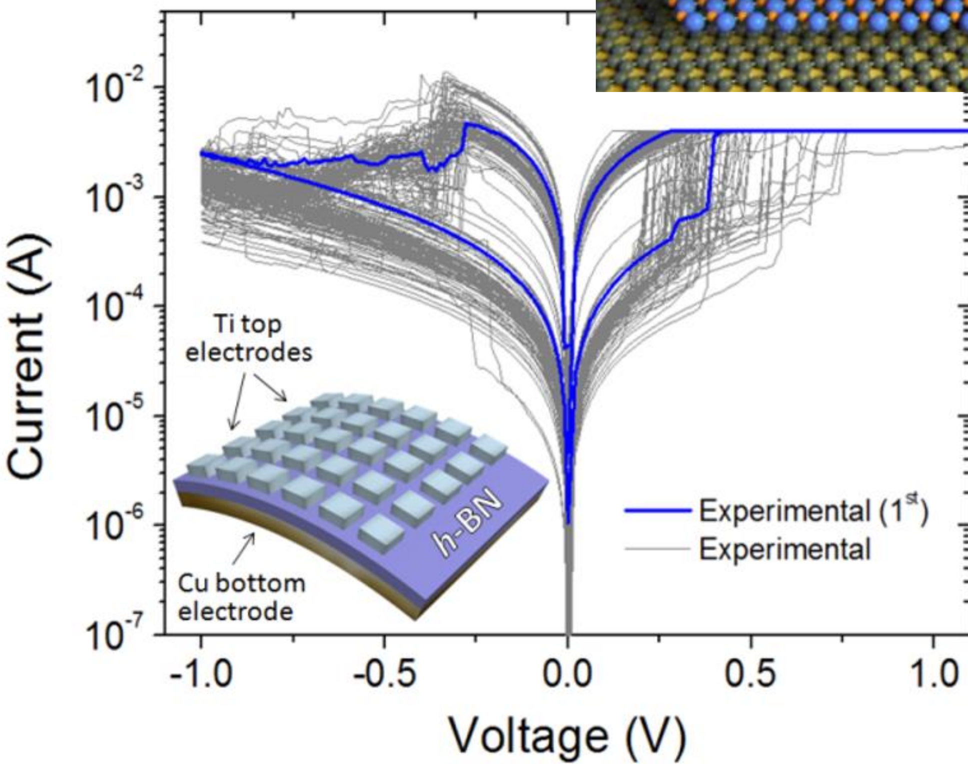
Some electrode materials favour the switching process

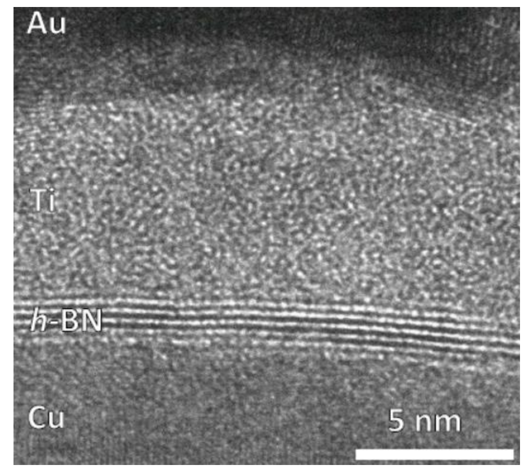
Newcomers: 2D materials

- h-boron nitride
- MoS_2
- Graphene



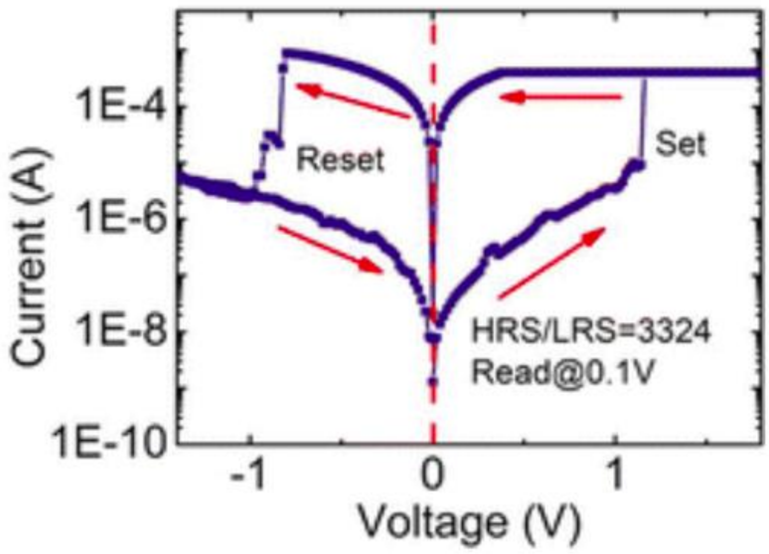






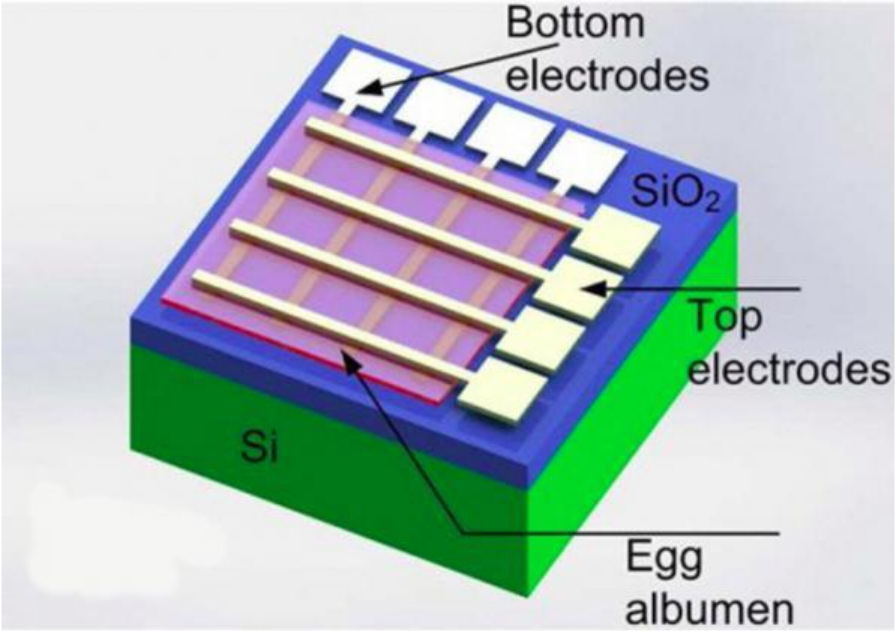
Variability and reliability: big problems for industry!

EGG: the material of the future?



Eggs used to make memristors:
biocompatible and dissolvable electronic devices

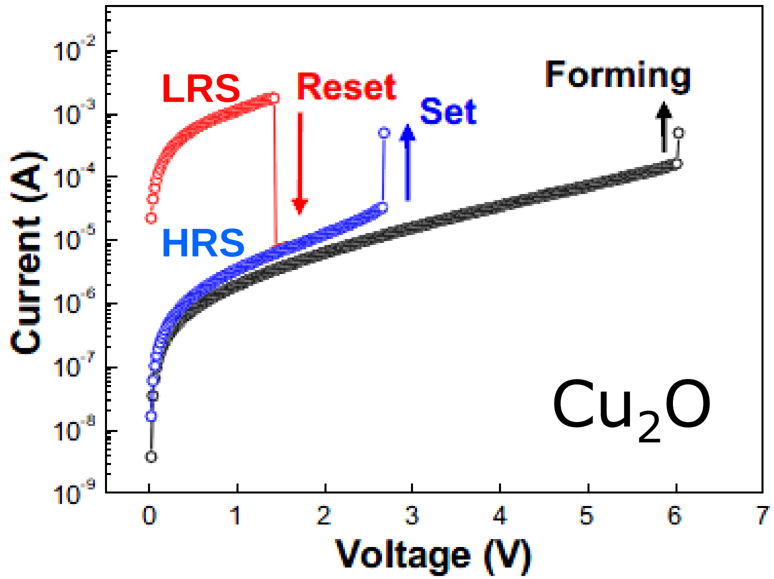
Researchers at two Chinese universities, the Cavendish Laboratory at Cambridge University and the University of Bolton, UK, have produced a memristor made from egg proteins, magnesium and tungsten



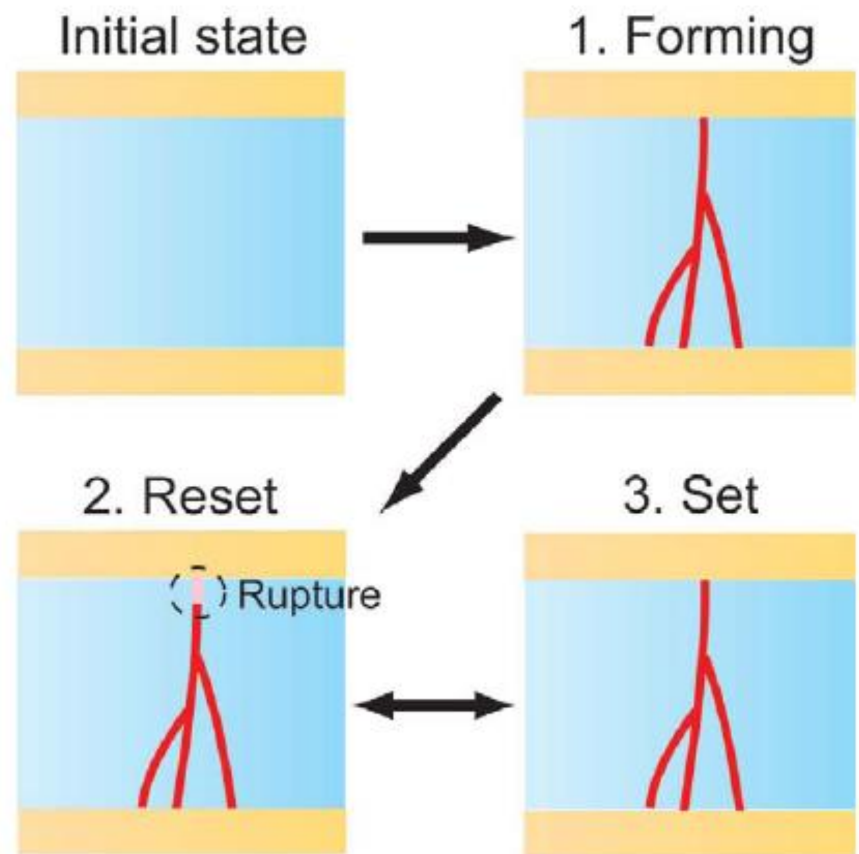
EETimes, April 2016

Forming, set and reset: unipolar mode

Initial electroforming step required to activate the switching property



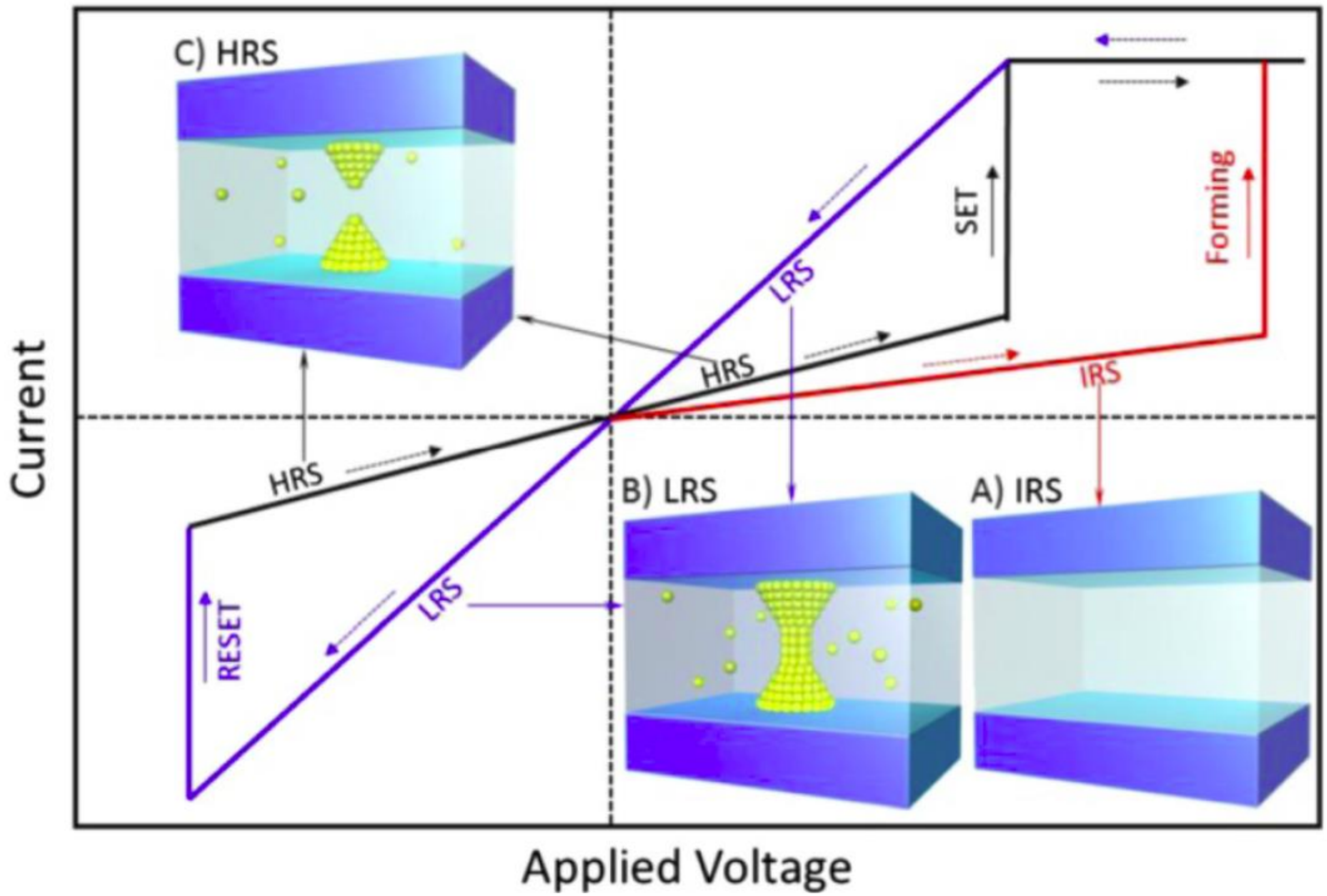
S. Kang *et al*, APL (2009)



A. Sawa, Mat Today (2008)

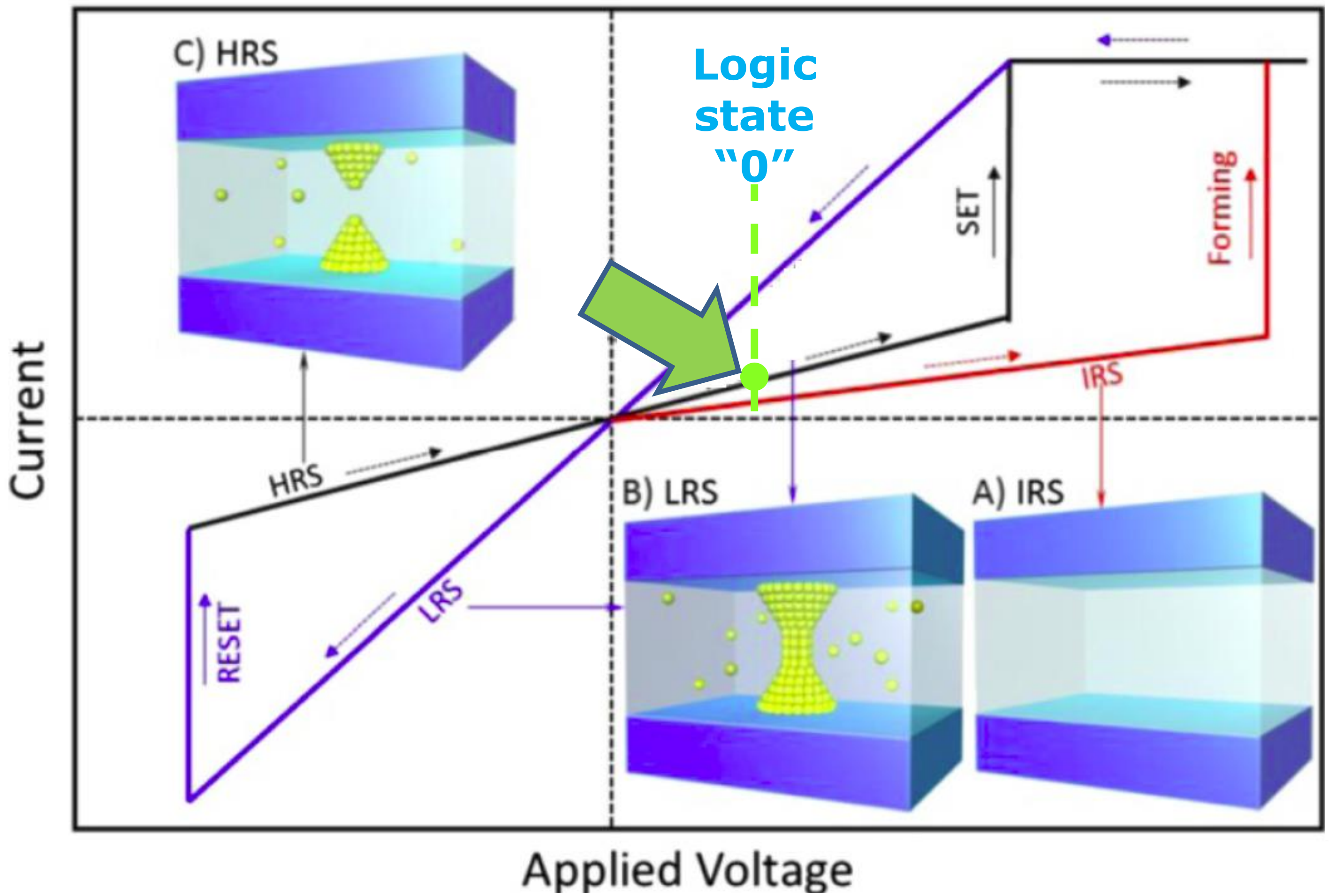
RESET and SET events: rupture and regeneration of the filamentary path (antifuse behavior)

Forming, set and reset: bipolar mode



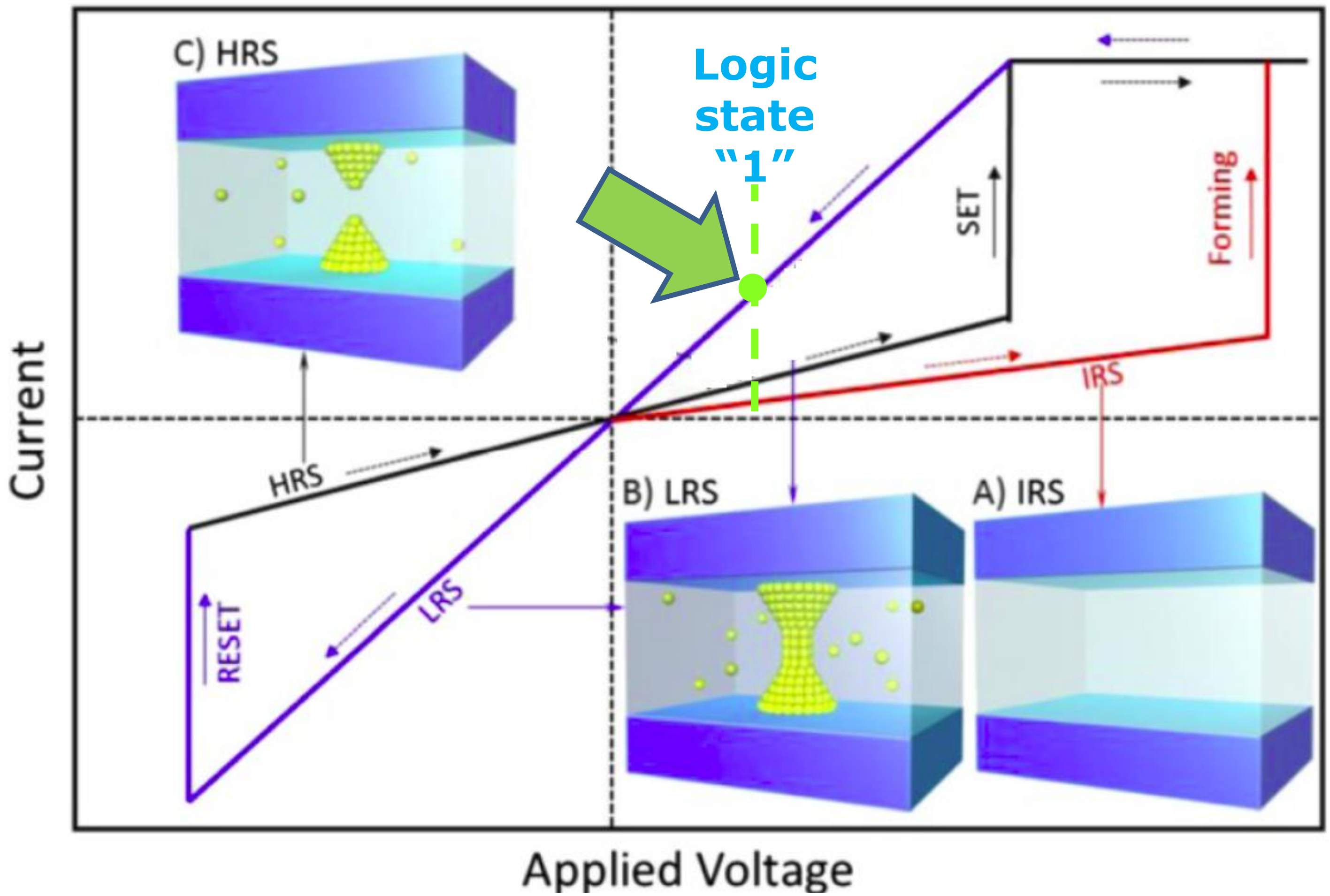
Y. Li *et al*, NRL (2015)

Memory effect: how information is stored



READ OPERATION: low current → logic state "0"

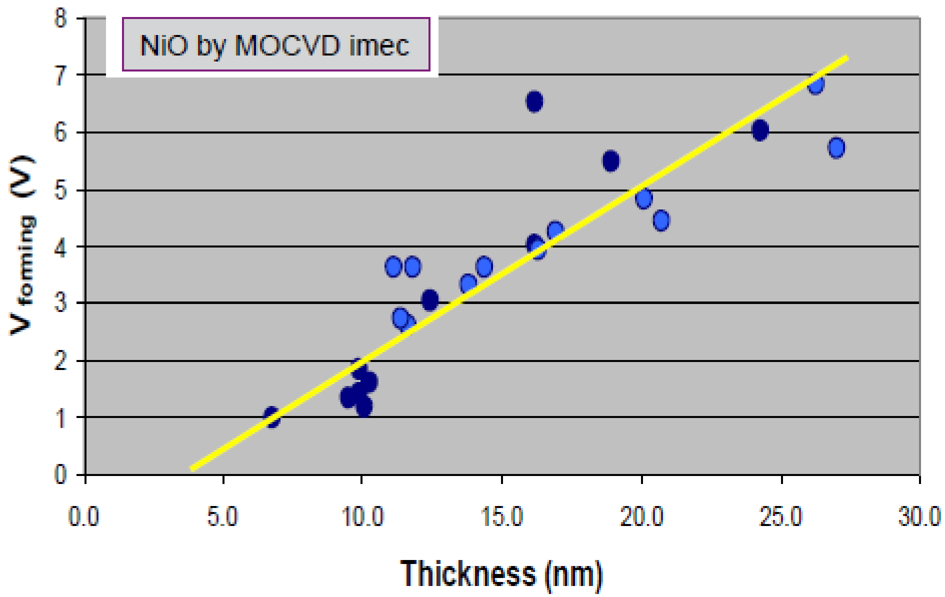
Memory effect: how information is stored

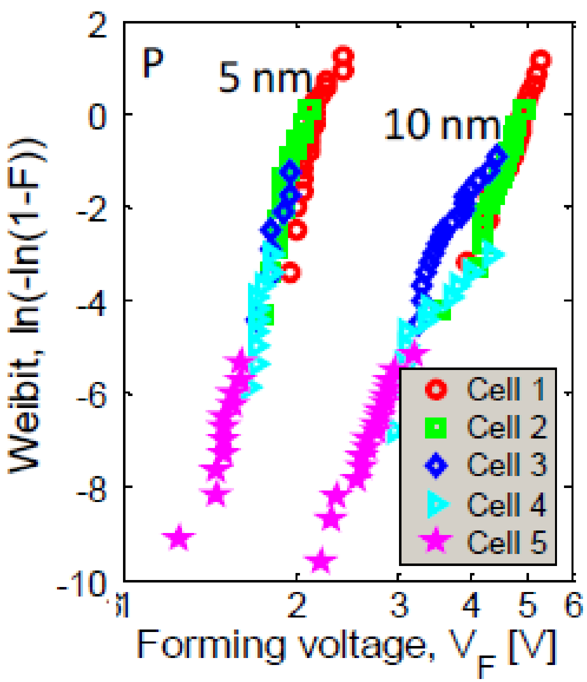


READ OPERATION: high current → logic state "1"

Forming process

Corresponds to a breakdown event in dielectrics (defects & percolation path generation)



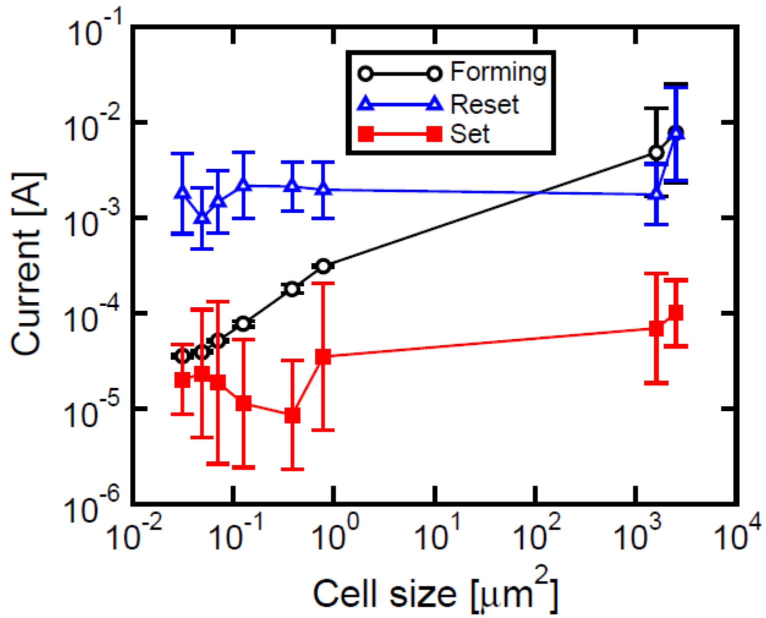


For very thin oxides no forming seems to be required:
Forming should be avoided

Weibits independent of device area:
BD events follow a Poisson process

B.Govoreanu, SSDM 2011

Area scaling of RS

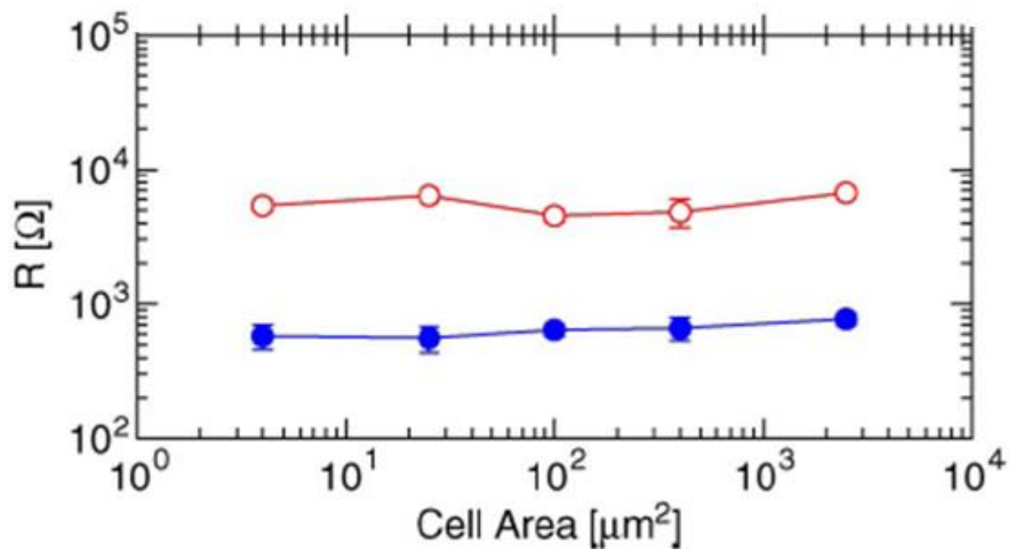


"… neither the set nor the reset current shows any area dependence due to the filamentary nature of conduction."

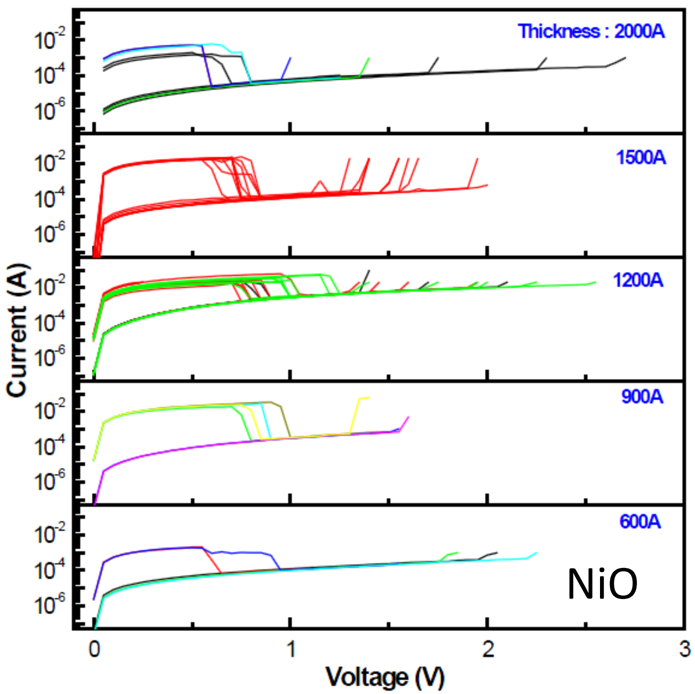
D. Ielmini, NiO RRAMs

"*Experimental data do not display any obvious dependence on area, indicating that resistive switching is a filamentary process*"

F. Nardi *et al*, IEEE TED (2012)



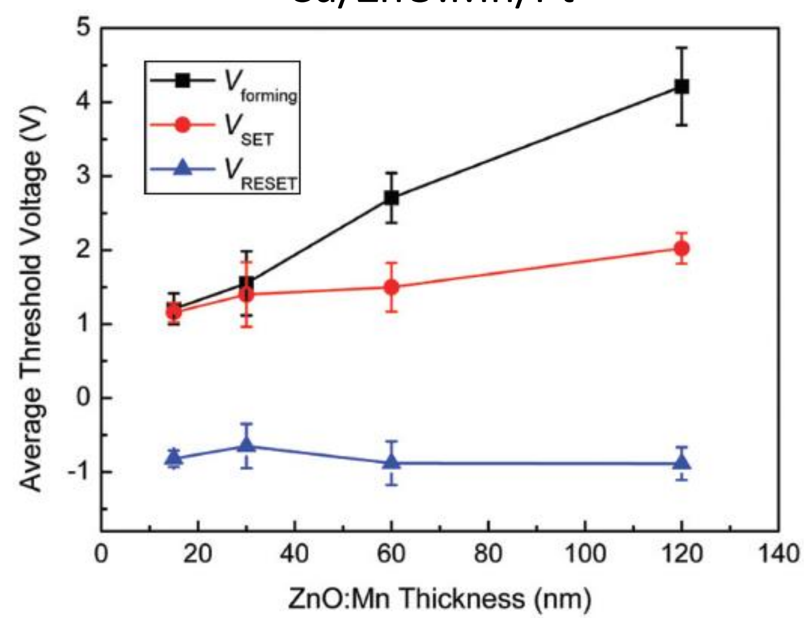
Thickness scaling of RS



SET and RESET voltages:
"*No appreciable dependence of memory switching on thickness*"

S. Seo *et al*, Samsumg Electronics (2011)

Cu/ZnO:Mn/Pt

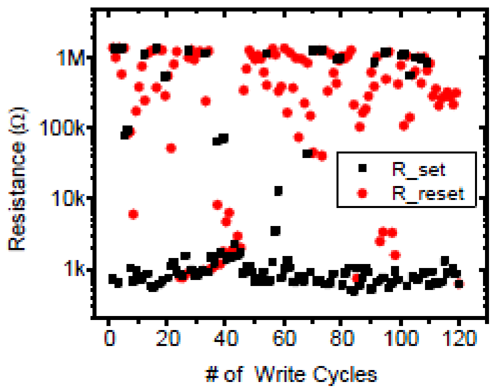


"…little or weak dependence on film thickness is observed, which means that the bias voltage mainly drops on a local effective region, and the thickness of this region does not significantly vary with bulk thickness."

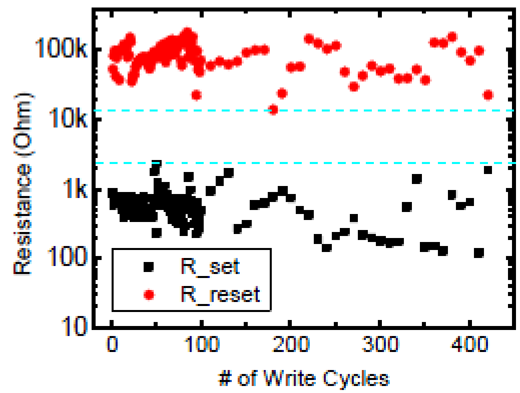
Y. Yang *et al*, NJP (2010)

The role played by the electrodes

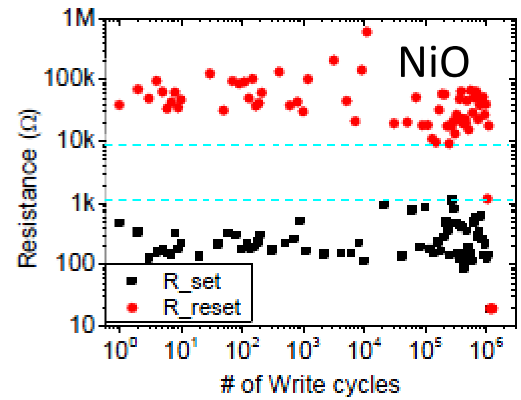
Poly Si Electrode



W Electrode



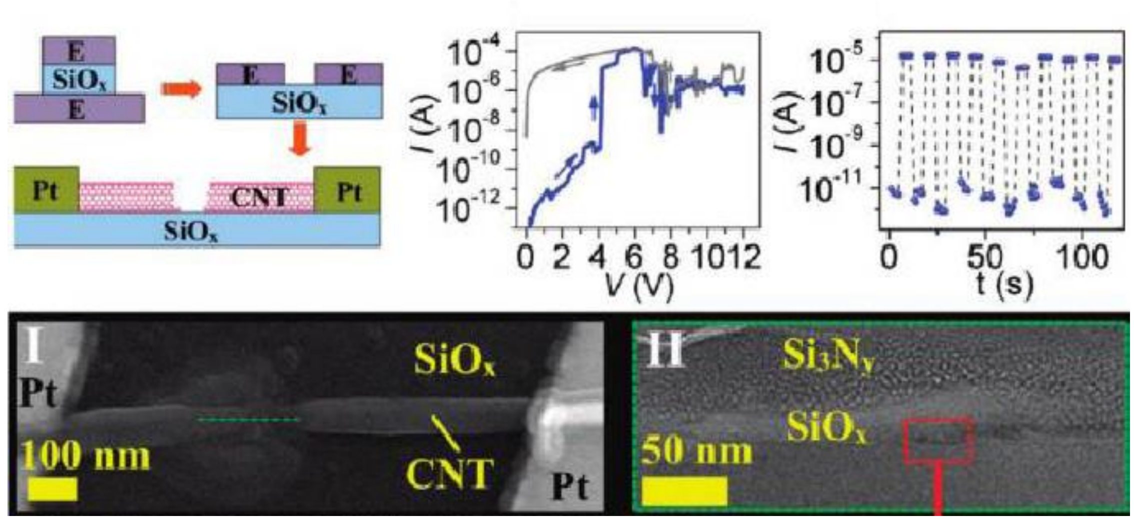
Noble Metal Electrode



S. Seo *et al*, Samsumg Electronics

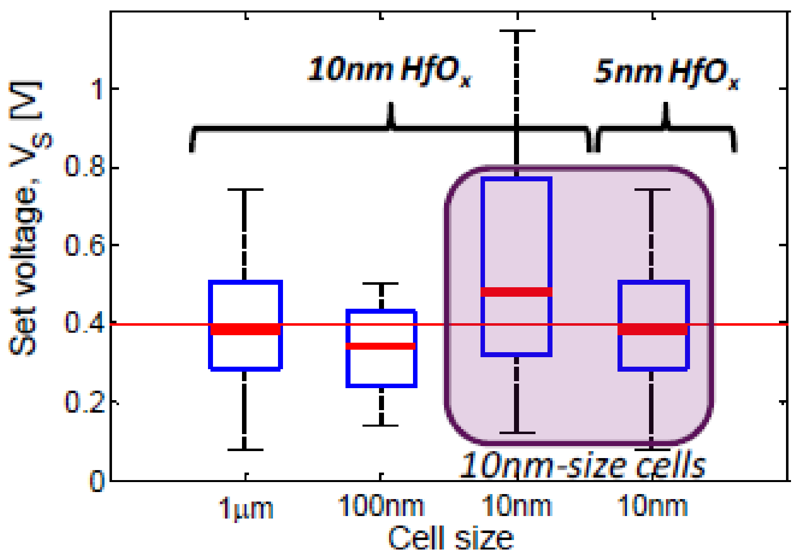
“…resistive switches and memories that use SiO_x as the sole active material and can be implemented in entirely metal-free embodiments.”

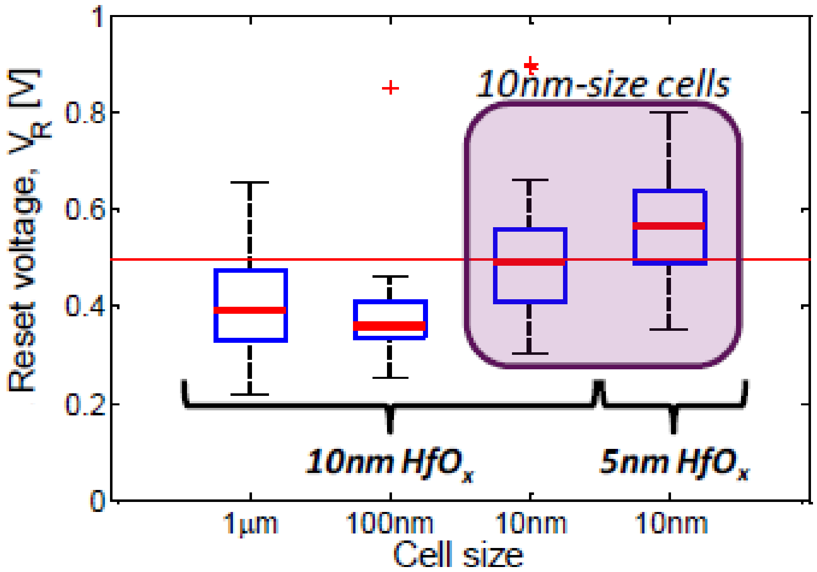
J. Yao *et al*, NL (2010)

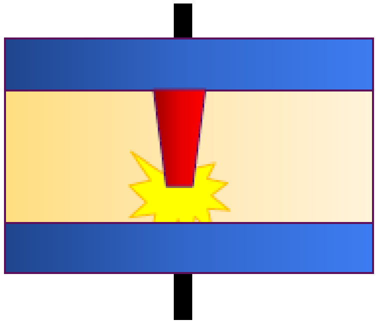


Switching site in a CNT-SiO_x nanogap system

Localized switching region





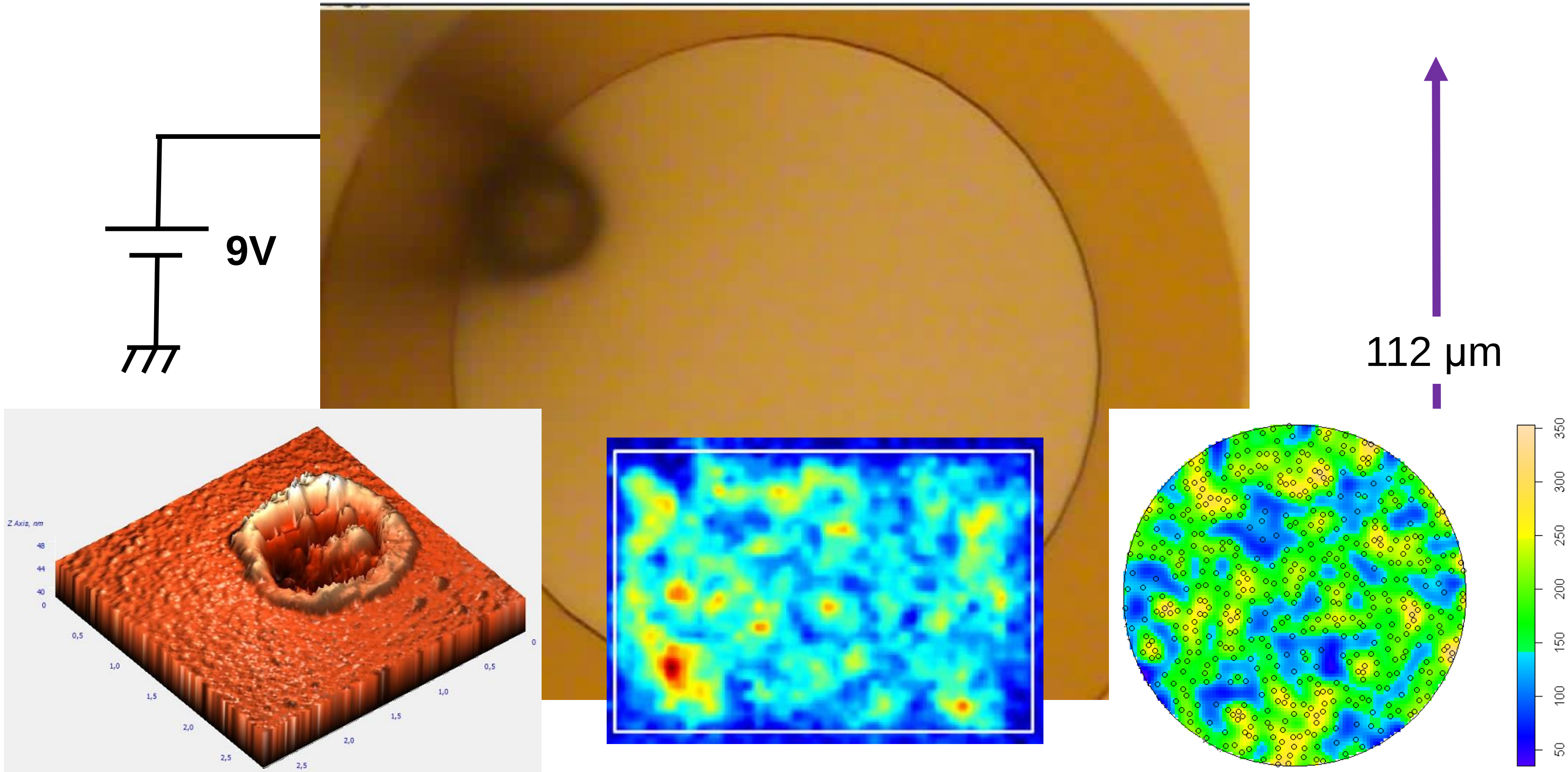


"*The absence of cell area and oxide thickness effect is indicative of a local filament switching*"

B. Govoreanu *et al*, IEDM (2011)

Generation of filaments during constant voltage stress

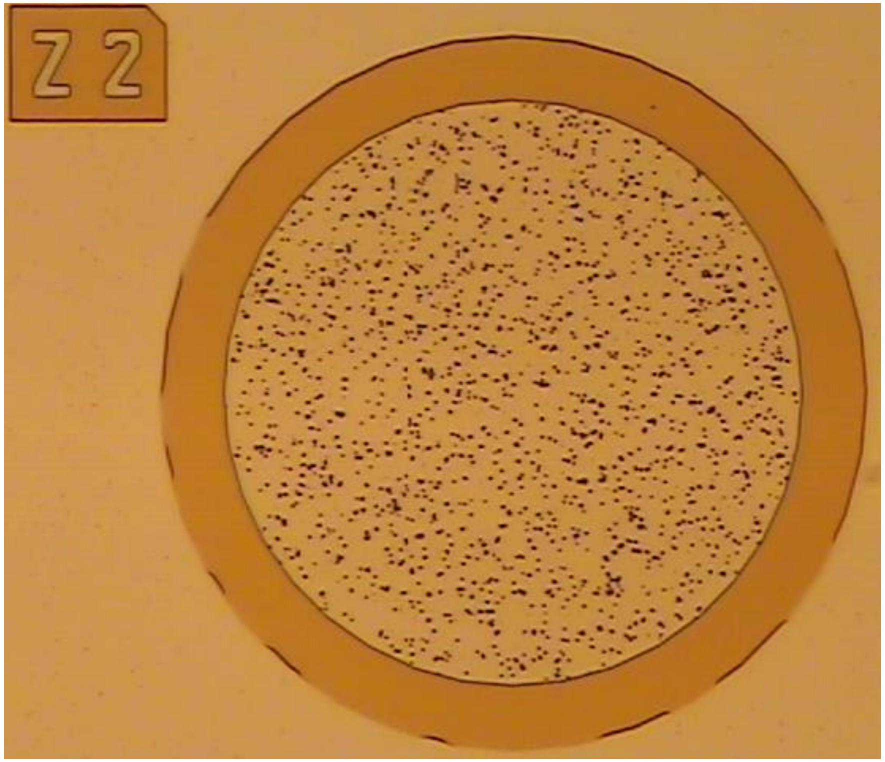
Top view of Pt/HfO_2(20nm)/Pt capacitor

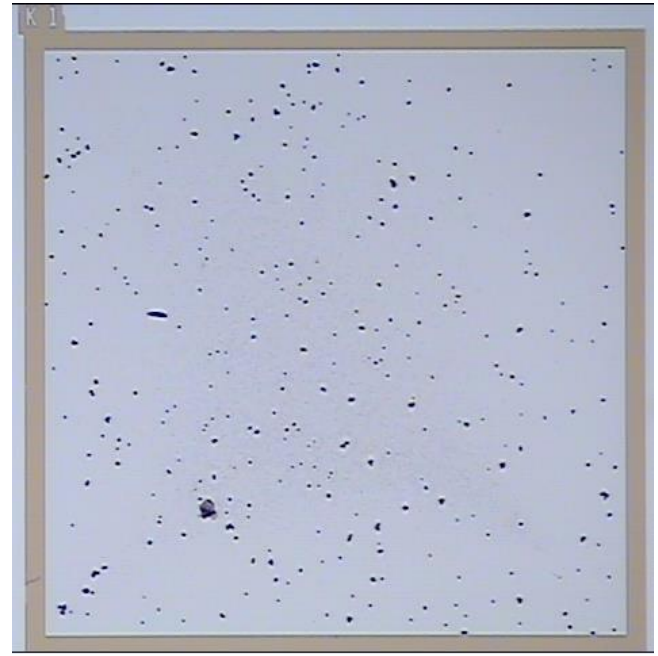


AFM | Infrared thermography | Spatial Statistics

In collaboration with Tyndall National Institute, Ireland

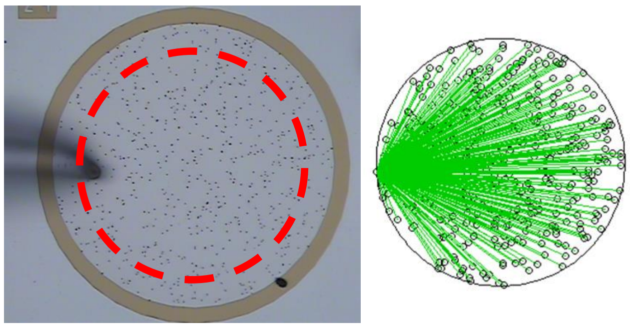
Multifilamentary patterns (not reversible)



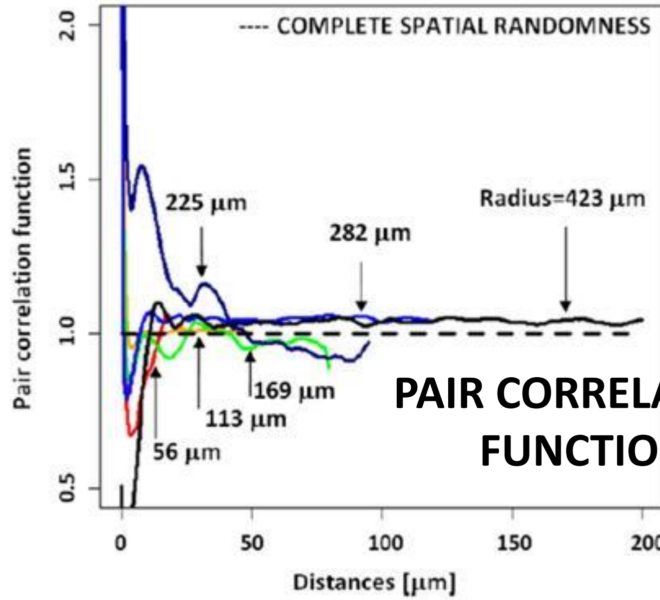


MIS and MIM capacitors with high-K dielectric

Techniques used to assess BD spot/filament distribution

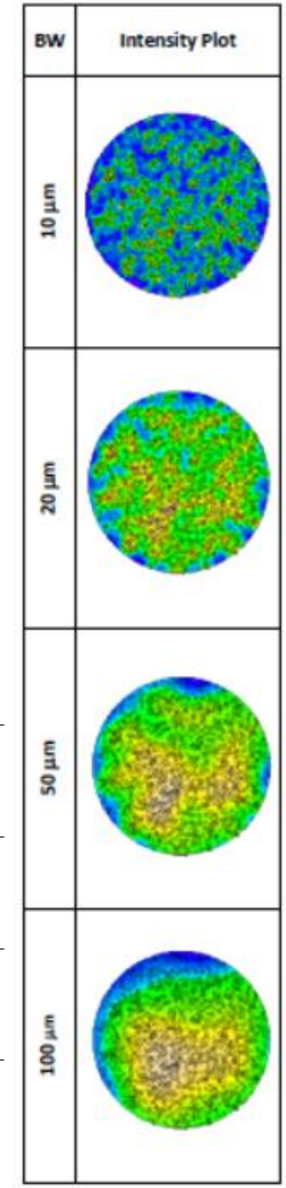


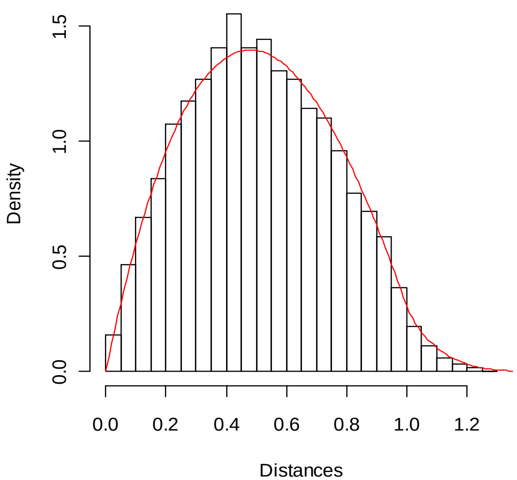
POINT-TO-EVENT DISTANCES



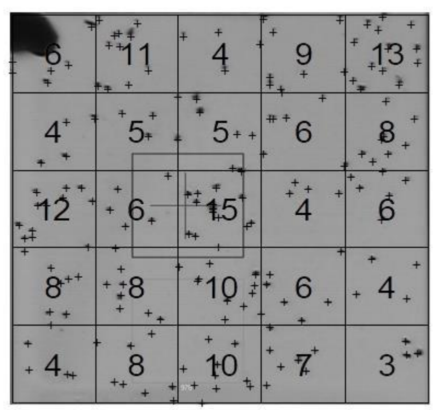
PAIR CORRELATION FUNCTION

INTENSITY PLOTS

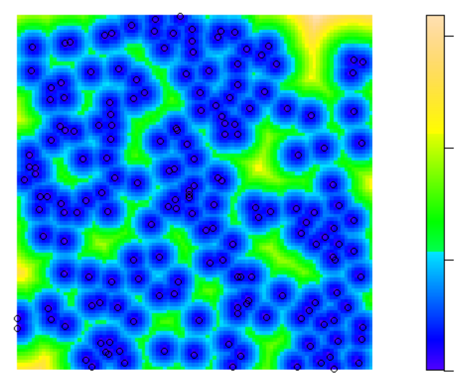




DISTANCE METHOD

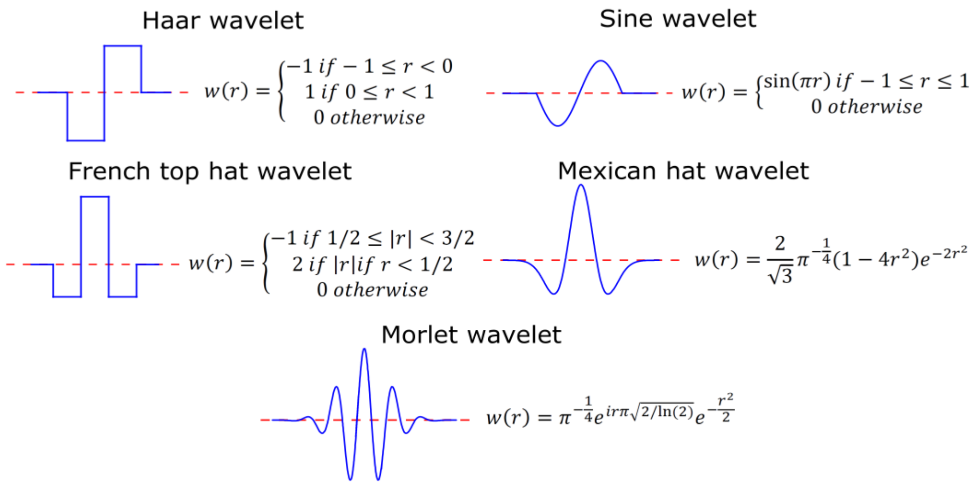


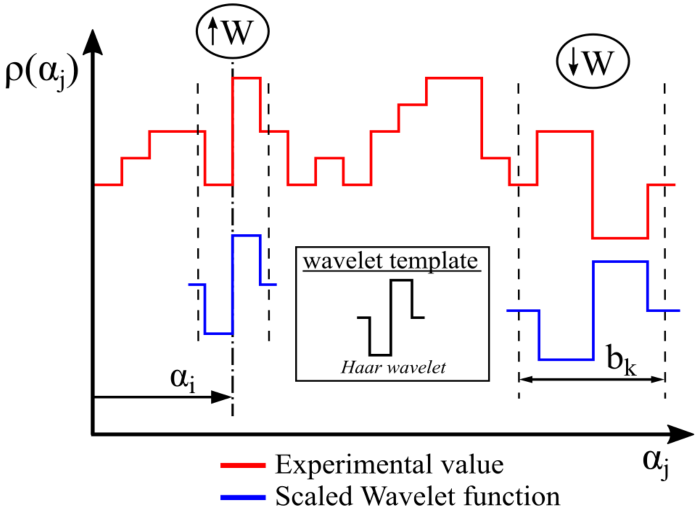
QUADRAT COUNTS METHOD

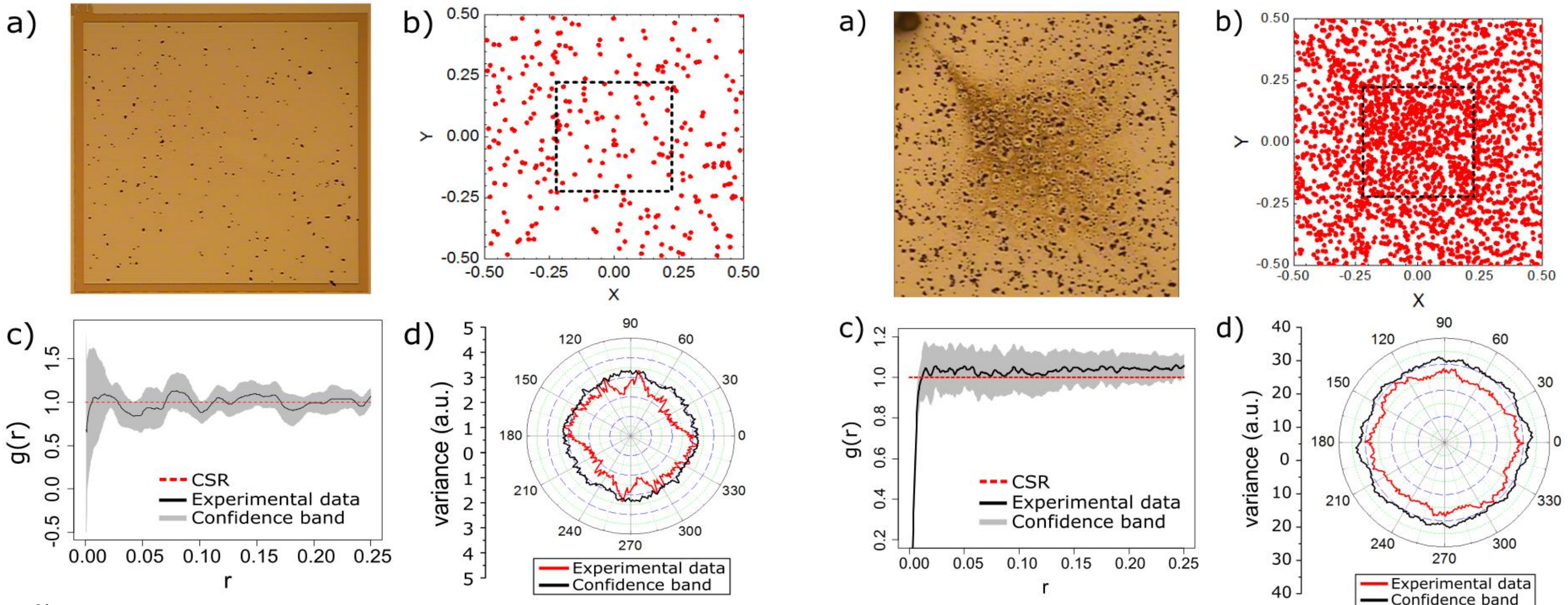


NEIGHBOUR METHOD

Spatial statistics using angular wavelet analysis

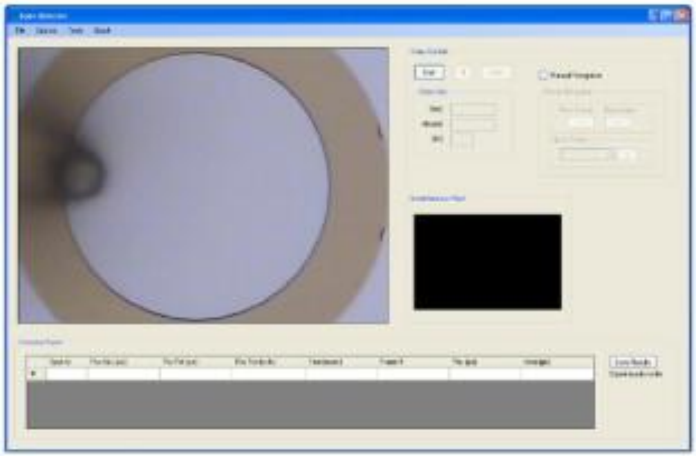


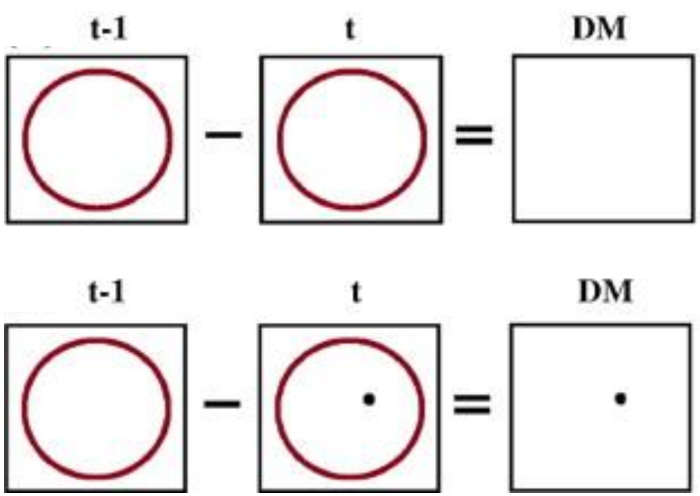




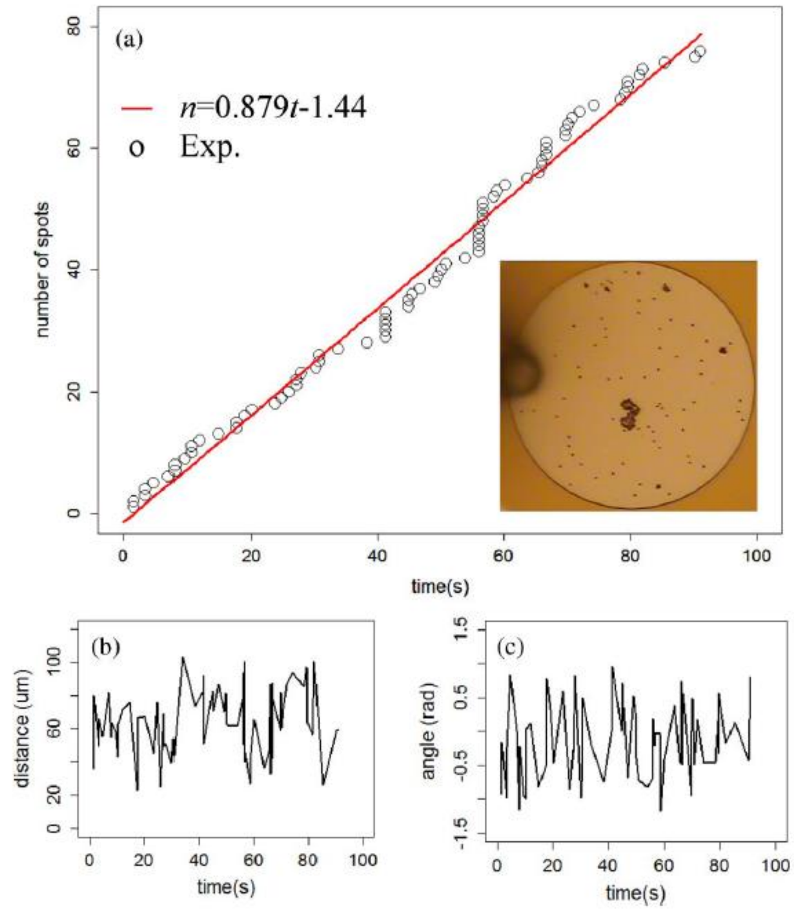
Muñoz Gorriz *et al*, Mic Eng 2017

Multifilamentary conduction





Constant Voltage Stress



Filaments are neither spatial nor temporal correlated

X. Saura *et al*, Mic Rel 2013

Outline

- Introduction to filamentary-type ReRAM
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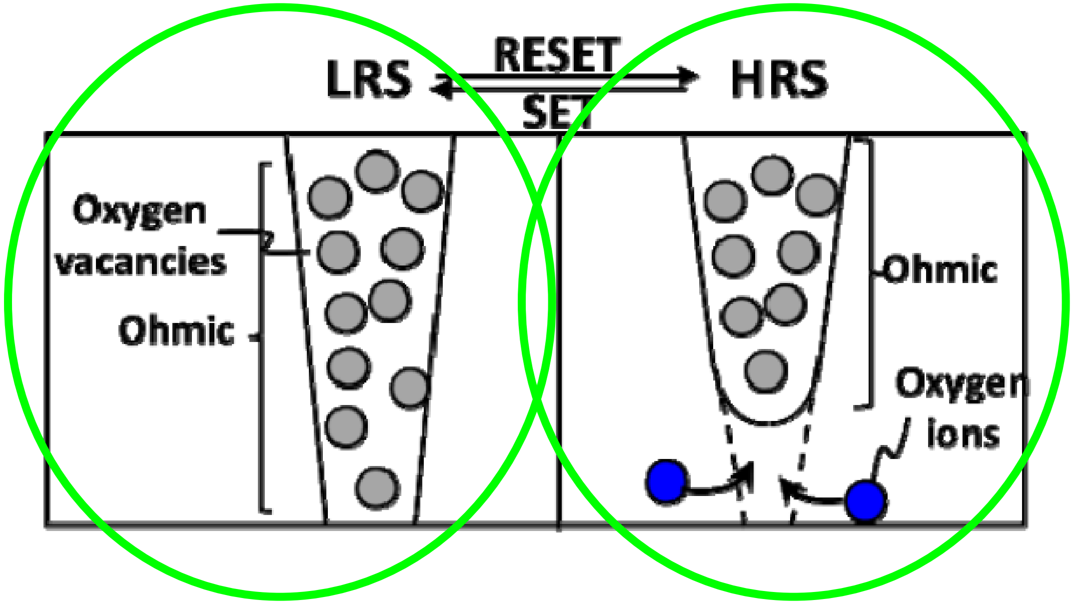
- Model implementation
- The problem of variability
- Final comments

Conventional model for the Set/Reset transition

- SET: generation of a filamentary conduction structure (LRS)
- Chain of oxygen vacancies exhibits ohmic behavior (linear I-V characteristic)



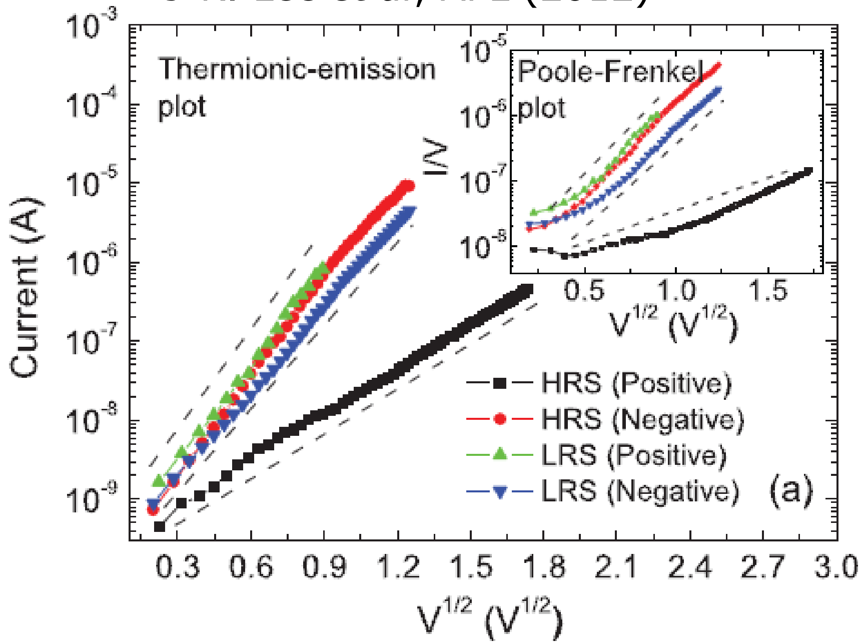
- RESET: The constriction vanishes or locally reduces leading to an increment of the structure resistance (HRS)

REDOX model: the movement of oxygen ions by electromigration annihilates the vacancies

K. Szot *et al*, Nat Mat (2006)

Poole-Frenkel and thermionic conduction

J-K. Lee *et al*, APL (2012)



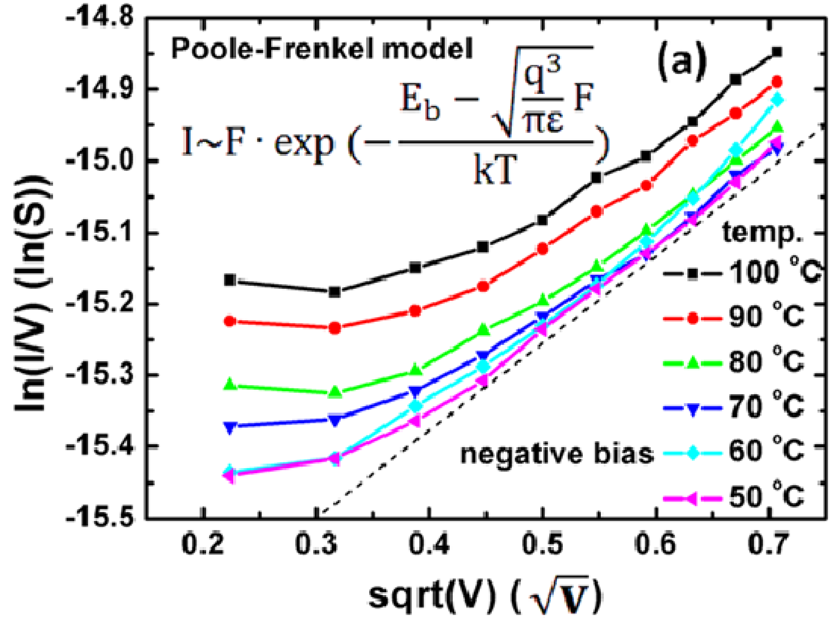
$$J = A^* T^2 \exp\left(\frac{-q(\Phi_B - \sqrt{qE/4\pi\varepsilon_r\varepsilon_0})}{k_B T}\right)$$

In most of the cases fitting parameters are not reported!!!

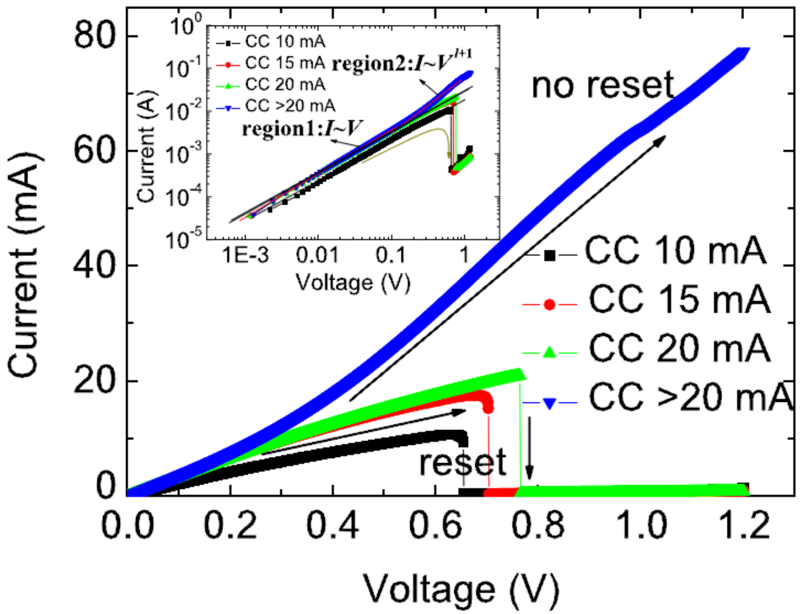
"The value of the extracted dielectric constant ε_r=79 is much higher than the known value 20 for HfO_2. …fitting to a P-F model is unreasonable."

S. Yu *et al*, APL (2011)

TiN/HfOx/Pt



Space-charge limited conduction

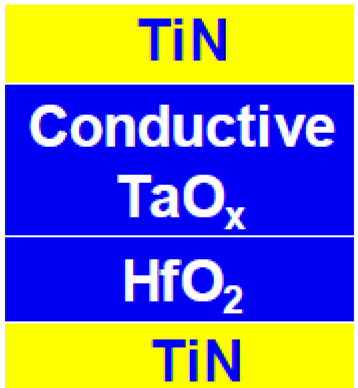


"Our observed I –V curves with current compliance higher than 20 mA, are probably in agreement with the prediction of SCLC"

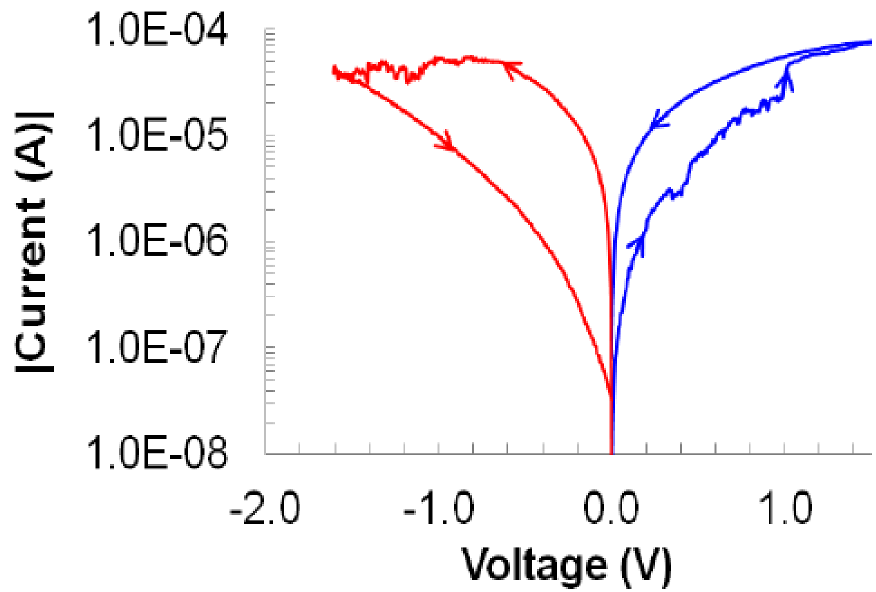
$$J = q^{1-l}\mu_p N_V \left(\frac{2l+1}{l+1}\right)^{l+1}\left(\frac{l}{l+1}\frac{\varepsilon_0\varepsilon_r}{N_t}\right)^{l}\frac{V^{l+1}}{d^{2l+1}}$$

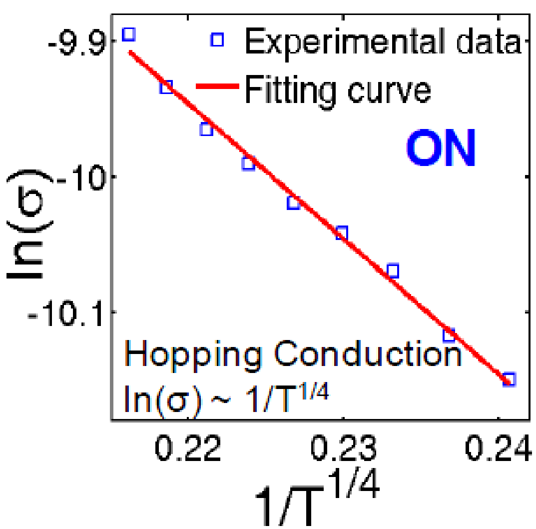
SCLC has a precise dependence with oxide thickness !!!

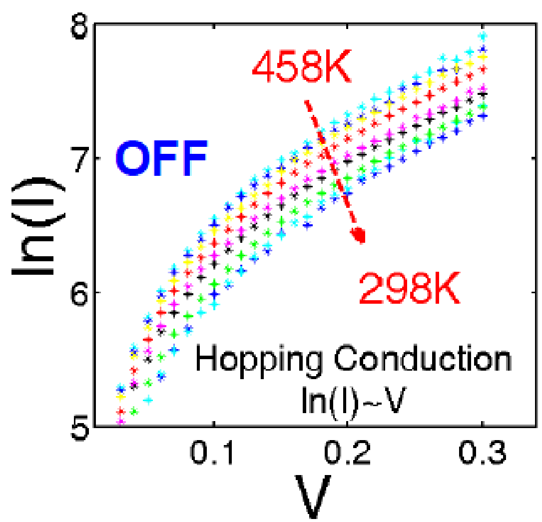
Hopping conduction



Conductive Metal Oxide (CMO) believed to be a current limiter







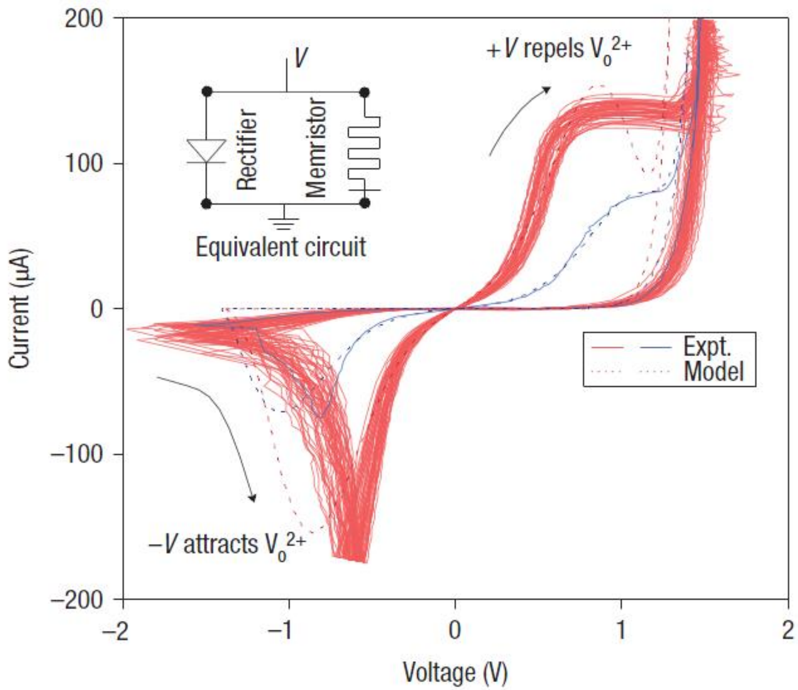
"Explored fit of 1kb data with Schottky, Frenkel Poole, hopping models. Hopping gave the best fit."

Sekar, IEDM (2014)

Tunneling + diode

“…which was chosen more for its simplicity and ability to reproduce the I-V behaviour than as a detailed physics model.”

J. Joshua Yang *et al*, Nat Nano (2008)



$$I = w^n \beta \sinh(\alpha V) + \chi(\exp(\gamma V) - 1)$$

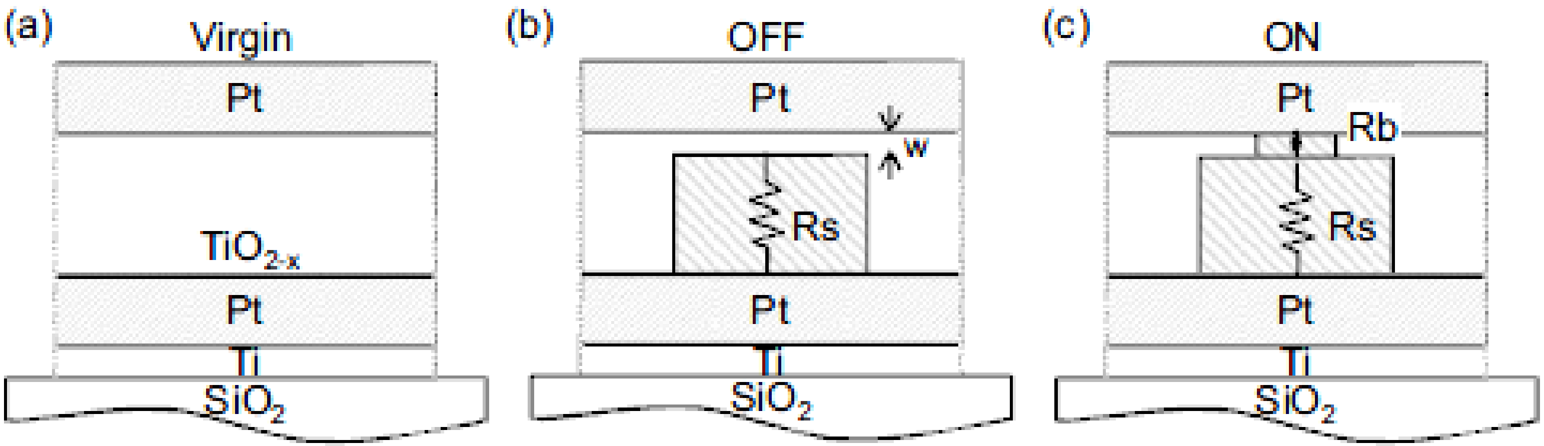
tunneling through a thin residual barrier; w is the state variable of the memristor

I-V approximation for the diode-like rectifier

Both LRS and HRS states are treated as separate entities

Tunneling + diode

Electroformed TiO_2 memristive switch



"… *transition between a nearly ohmic LRS and a HRS characterized by conduction through a barrier of width W*."

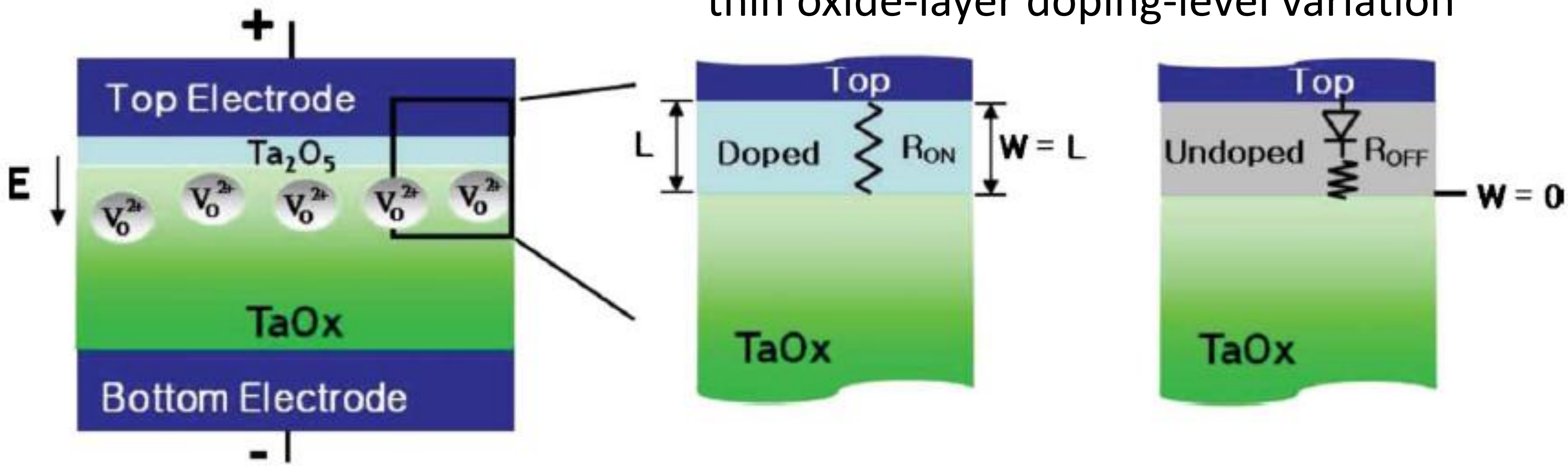
Diode-like conduction with series resistance

$$i = i_0 \left[\exp\left(\frac{v - iR_S}{v_0} \right) - 1 \right]$$

Borghetti *et al*, JAP (2009)

Schottky barrier modulation

thin oxide-layer doping-level variation



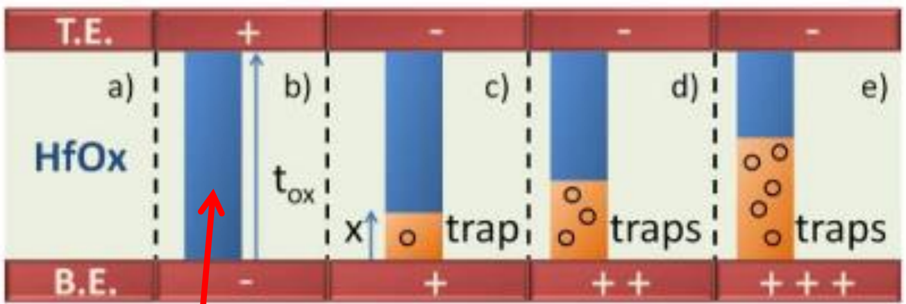
LRS **HRS**

$$I(t) = \begin{cases} I_0\left[\exp\left\{\dfrac{q}{\eta kT}[V(t) - I(t)R(t)]\right\} - 1\right] & \text{for } V > 0 \\ I_0 & \text{for } V < 0 \end{cases}$$

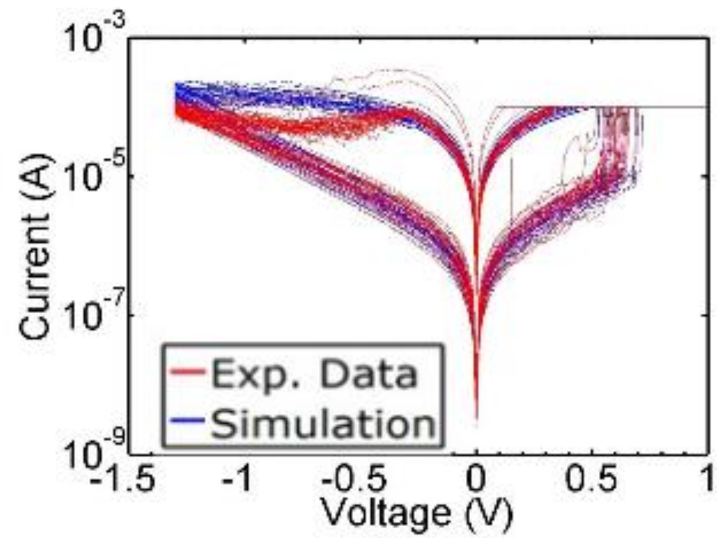
"The system can be described by electric conduction through a Schottky barrier connected in series with a variable resistance R"

J. Hur *et al*, PR (2010)

Resistance modulation + trap assisted tunneling



x: barrier thickness



$$R_{SET} = \rho_{CF}\frac{t_{OX}}{S}$$

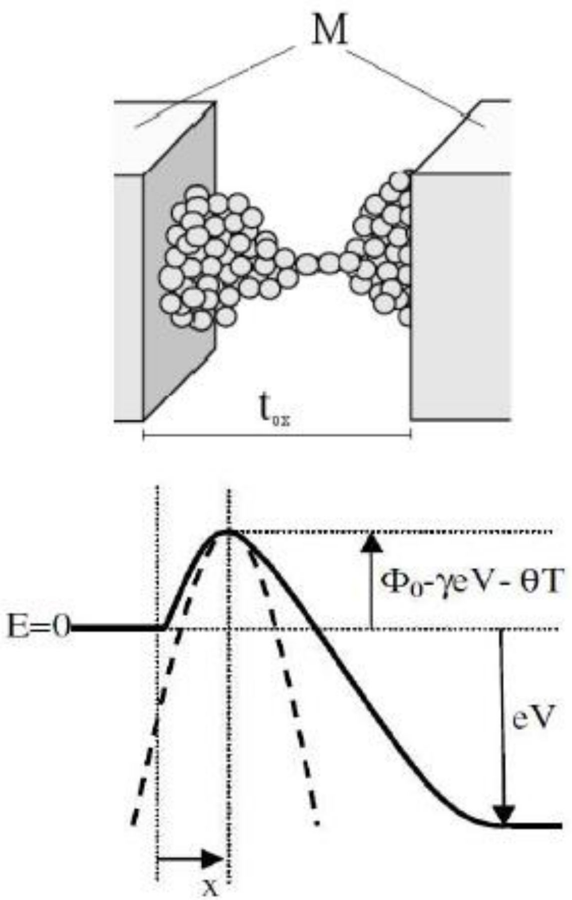
$$R(x,T) = R_{SET}\left(\frac{t_{OX}-x}{t_{OX}}\right) + R_{SET}\left[e^{\left(\frac{x}{k}\right)} - 1\right] \cdot F_T$$

Temperature dependence of the current in the barrier (TAT)

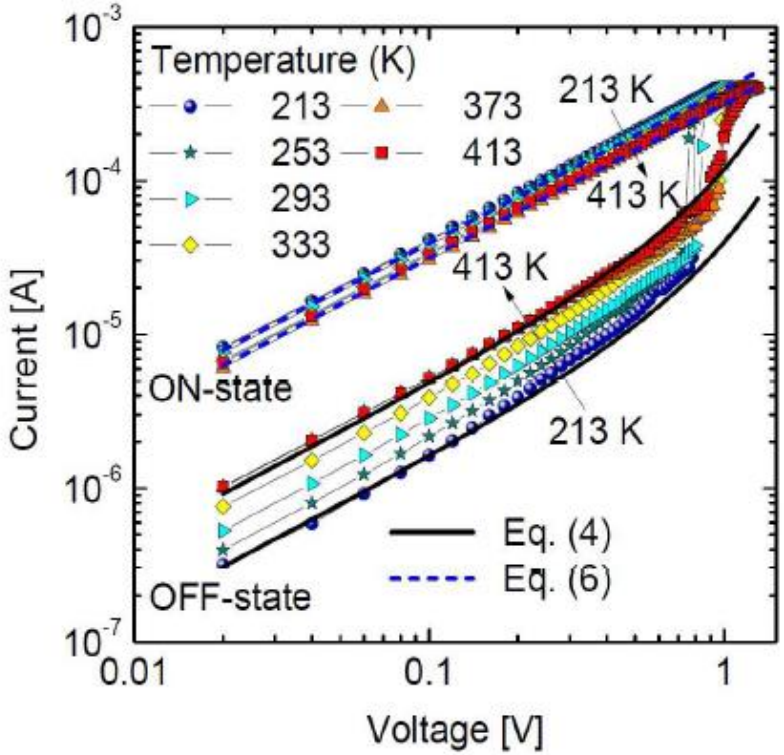
$$F_T(T) = e^{\frac{E_R}{k_B T}}$$

F. Puglisi *et al*, EDL (2013)

Quantum point-contact (QPC) model



Modeling of the temperature dependence:

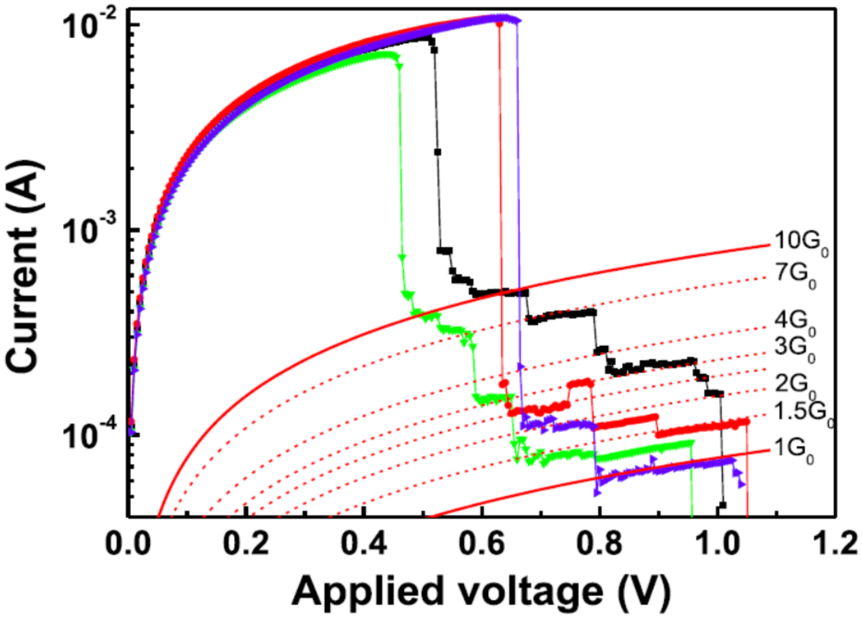


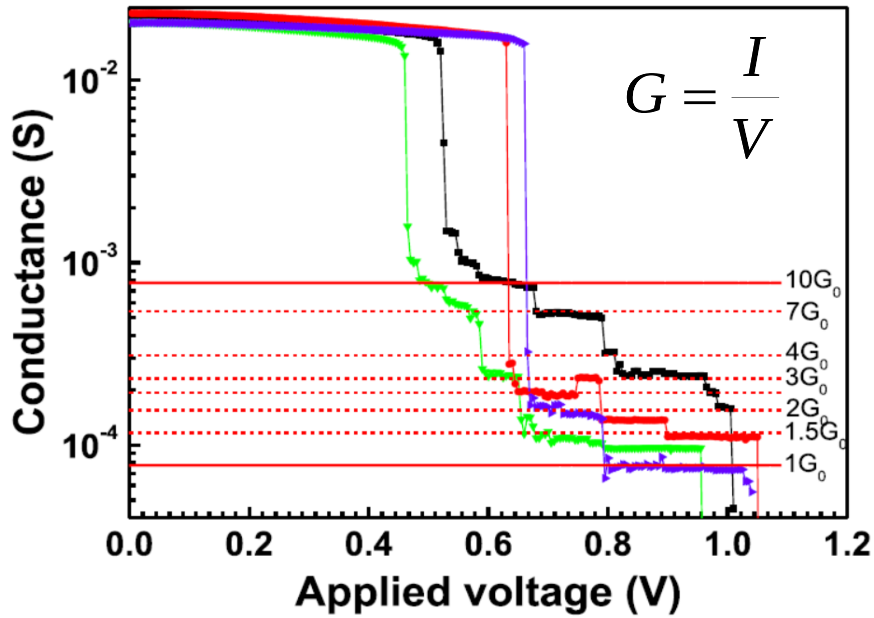
$$I_{OFF} = \frac{2e}{\alpha h} \frac{\exp[-\alpha(\Phi_0 - \gamma eV - \theta T)]}{\mathrm{sinc}(\pi \mathrm{k} \mathrm{T} \alpha)} [1 - \exp(-\alpha eV)]$$

C. Walczyk *et al*, TED (2011)

Formation of a quantum wire

Conductance steps measured in the RESET process of a unipolar Pt/HfO_2/Pt RRAM device





$$G = \frac{I}{V}$$

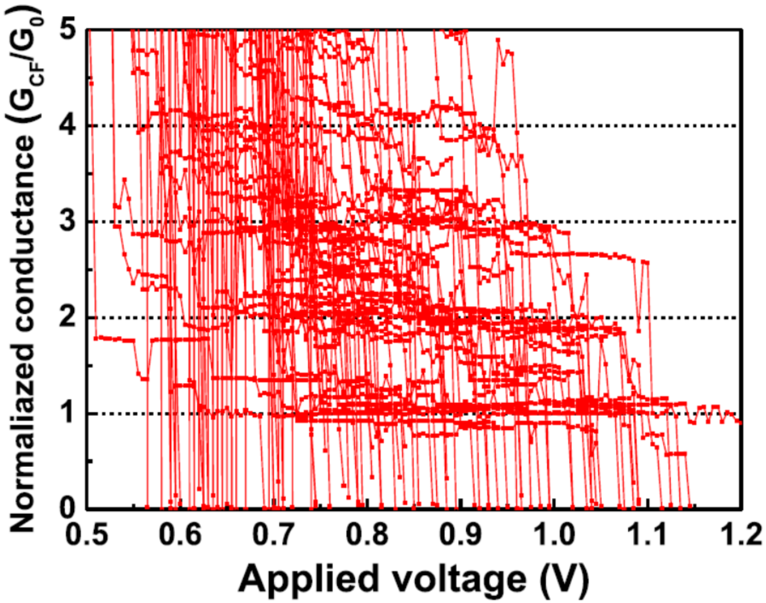
$$\boxed{G_0 = \frac{2e^2}{h}}$$

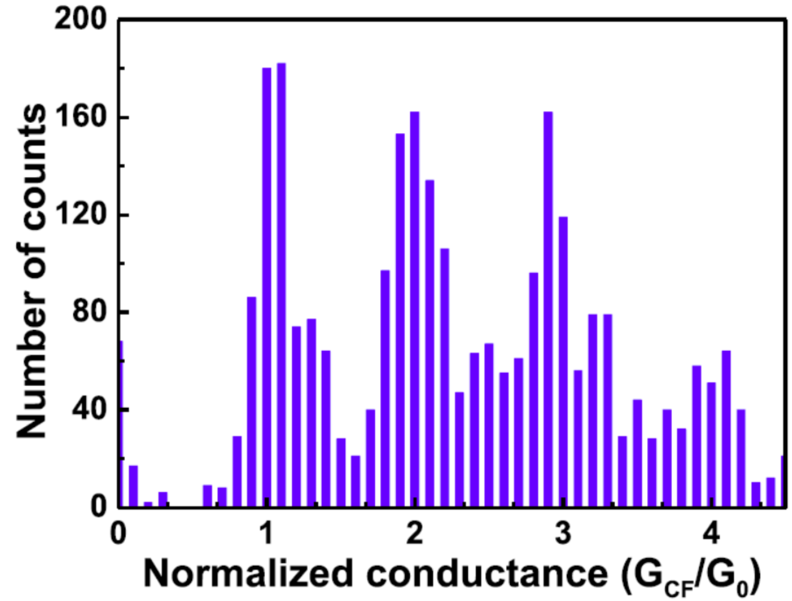
Quantum conductance unit

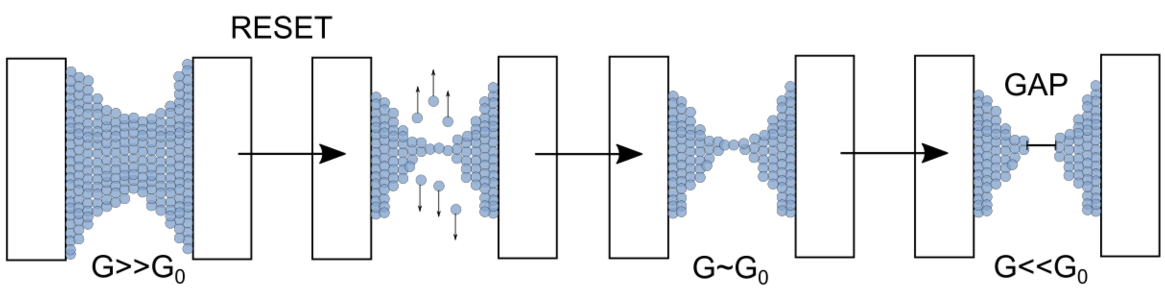
$$R_0 = G_0^{-1} = 12.9\ \mathrm{K}\Omega$$

Resistance of a monomode ballistic conductor

Formation of a quantum wire



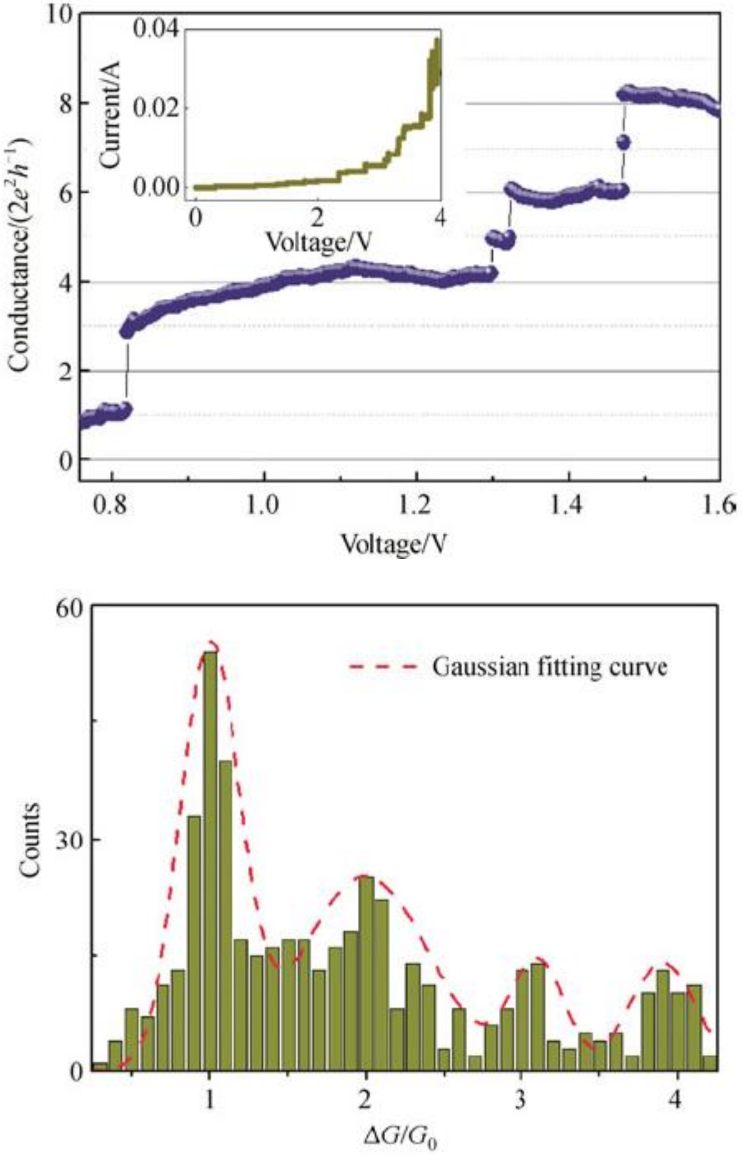




"The peaks at roughly integer multiples of G_0 can either be due to the CF behaving as a QW or to a nanoscale CF cross section corresponding to few atomic-size conducting defects."

J. Suñé *et al*, JAP (2012)

Conductance quantization in RS devices

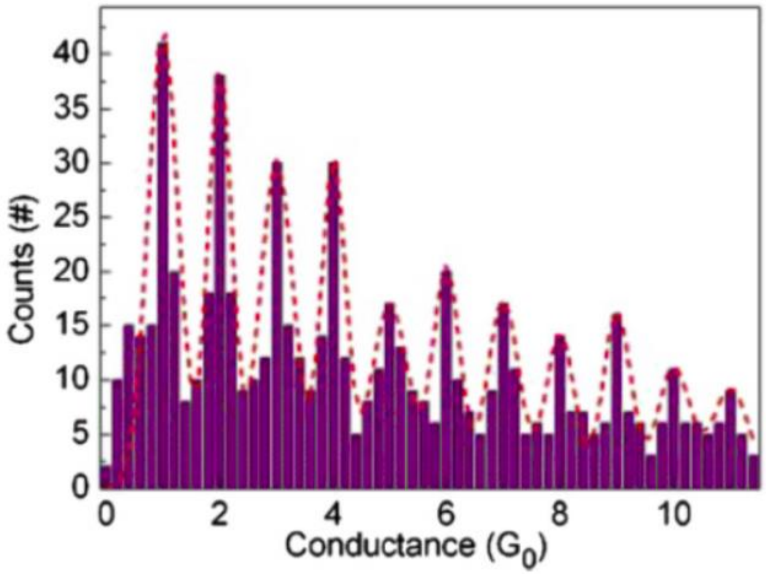


- **Bipolar RS in Nb/ZnO/Pt**

"*Statistics count of the conductance changes from two hundred curves confirms the quantum conductance behaviors, which demonstrates the formation of discrete quantum channels in the device*"

X. Zhu *et al*, Adv. Mater. (2012)

Conductance quantization in RS devices

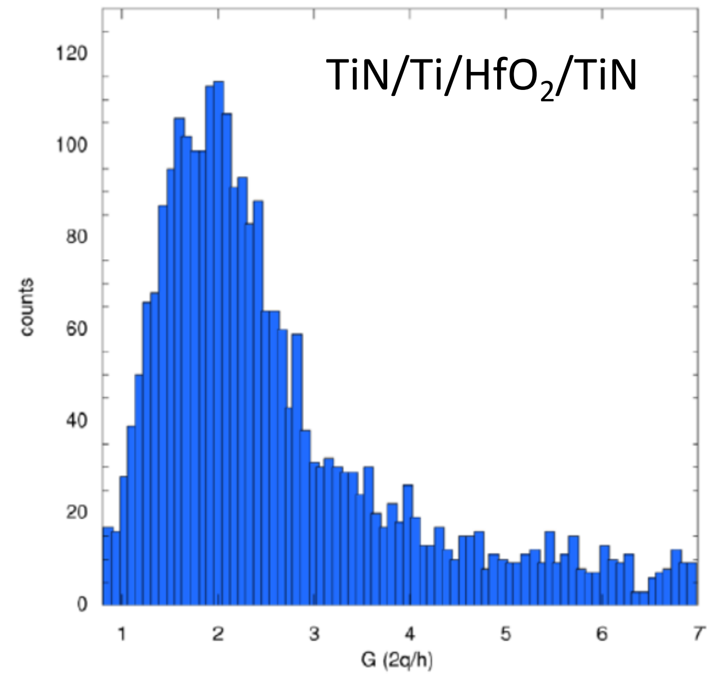


Data extracted from pulsed measurements on $Ti/Ta_2O_5/Pt$ cells

C. Chen *et al*, APL (2015)

"*Fluctuations are likely due to the fluctuation of filament geometry and then the fluctuation of the number of atoms in the contention*."

S. Blonkowski *et al*, J. Phys. D (2015)

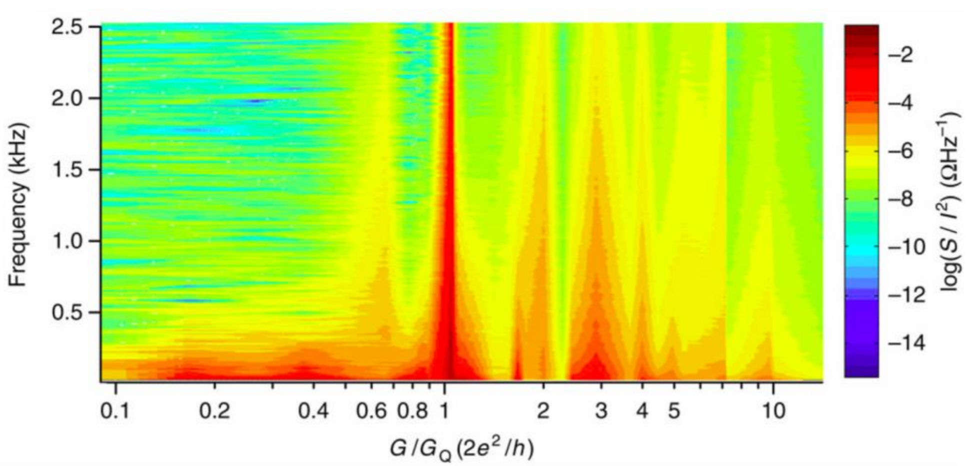


NATURE COMMUNICATIONS | ARTICLE OPEN

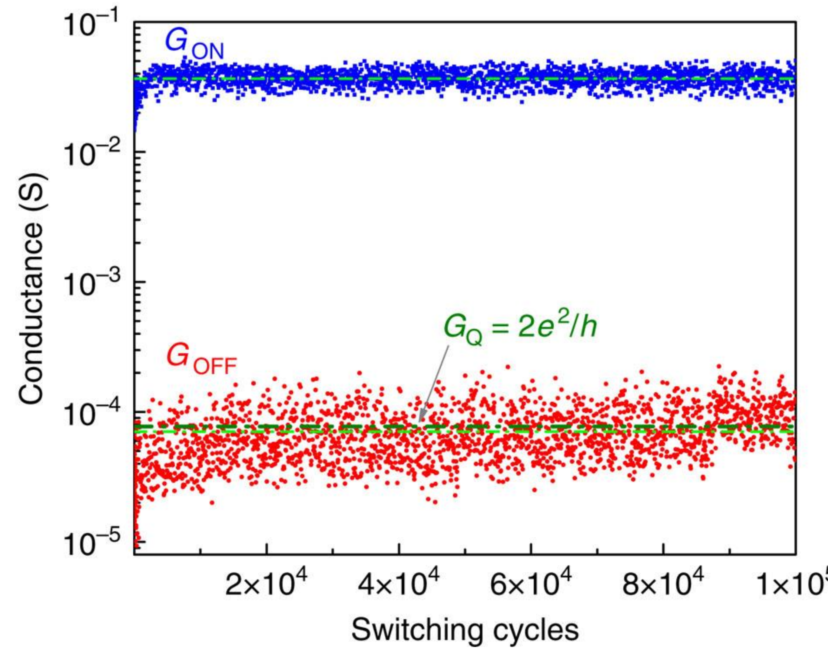
Quantized conductance coincides with state instability and excess noise in tantalum oxide memristors

Wei Yi, Sergey E. Savel'ev, Gilberto Medeiros-Ribeiro, Feng Miao, M.-X. Zhang, J. Joshua Yang, Alexander M. Bratkovsky & R. Stanley Williams

Nature Communications **7**, Article number: 11142 | doi:10.1038/ncomms11142
Received 25 August 2015 | Accepted 25 February 2016 | Published 04 April 2016



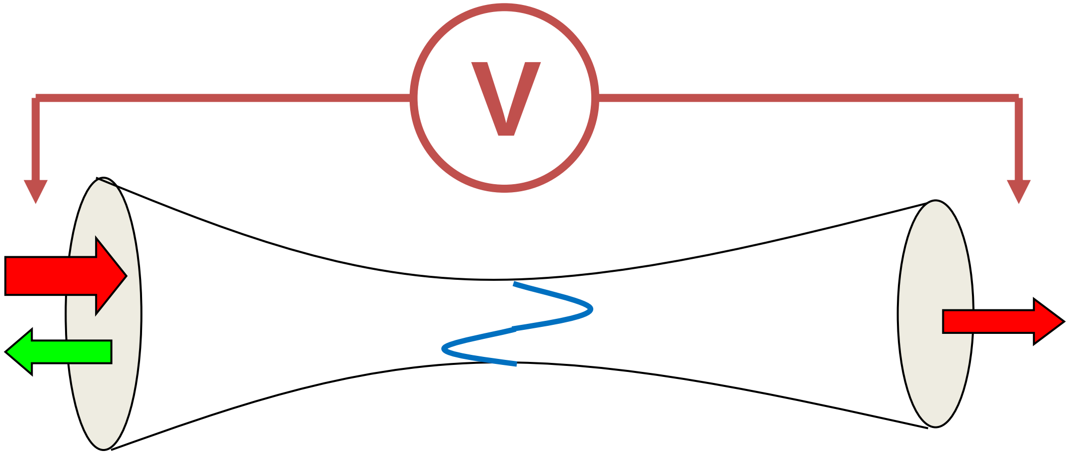
Large peak in the noise amplitude at the conductance quantum G_Q=$2e^2/h$



The Landauer approach

As occurs in a potential well, a narrow constriction induces the lateral quantization of the electron wave function

R. Landauer, 1927-1999



T∓1

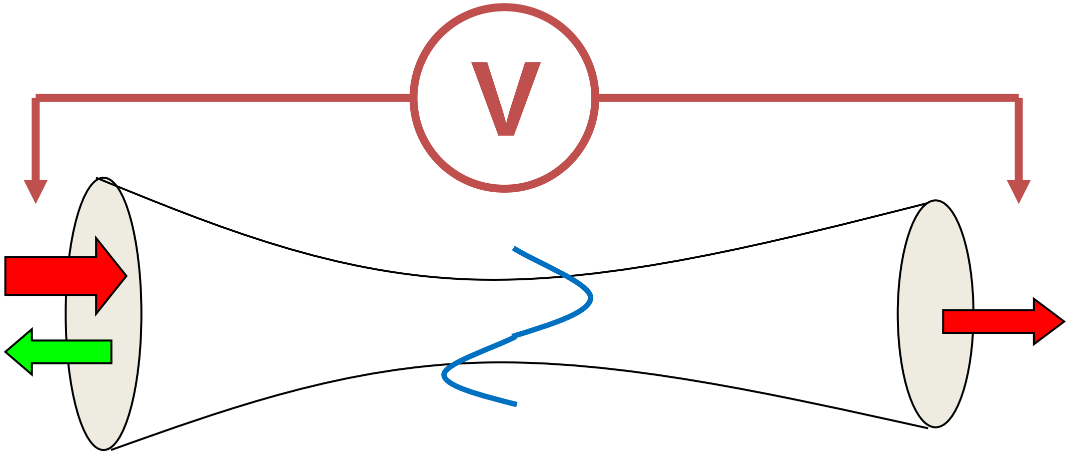
T: transmission probability

V: applied voltage

The Landauer approach


R. Landauer, 1927-1999

As occurs in a potential well, a narrow constriction induces the lateral quantization of the electron wave function



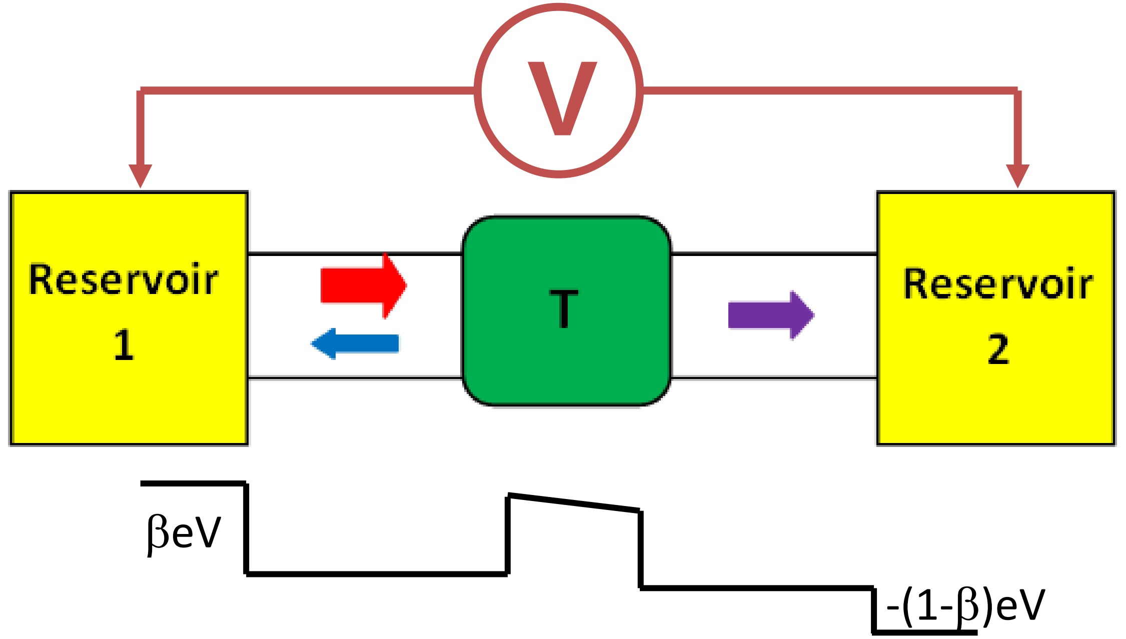
T<1

T: transmission probability

V: applied voltage

$$I = G_0 T V \quad \Rightarrow \quad G = \frac{dI}{dV} = G_0 T \;\overset{\text{Ballistic Conductor}}{\underset{T=1}{\Longrightarrow}}\; G = G_0$$

Finite-bias Landauer approach



T: transmission probability

V: applied voltage

$$I = \frac{2e}{h}\int_{-\infty}^{+\infty} T(E)\{f[E-\beta eV] - f[E+(1-\beta)eV]\}dE$$

β: fraction of the potential that drops at the source side 0<β<1

T: Transmission probability

f: Fermi function

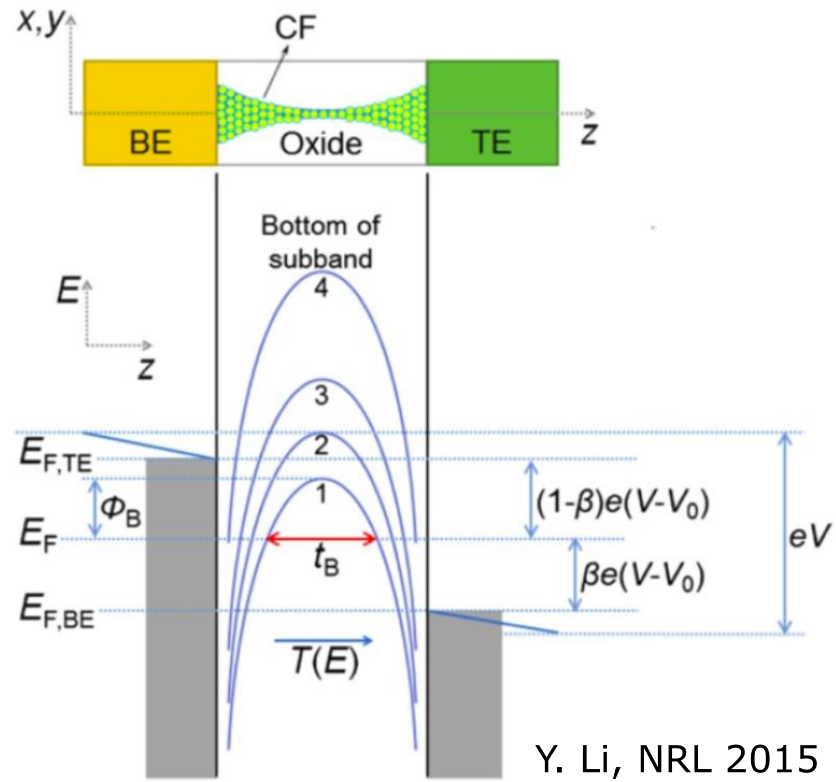
Quantum point contact model for dielectric breakdown

Constriction

(parabolic-shaped)

Potential barrier

(not material)



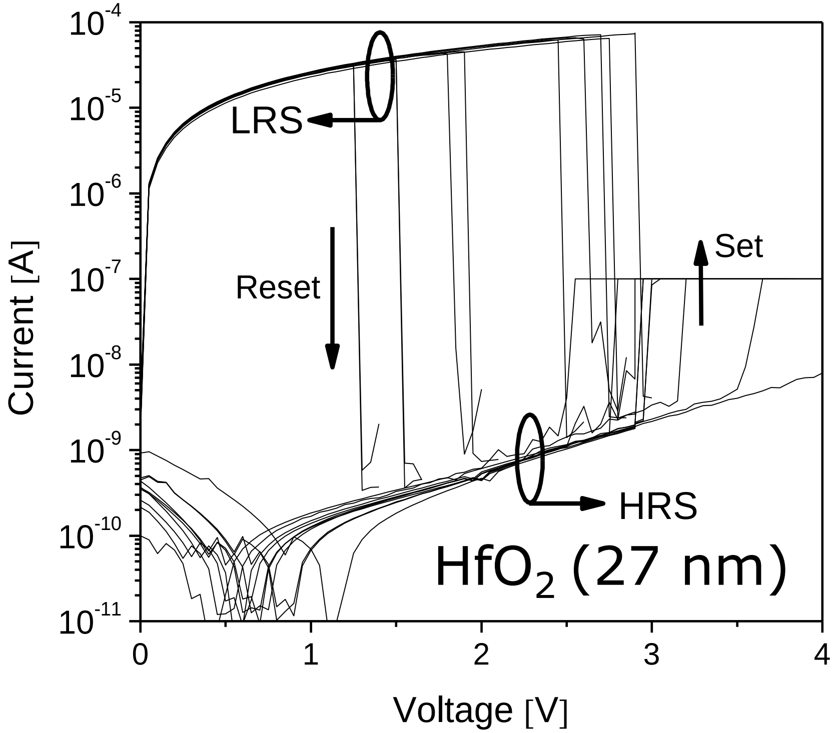
Y. Li, NRL 2015

$$I(V)=\frac{2e}{h}\left\{e(V-V_0)+\frac{1}{\alpha}\ln\left[\frac{1+\exp\{\alpha[\Phi-\beta e(V-V_0)]\}}{1+\exp\{\alpha[\Phi+(1-\beta)e(V-V_0)]\}}\right]\right\}$$

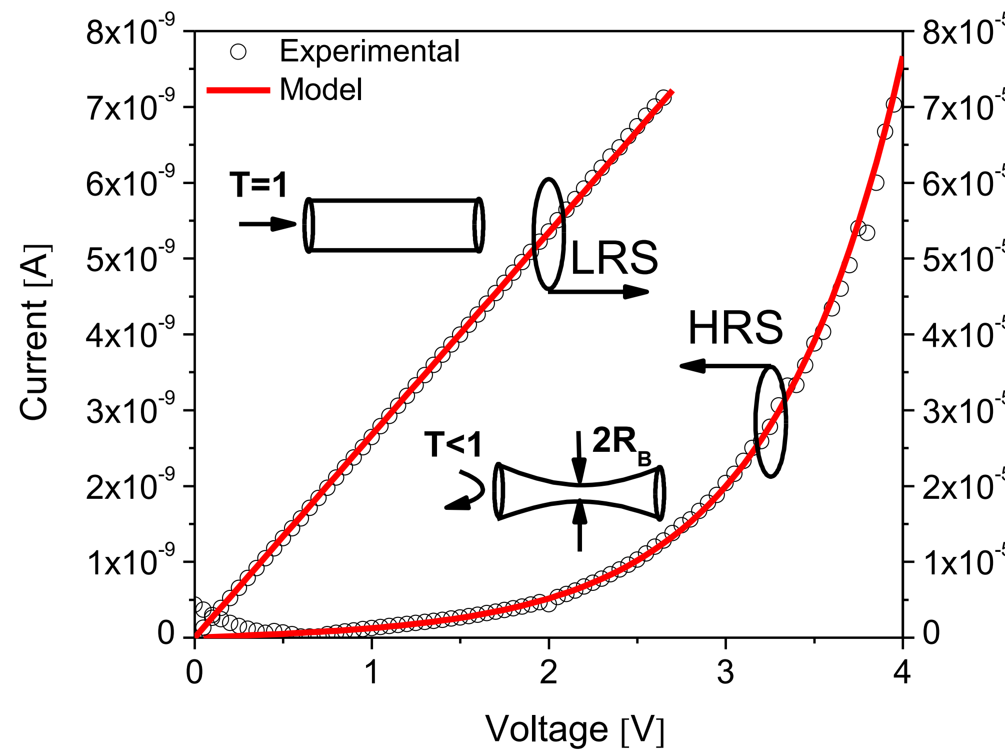
Miranda & Suñé, IEDM'00, IRPS'01

Application to Au/HfO_2/TiN RS structures

EXPERIMENTAL RESULTS



MODEL

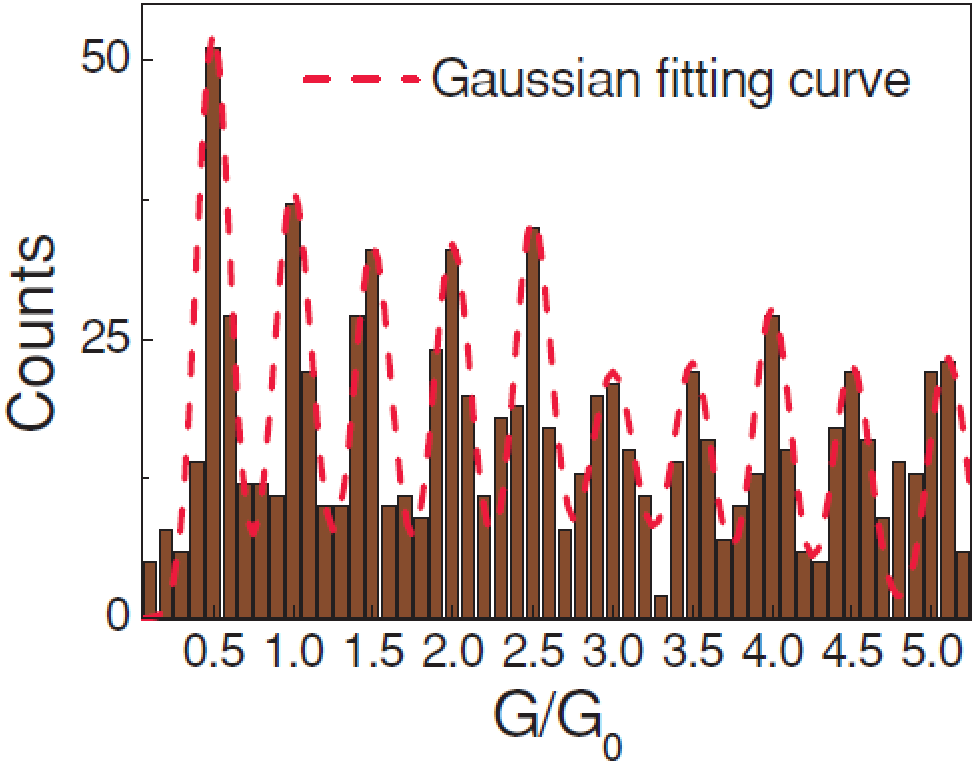


The constriction's cross-section determines the conduction mode: HRS or LRS

E. Miranda *et al*, EDL (2010), *in collaboration with IHP, Germany*

Nonlinear conductance quantization effects

ITO/ZnO/ITO

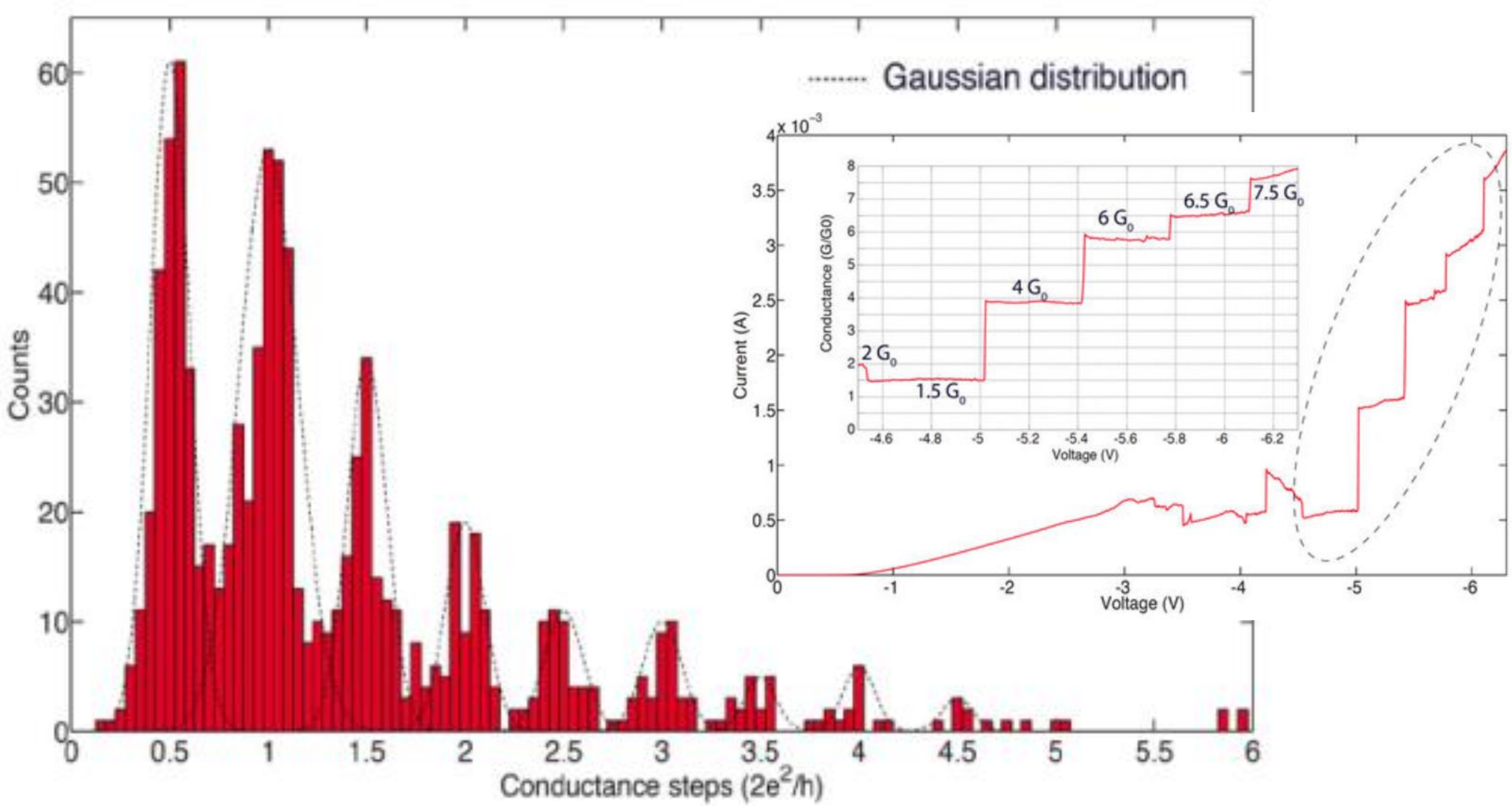


" …this conductance quantization behavior is a universal feature in filamentary-based RRAM devices."

X. Zhu *et al*, Adv. Mater. (2012)

Peaks are also observed at half-integer multiples of G_0

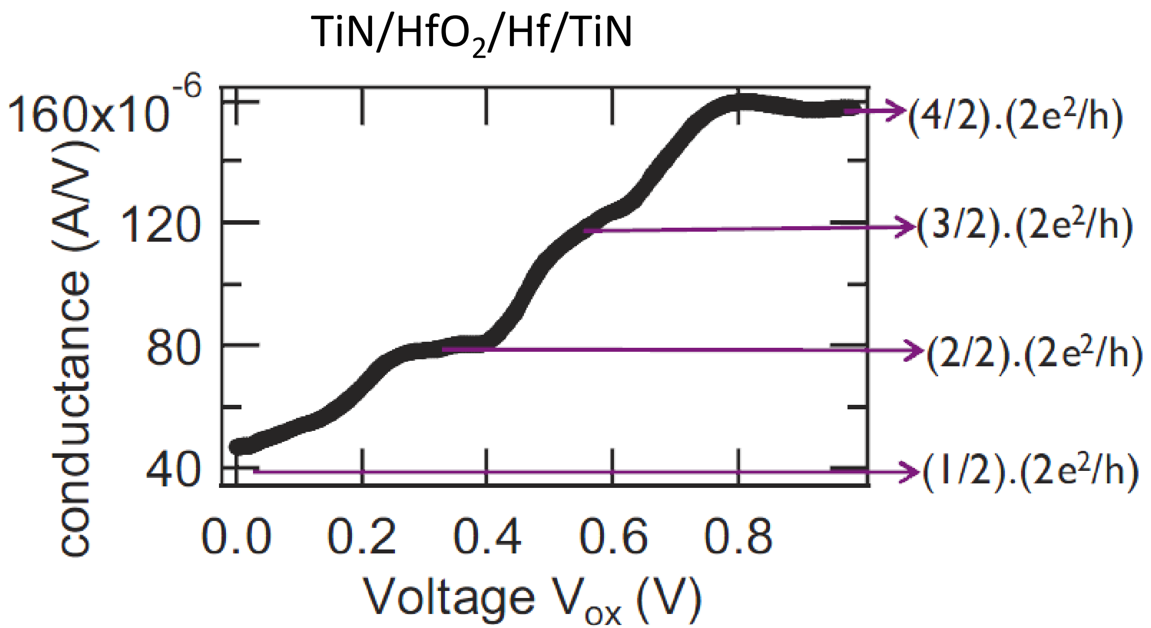
Nonlinear conductance quantization effects



Histogram of conductance changes collected from the SET characteristic of SiO_x-based ReRAM devices

A. Mehonic *et al*, Sci Rep (2012)

Nonlinear conductance quantization effects



IMEC:

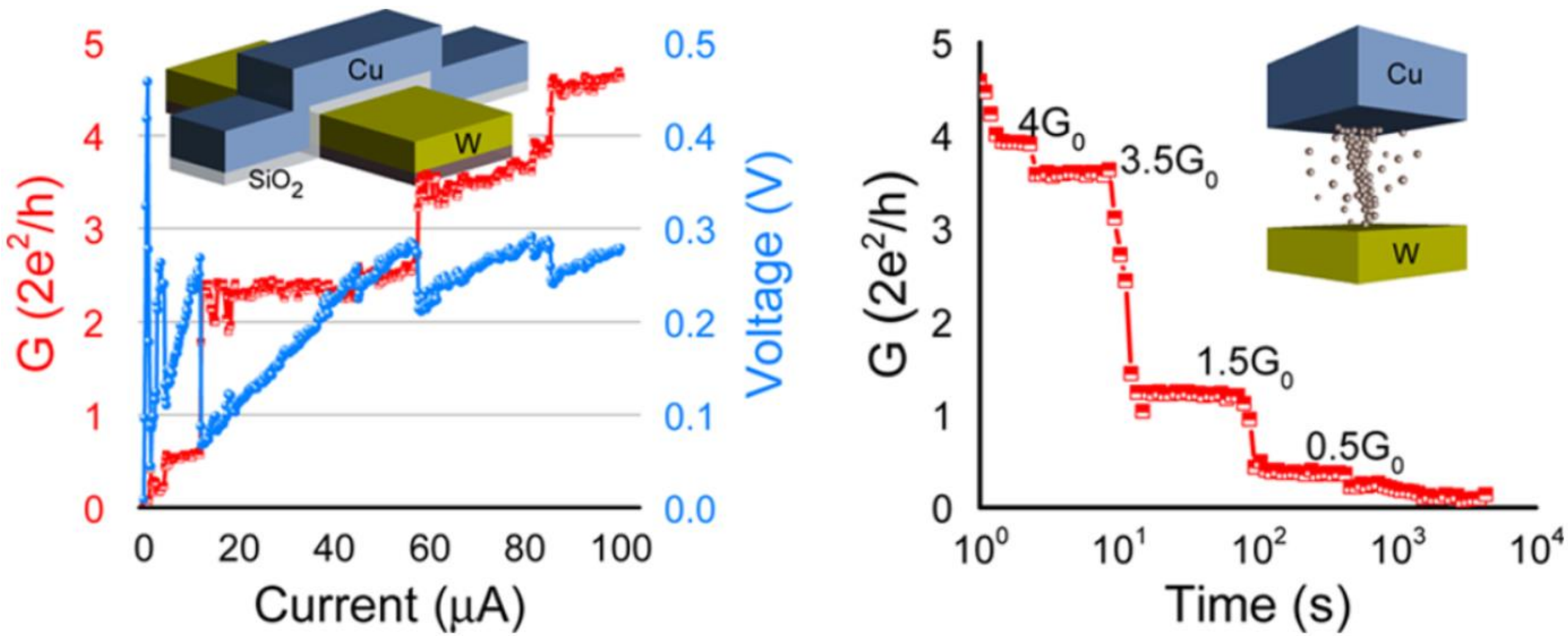
The conductance plateaus correspond to integer and half integer multiples of $2e^2/h$

"*These observations confirm the picture of filament conduction being controlled by electron transmission through discrete energy levels*."

R. Degraeve *et al*, IEEE (2012)

Nonlinear conductance quantization effects

Cu/SiO_2/W memristor with half-integer quantum conductance states

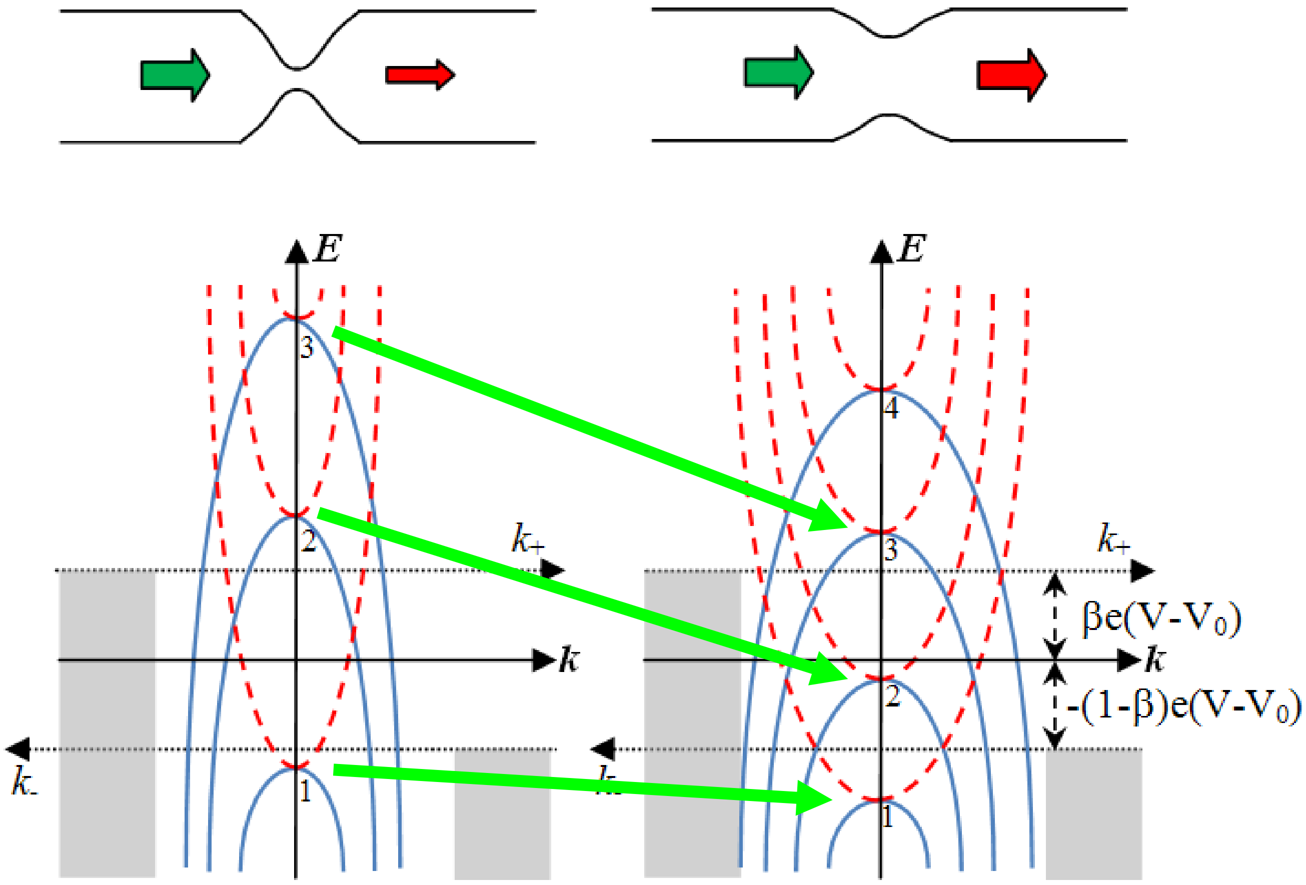


"This is attributed to the nanoscale filamentary nature of Cu conductance pathways formed inside SiO_2."

S. R. Nandakumar *et al*, Nano Lett (2016)

Subbands in tube-like constrictions

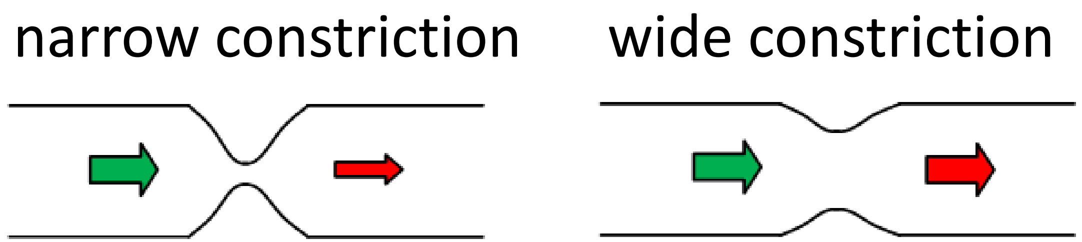
narrow constriction **wide constriction**



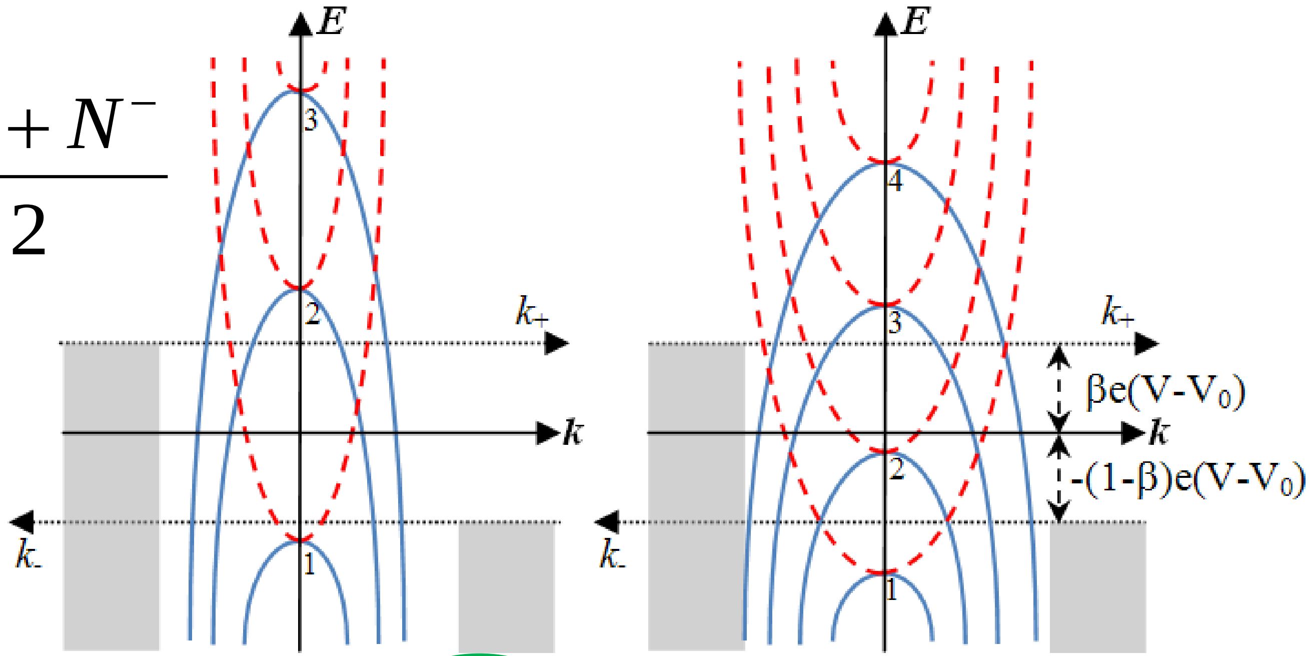
Blue: longitudinal bands **Red: transversal bands**

E. Miranda *et al*, APL (2012)

Subbands in tube-like constrictions

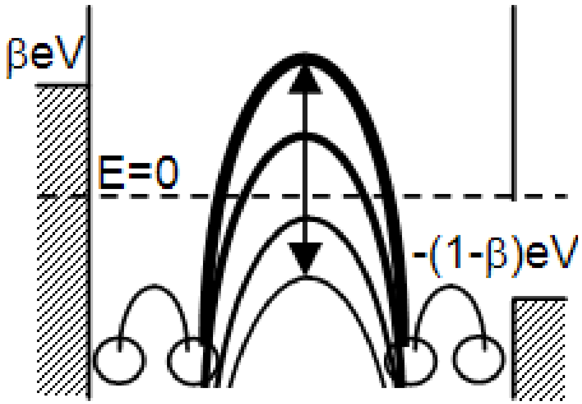


$$N = \frac{N^+ + N^-}{2}$$



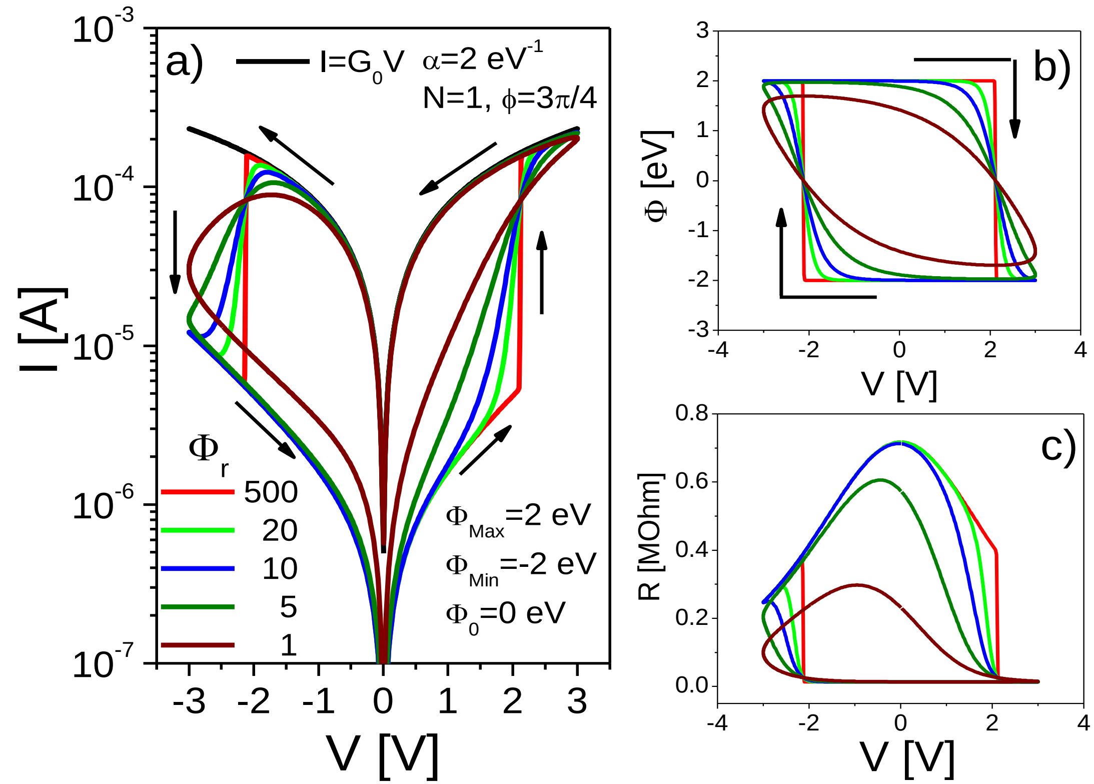
$N^+ = 1 \,\&\, N^- = 1 \Rightarrow N = 1$ $\quad$ $N^+ = 2 \,\&\, N^- = 1 \Rightarrow N = 3/2$

The quantum point-contact memristor



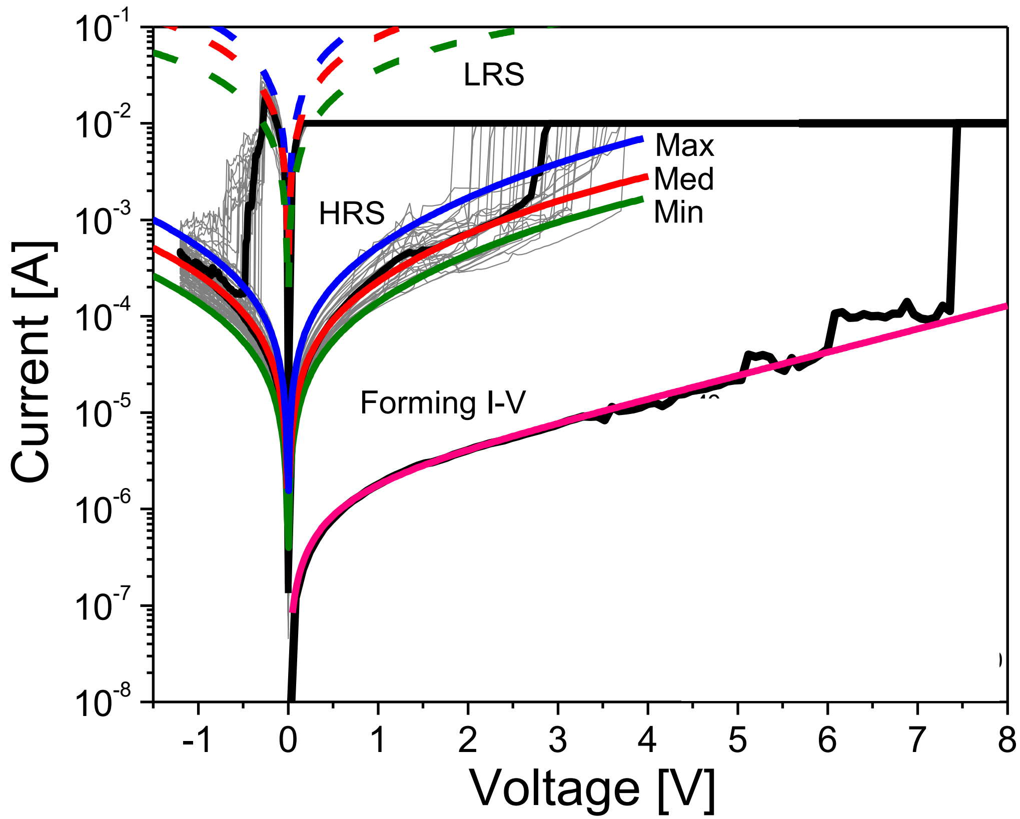
Modulation of the barrier height/width caused by the movement of atoms/vacancies

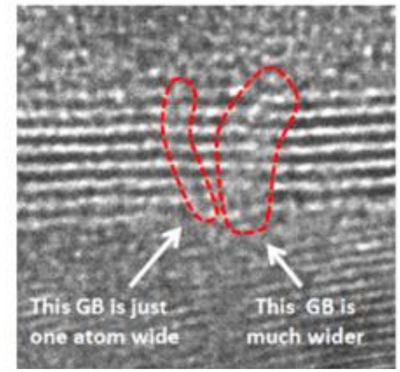
Generation of the hysteretic loop in the I-V characteristic of RS devices

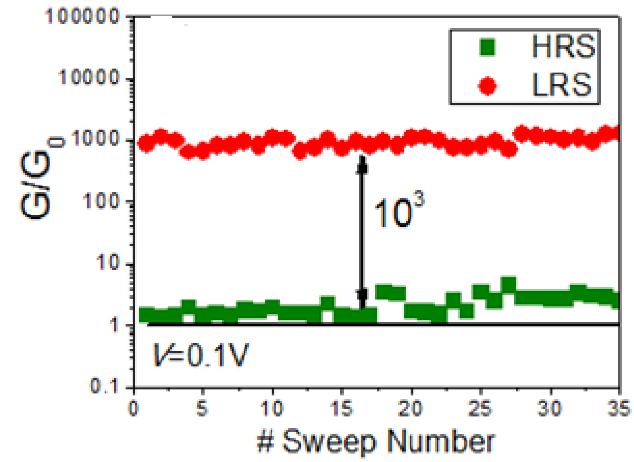


E. Miranda *et al*, EDL (2012)

Filamentary conduction in Graphene/h-BN/Graphene







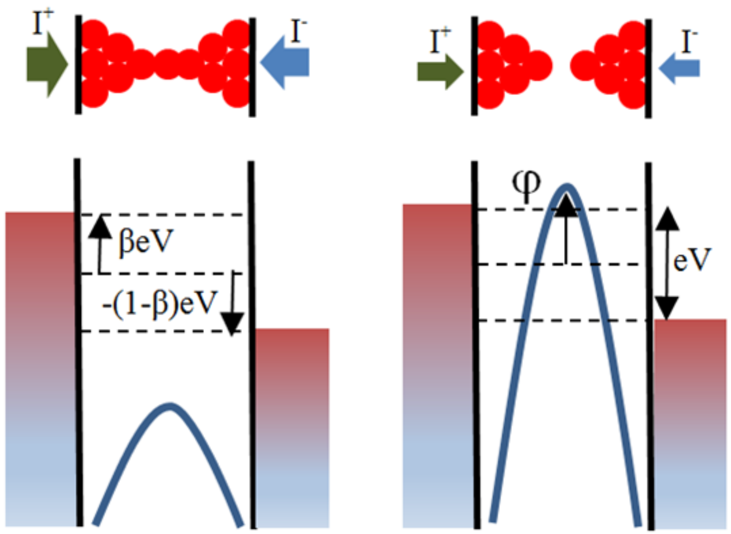
$$I = G_0 n(V - IR_S) + \frac{2e(N-n)}{\alpha h} \exp(-\alpha\varphi)\{exp[\alpha e(V - IR_S)] - 1\}$$

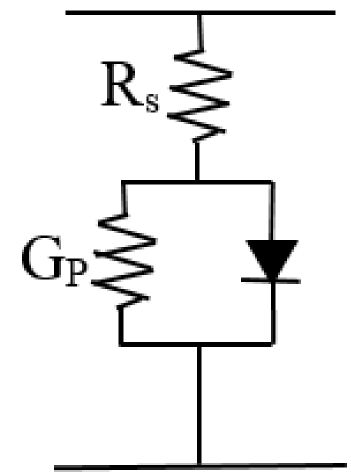
N: number of filaments *n:* number of completely formed filaments

C. Pan *et al*, 2D Materials (2017)

Equivalent electrical circuit model

$$I = G_0 n(V - IR_S) + \frac{2e(N-n)}{\alpha h}\exp(-\alpha\varphi)\{exp[\alpha e(V - IR_S)] - 1\}$$





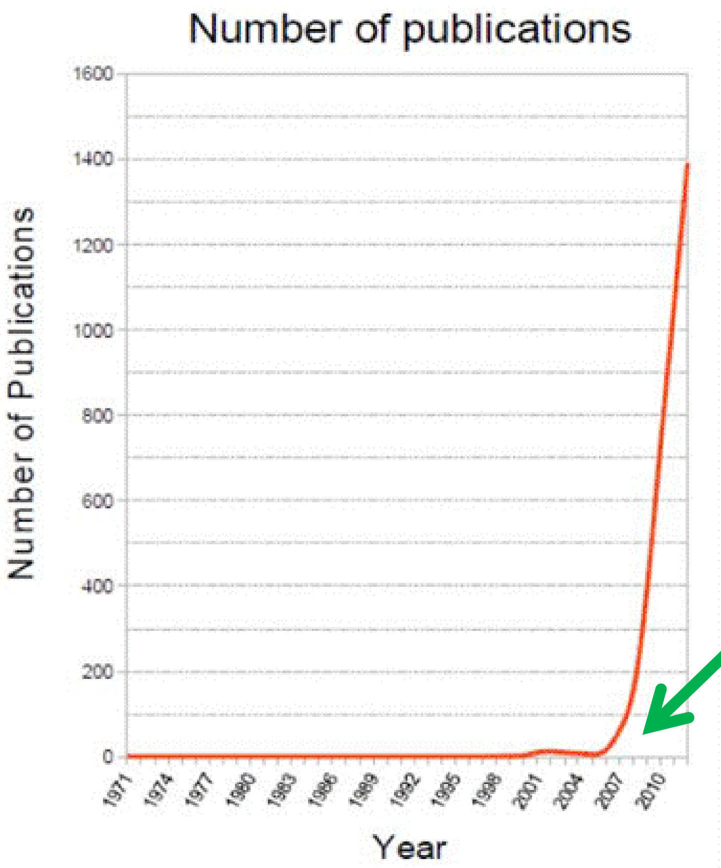
$$I = G_P(V - IR_S) + I_0\{exp[\alpha(V - IR_S)] - 1\}$$

This is the starting point of our own memristive approach

Outline

- Introduction to filamentary-type ReRAM
- Physical models and quantum limit
- The circuital approach
- Model implementation
- The problem of variability
- Final comments

2008 HP's breakthrough



Accumulated number of reports on memristor since 1971

A practical implementation of a memristor?

nature Vol 453 | 1 May 2008 | doi:10.1038/nature06932

LETTERS

The missing memristor found

Dmitri B. Strukov[1], Gregory S. Snider[1], Duncan R. Stewart[1] & R. Stanley Williams[1]

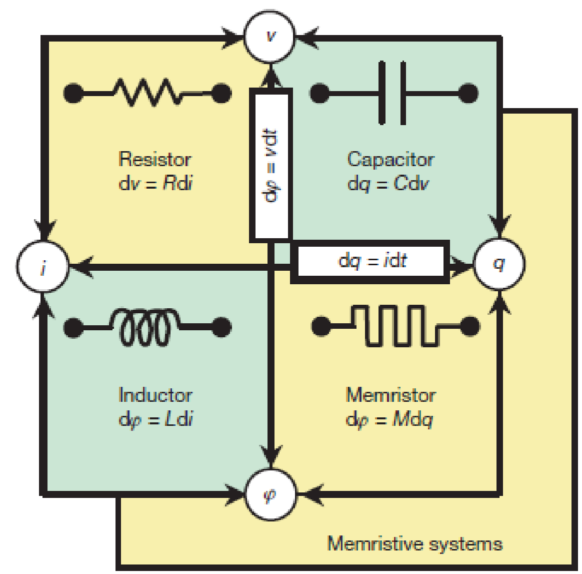


Figure 1 | The four fundamental two-terminal circuit elements: resistor, capacitor, inductor and memristor. Resistors and memristors are subsets of a more general class of dynamical devices, memristive systems. Note that R, C, L and M can be functions of the independent variable in their defining equations, yielding nonlinear elements. For example, a charge-controlled memristor is defined by a single-valued function $M(q)$.

As time goes by…

SCIENTIFIC REPORTS

The Missing Memristor has Not been Found

Sascha Vongehr & Xiangkang Meng (2015)

Many researchers have raised serious doubts!

- *"The devices were not new and the hypothesized device needs magnetism"*
- *"The originally hypothesized memristor device is missing and likely impossible"*
- *"The originator of the prediction accepted the discovery"*

and more recently …

SCIENTIFIC REPORTS

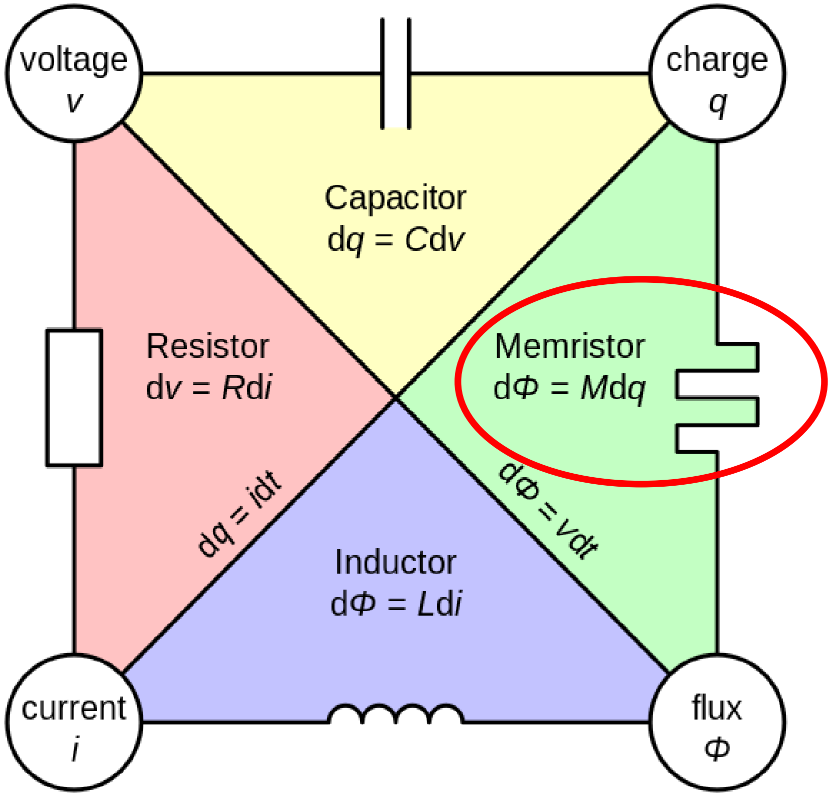
The case for rejecting the memristor as a fundamental circuit element

Isaac Abraham (July 2018)

Many researchers have raised serious doubts!

- *"The ideal memristor is an unphysical active device and any physically realizable memristor is a nonlinear composition of resistors with active hysteresis."*
- *"We also show that there exists only three fundamental passive circuit elements."*

Memristors



- Four fundamental quantities: *i*, *v*, *q*, *Φ*
- 5 out of 6 pairwise relations known very well
- Using symmetry arguments Prof. Chua (1971) proposed the missing link: MEMRISTOR
- Memristor = Memory + Resistor
- *M*: Memristance

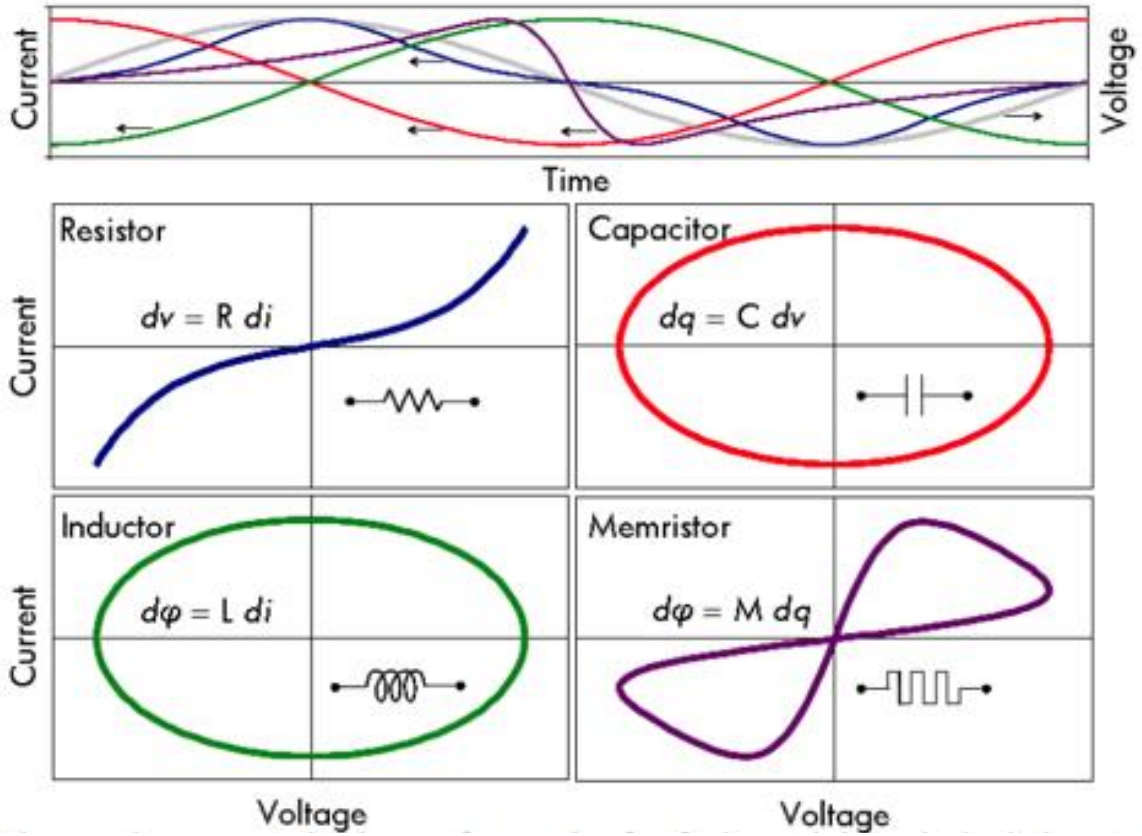
$$V(t) = M(w)I(t)$$

M depends on the hystory of the device and retains its value even if the power is turned off

Picture taken from Parcly Taxel

Response to a sinusoidal excitation

Unlike capacitors and inductors, MEMRISTORS do not store energy



MEMRISTORS cannot be constructed by combining the other devices and are characterized by “pinched” Lissajous curves

Memristive devices

- Memristive devices are defined in terms of two coupled equations:

$$y(t) = g(x,u,t)u(t)$$

$$\frac{dx}{dt} = f(x,u,t)$$

u(t) is the input signal (current or voltage)

y(t) is the output signal (voltage or current)

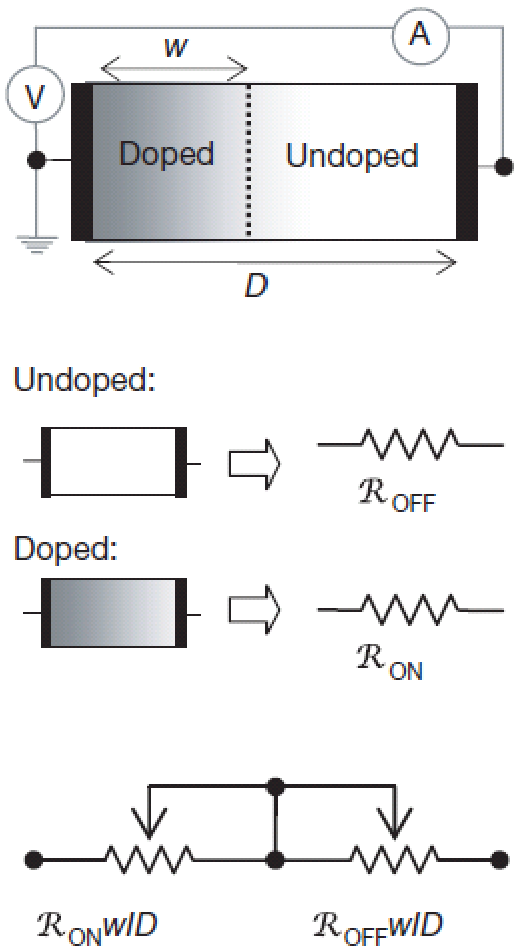
x is the variable which describes the state of the device

g and *f* are continuous functions

- If both *g* and *f* are linear functions $\Rightarrow$ linear memristive system

Chua and Kang, Proc IEEE **64**, 209 (1976)

HP memristor model (2008)



- TiO_2 film (*D*) has a region with a high concentration of dopants (R_{ON}) and a region with a low concentration (R_{OFF})
- *V(t)* across the device moves the boundary *w* between the two regions by causing the charged dopants to drift

Transport Equation

$$V(t) = R(\lambda) I(t)$$

$$\lambda = w / D \qquad R(\lambda) = R_{ON}\lambda + R_{OFF}(1-\lambda)$$

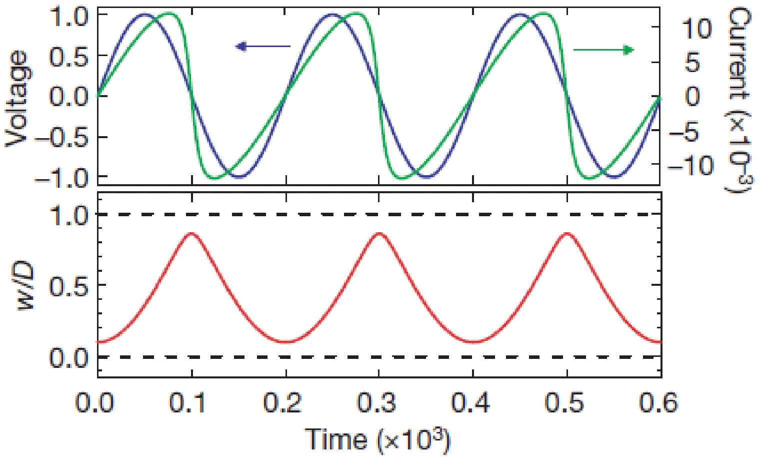
State Equation

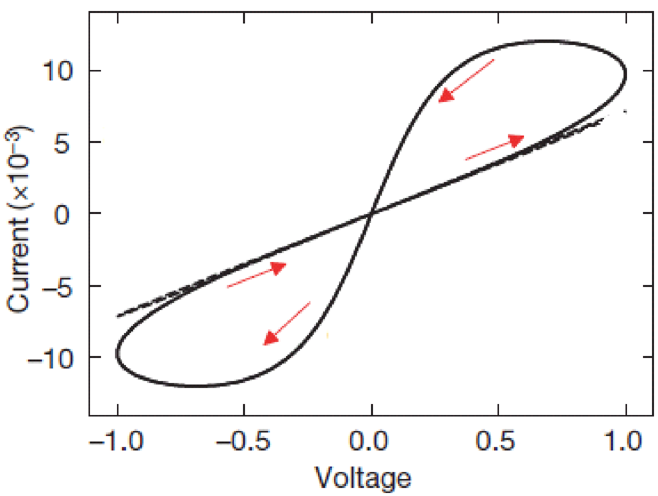
$$\frac{d\lambda}{dt} = \eta I(t)$$

Strukov *et al,* Nature **453**, 80 (2008)

Introduction of the window function

Simulation results using HP model





$$V(t) = R(\lambda) I(t)$$

$$R(\lambda) = R_{ON}\lambda + R_{OFF}(1-\lambda)$$

$$\frac{d\lambda}{dt} = \eta \underbrace{\lambda(1-\lambda)}_{\text{window function (\textit{ad hoc})}} I(t)$$

$$f(0) = f(1) = 0$$

- *Introduced to control the state variable at the turning points*
- *Introduction of window functions can lead to serious mathematical problems*

Some window functions

Strukov/Benderli (2008)

$$f_B(\lambda) = \lambda(1-\lambda)$$

Joglekar (2009)

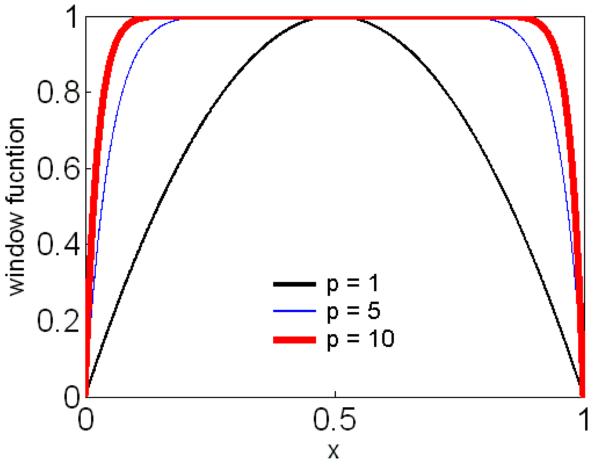
$$f_J(\lambda) = 1 - (2\lambda - 1)^{2p}$$

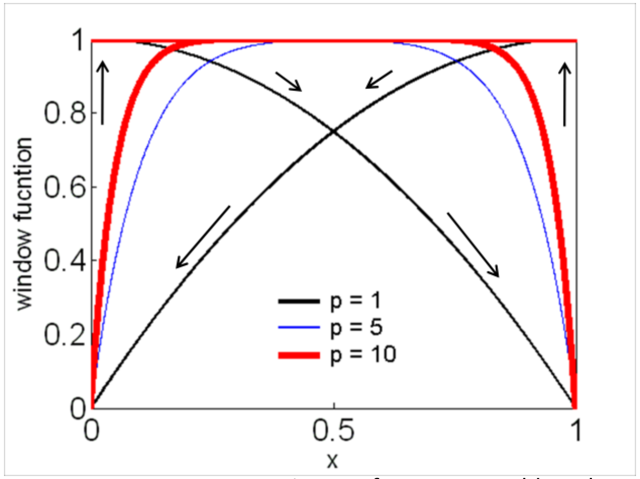
Biolek (2009)

$$f_B(\lambda) = 1 - (\lambda - H(-I))^{2p}$$

Prodromakis (2011)

$$f_P(\lambda) = \max(f)\left\{1 - \left[(\lambda - 0.5)^2 + 0.75\right]^p\right\}$$





Pictures from McDonald et al

- Required for imposing boundary conditions on λ

Memdiode equations

Transport Equation

original

$$I = V / R(\lambda)$$
$$R(\lambda) = R_{ON}\lambda + R_{OFF}(1-\lambda)$$

new

$$I = \mathrm{sgn}(V)\left[(\alpha R)^{-1} W\left\{\alpha R I_0(\lambda)\exp\left[\alpha\left(|V| + R I_0(\lambda)\right)\right]\right\} - I_0(\lambda)\right]$$
$$I_0(\lambda) = I_{0\max}\lambda + I_{0\min}(1-\lambda)$$

State Equation

original

$$\frac{d\lambda}{dt} = \eta\lambda(1-\lambda)I$$

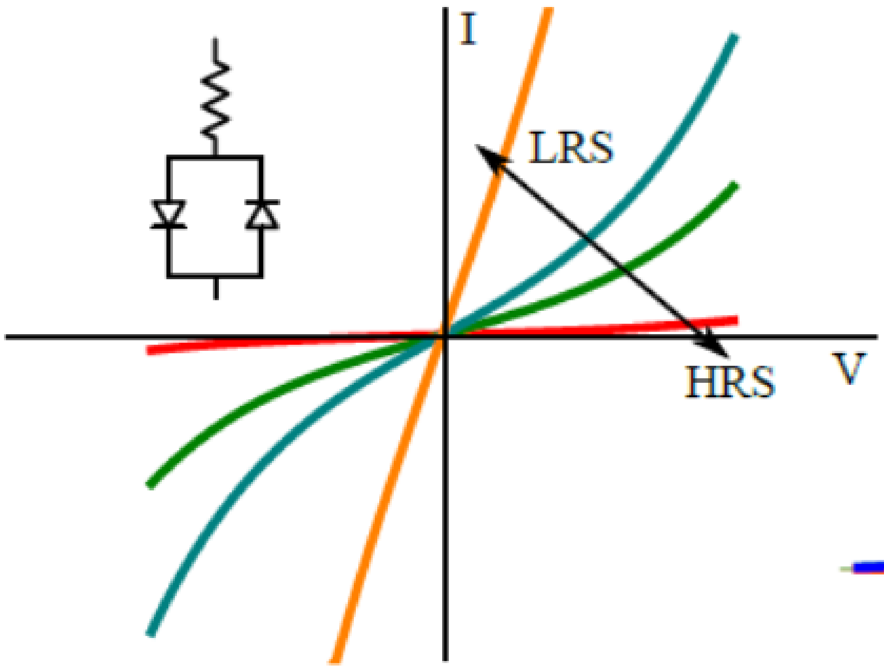
new

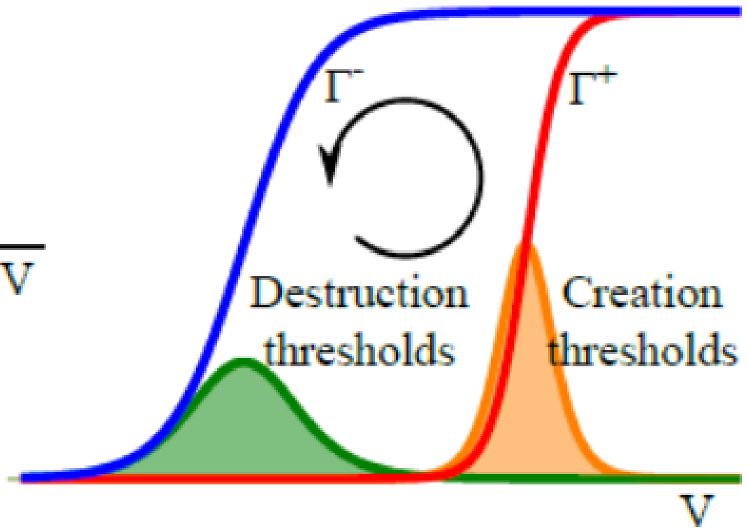
$$\frac{d\lambda}{dt} = \eta\lambda(1-\lambda)\dot{V}$$

ANALOG BEHAVIORAL MODEL (ABM)

E. Miranda, TNANO **14**, 787 (2015)

The memdiode concept





Transport
Equation
(electrons)

State
Equation
(ions or vacancies: channels)

Origin of the nonlinear transport equation

Instead of resistor-like behavior, diode-like conduction is assumed:

$$I = I_0\left[\exp(\alpha V) - 1\right]$$

- Schottky emission
- Electrochemical filamentation
- Tunneling through a gap barrier
- Quantum point-contact conduction

Origin of the nonlinear transport equation

Series resistance

$$I = I_0 \{\exp[\alpha(V - IR)] - 1\}$$

$$V >> IR \quad \begin{cases} V >> 0: & I = I_0[\exp(\alpha V) - 1] \\ V \approx 0: & I = I_0 \alpha V \end{cases}$$

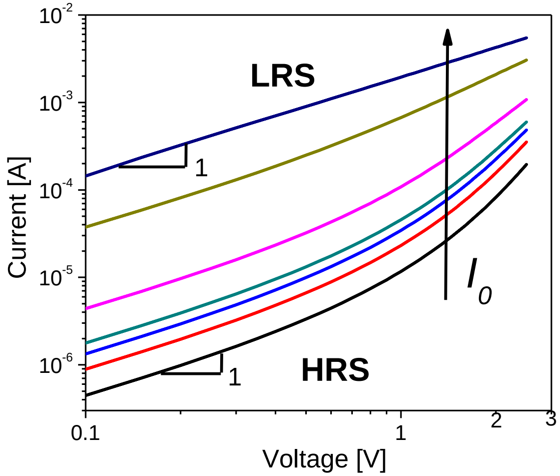
Exponential **HRS**

Linear **HRS**

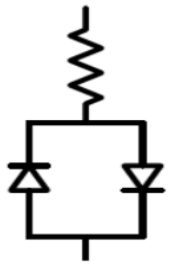
$$V \approx IR \quad \longrightarrow \quad I = \frac{I_0 \alpha}{1 + I_0 \alpha R} V$$

Linear **LRS**

- The series resistance *R* acts as a feedback that controls the shape of the *I-V* through I_0
- Consistent with the experimental I-V curves of many RS devices



Origin of the nonlinear transport equation



$$I = I_0 \left\{ \exp\left[\alpha (V - IR) \right] - 1 \right\}$$

Two anti-parallel diodes

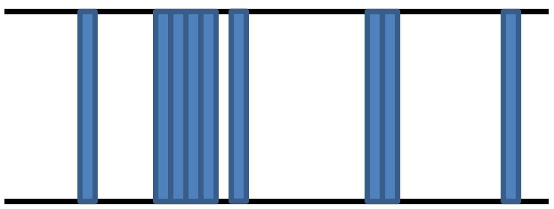
$$\boxed{\begin{gathered} I = \mathrm{sgn}(V) \left[(\alpha R)^{-1} W \left\{ \alpha R I_0(\lambda) \exp\left[\alpha \left(|V| + R I_0(\lambda) \right) \right] \right\} - I_0(\lambda) \right] \\ I_0(\lambda) = I_{0\max} \lambda + I_{0\min} (1 - \lambda) \end{gathered}}$$

W is the Lambert function $We^W = x$

- Analytic model (good approximations for *W*)
- Continuous and differentiable
- Linear (large I_0) or nonlinear (small I_0)
- Pinched I-V: $I(V=0)=0$

Origin of the state equation

- Let's assume Gaussian-distributed SET voltages for the individual channels

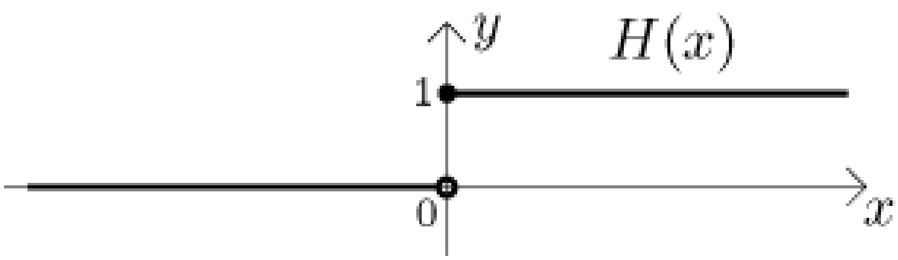


$$f(V) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{\left(V - V^{+}\right)^{2}}{2\sigma^{2}} \right]$$

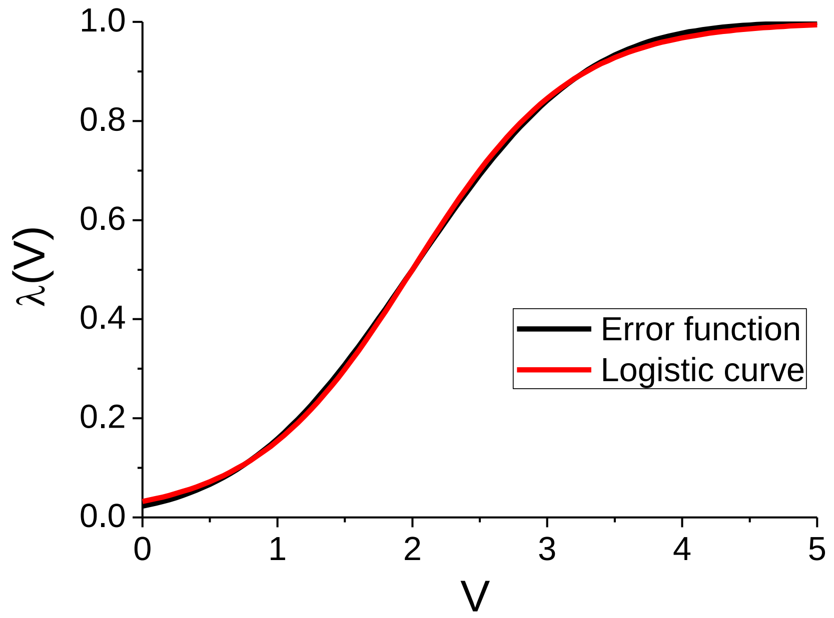
- Normalized number of activated channels at voltage *V*

Heaviside function

$$\lambda(V) = \underbrace{\int_{-\infty}^{+\infty} H(V-\xi)\, f(\xi)\, d\xi}_{\text{CONVOLUTION}}$$



Origin of the state equation



$$\lambda(V) = \frac{1}{2}\left[1 + erf\left(\frac{V - V^{+}}{\sqrt{2}\sigma}\right)\right] \approx \left\{1 + \exp\left[-\eta\left(V - V^{+}\right)\right]\right\}^{-1}$$

- Number of conducting channels grows up as a logistic curve

Origin of the state equation

$$\lambda(V) = \left\{1 + \exp\left[-\eta\left(V - V^{+}\right)\right]\right\}^{-1}$$

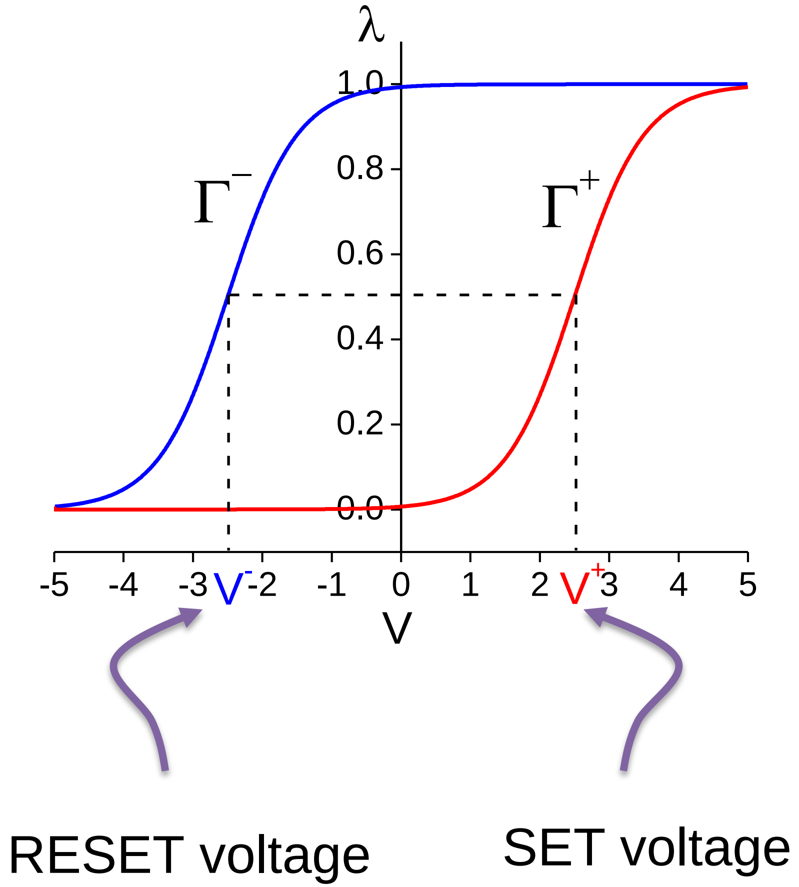
$$\frac{d\lambda}{dV} = \eta\lambda\left(1 - \lambda\right)$$

$$\frac{d\lambda}{dt} = \frac{d\lambda}{dV}\frac{dV}{dt} = \eta\lambda\left(1 - \lambda\right)\frac{dV}{dt}$$

First-order
State Equation

$$\boxed{\frac{d\lambda}{dt} = \eta\lambda(1 - \lambda)\dot{V}}$$

Major hysteretic loop



Ridge functions

$$\Gamma^{\pm}(V) = \left\{1 + \exp\left[-\eta^{\pm}\left(V - V^{\pm}\right)\right]\right\}^{-1}$$

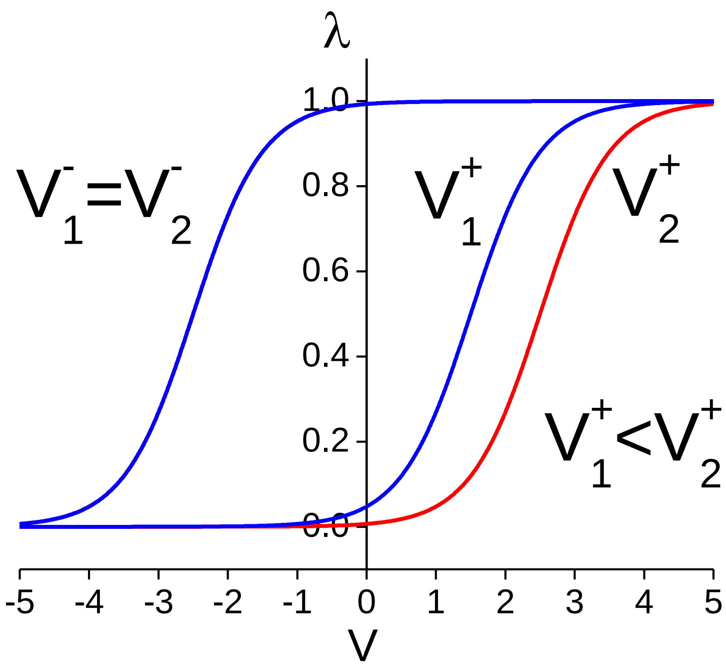
Admissible inputs: $-\infty \leq V \leq \infty$

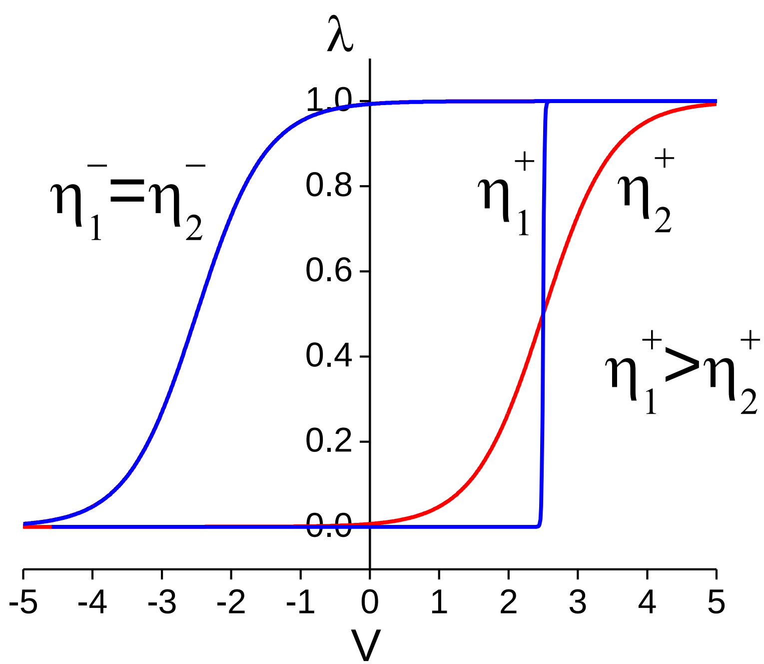
Bounded output: $0 < \lambda < 1$

Describe the creation and rupture of conducting channels

Logistic hysteron

Controlling the shape of the hysteron



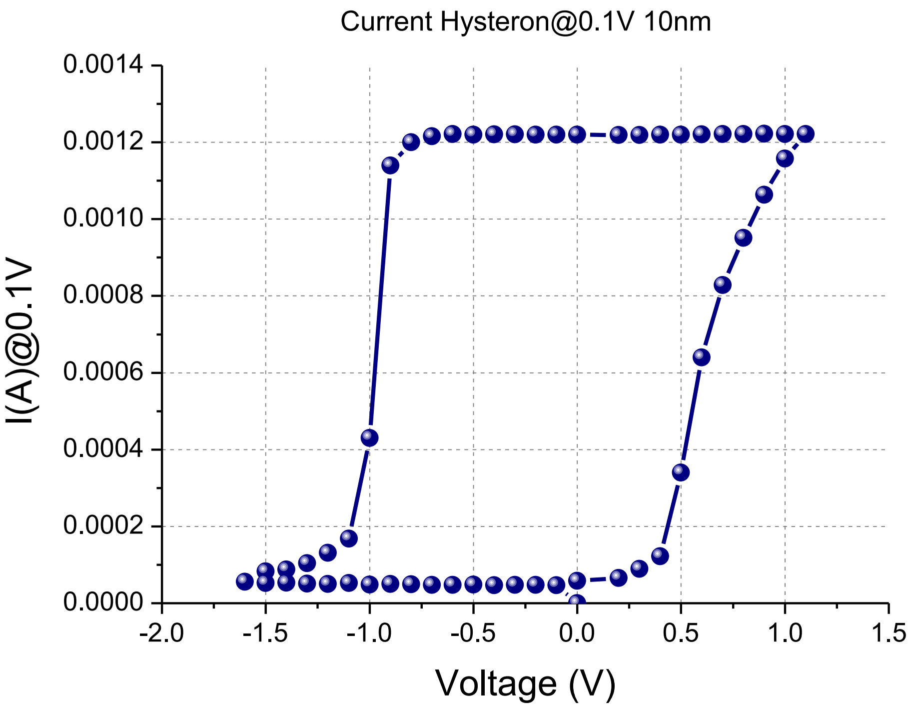


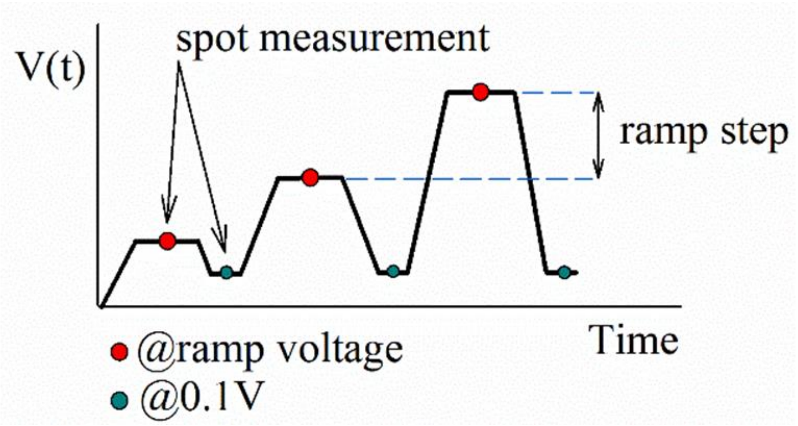
Control of **SET/RESET VOLTAGES**

Control of **TRANSITION RATES**

$$\Gamma^{\pm}(V) = \left\{1 + \exp\left[-\eta^{\pm}\left(V - V^{\pm}\right)\right]\right\}^{-1}$$

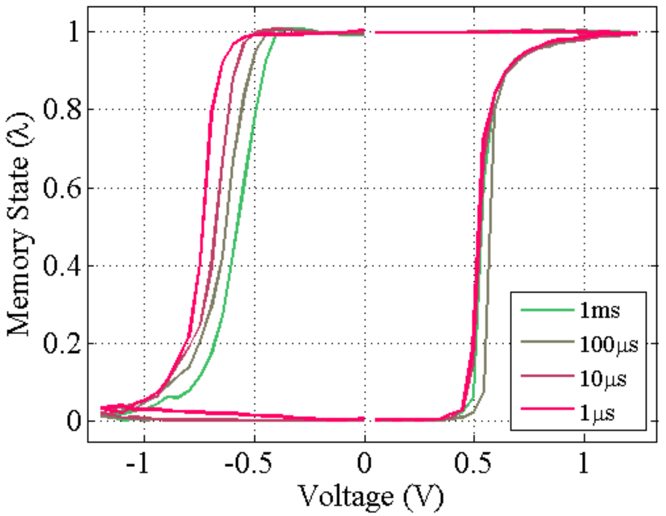
Experimental hysterons (current@low voltage)





TiN/HfO_2/Ti devices

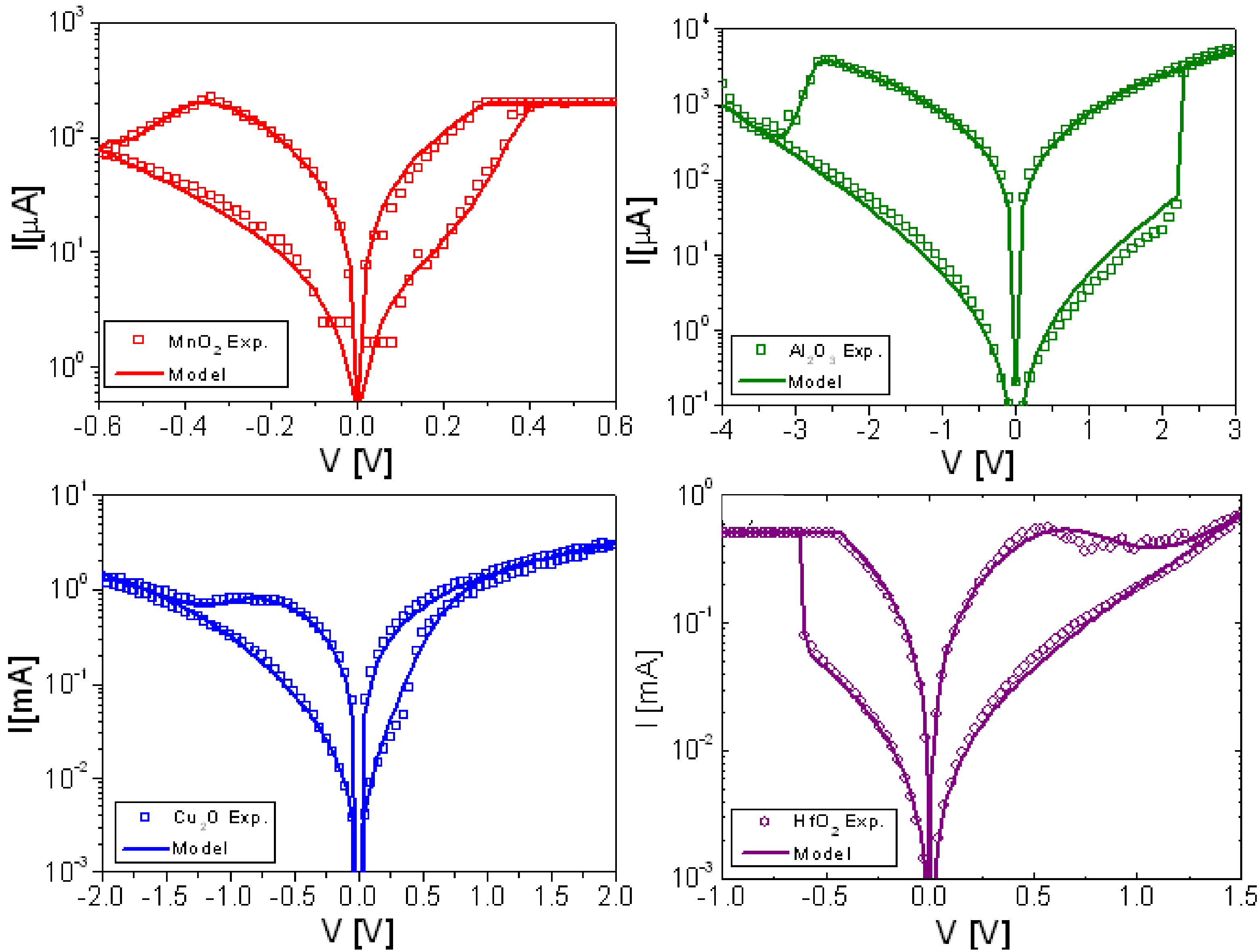
Results from LETI, Grenoble



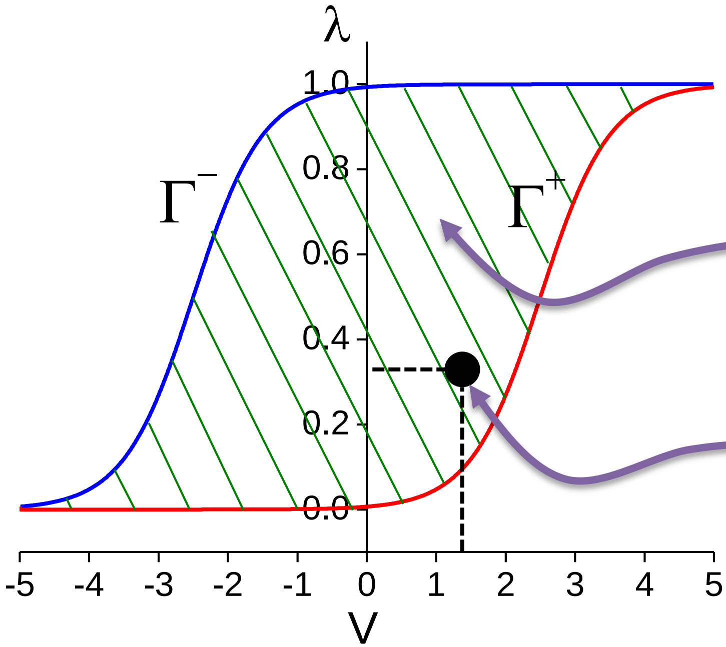
TiN-Ti/HfO_2/W devices

Results from Universidad de Valladolid

Experimental and model results



Minor hysteretic loops (neuromorphic applications)



Ridge functions

$$\Gamma^{\pm}(V) = \left\{1 + \exp\left[-\eta^{\pm}\left(V - V^{\pm}\right)\right]\right\}^{-1}$$

State space: domain of feasible states

$$\Omega(\Gamma^-, \Gamma^+)$$

State of the system (V, λ)

$$V(t) \quad \lambda(t)$$

Simplest case:

$$\frac{d\lambda}{dV} = 0 \;\; if \;\; (V, \lambda) \in \Omega$$

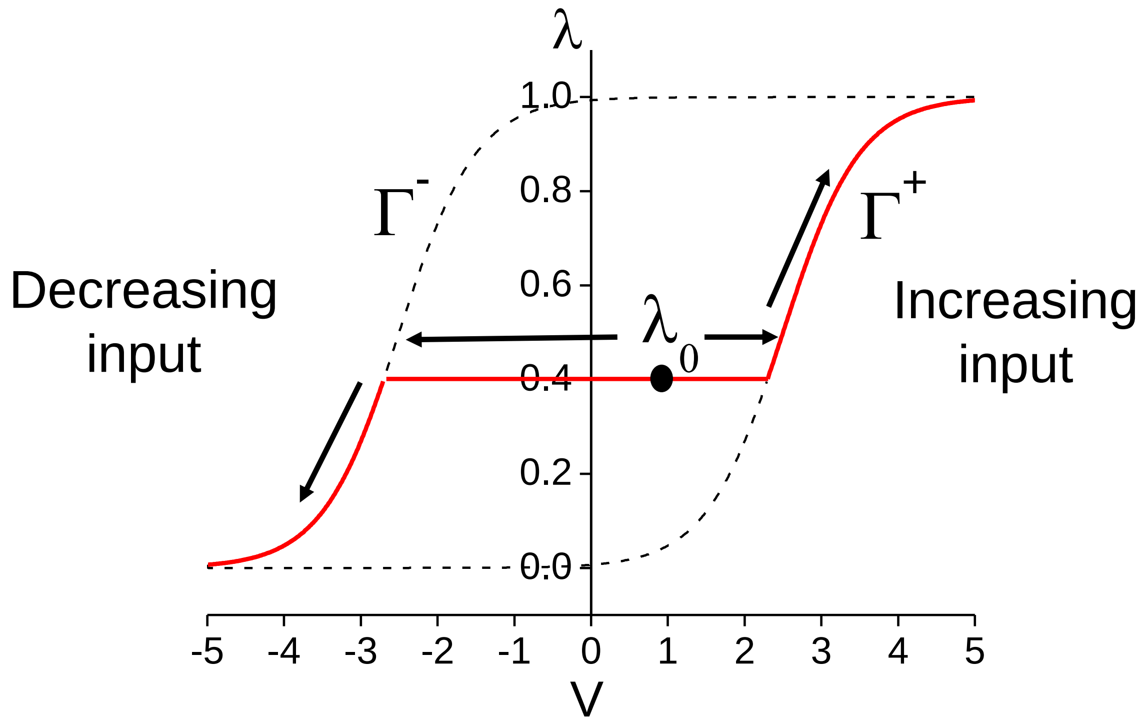
Channels can neither be created nor destructed inside Ω

$\tau_{ions} \gg \tau_{signal}$

Krasnosel'skii-Pokrovskii (KP) hysteresis operator

$$\lambda(t) = L[t_0, \lambda_0]V(t) \qquad \lambda(t_0) = \lambda_0$$

$$L[t_0, \lambda_0]V(t) \equiv \min\left\{\Gamma^-\left[V(t)\right], \max\left[\lambda_0, \Gamma^+\left[V(t)\right]\right]\right\}$$



M. Krasnosel'skiĩ and A. Pokrovskiĩ, *Systems with hysteresis*, Springer, 1989

Krasnosel'skii-Pokrovskii (KP) hysteresis operator

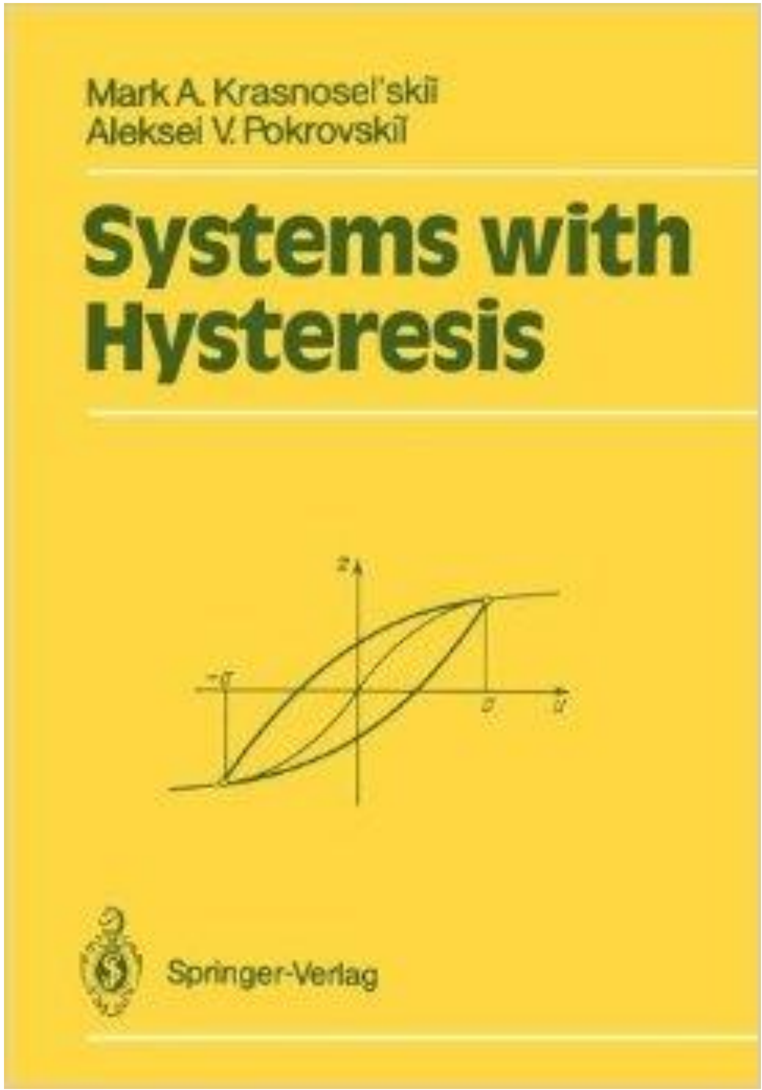
$$L[t_0,\lambda_0]V(t) \equiv \min\left\{\Gamma^-[V(t)], \max\left[\lambda_0, \Gamma^+[V(t)]\right]\right\}$$

The previous output is
the next initial state

$$\boxed{\lambda_t = \min\left\{\Gamma^-(V_t), \max\left[\lambda_{t-1}, \Gamma^+(V_t)\right]\right\}}$$

- State of the system described by a recursive relationship
- Deterministic and rate-independent process
- Short memory transducer with wiping-out property
- **No need to control the simulation timestep (algorithmic modeling)**
- **Applicable to arbitrary inputs (continuous or discontinuous)**

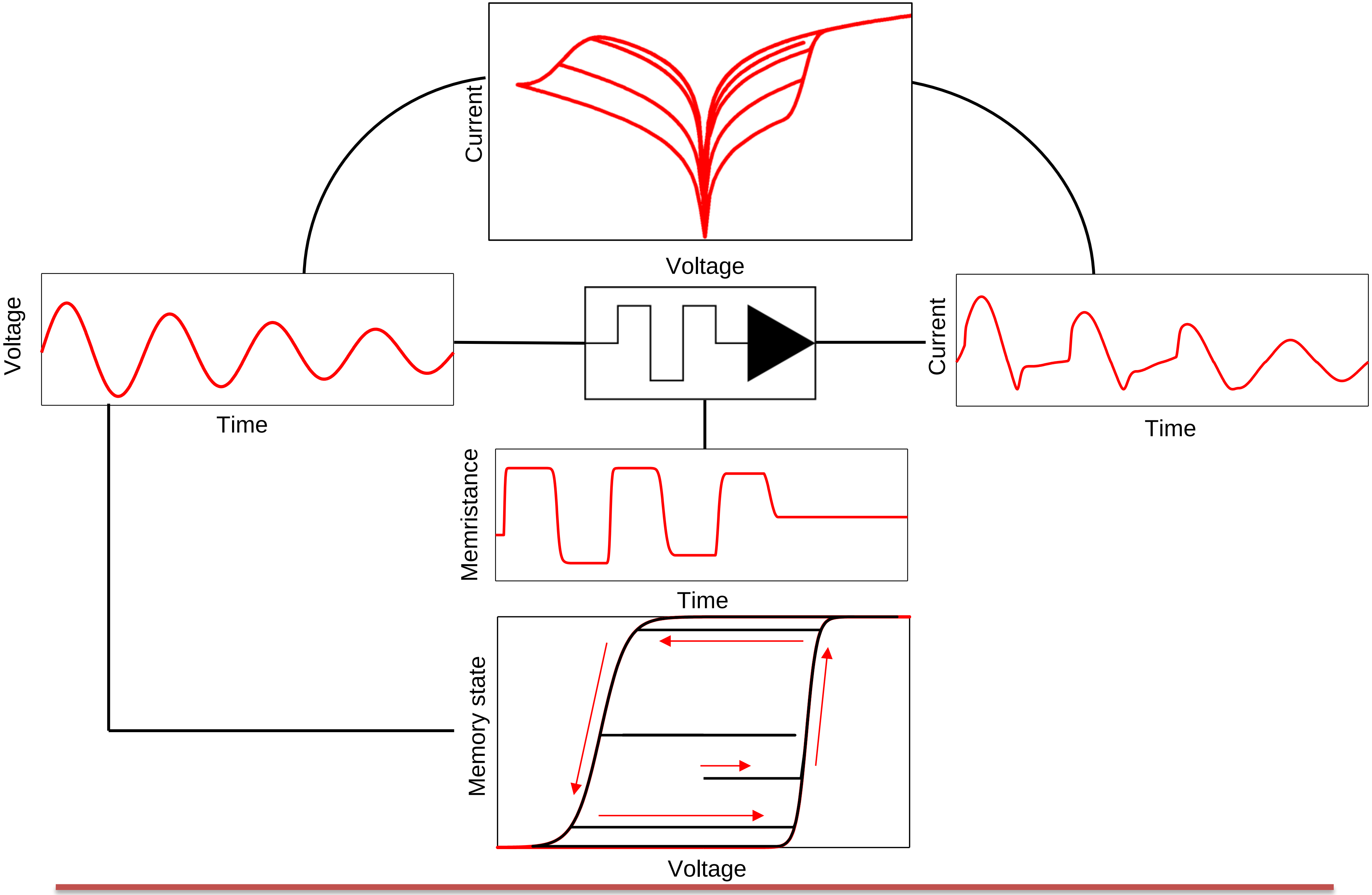
Systems with hysteresis (1989)



Mark Krasnosel'skii
(1920-1997)

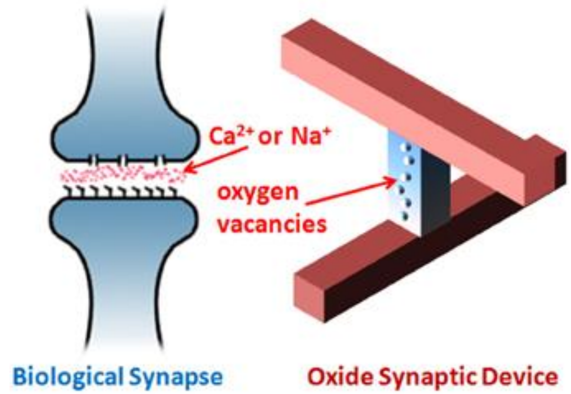
Alexei V. Pokrovskii
1948-2010

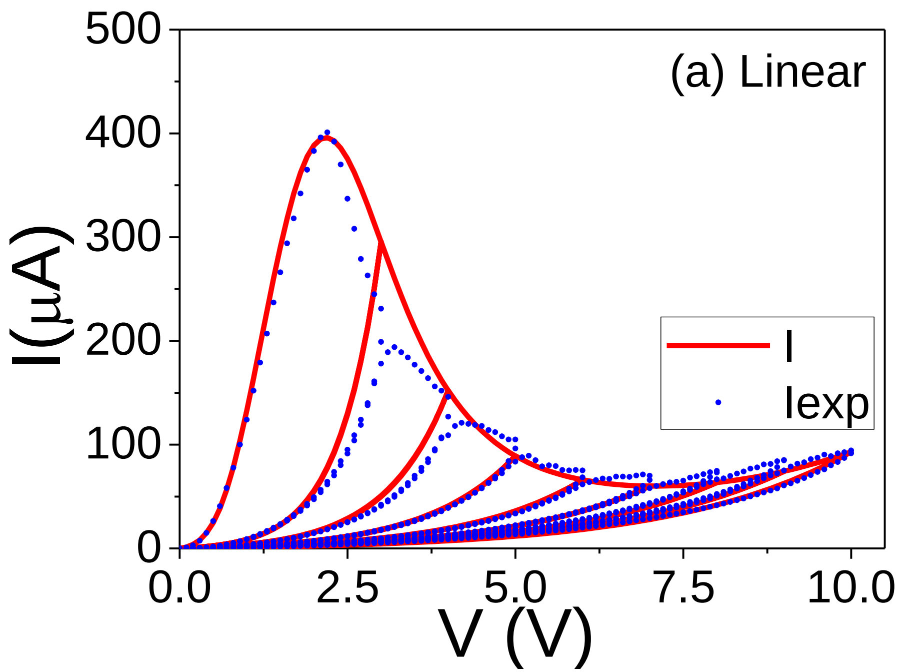
Time-independent model

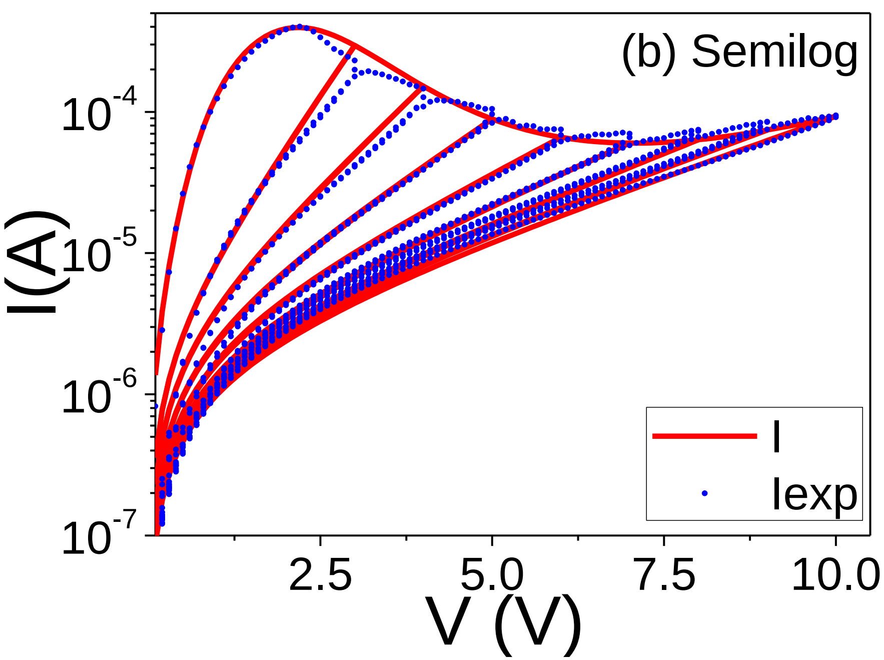


Model and simulation results for LCMO

Remember: we are interested in simulating the synaptic weight which is a continuous variable

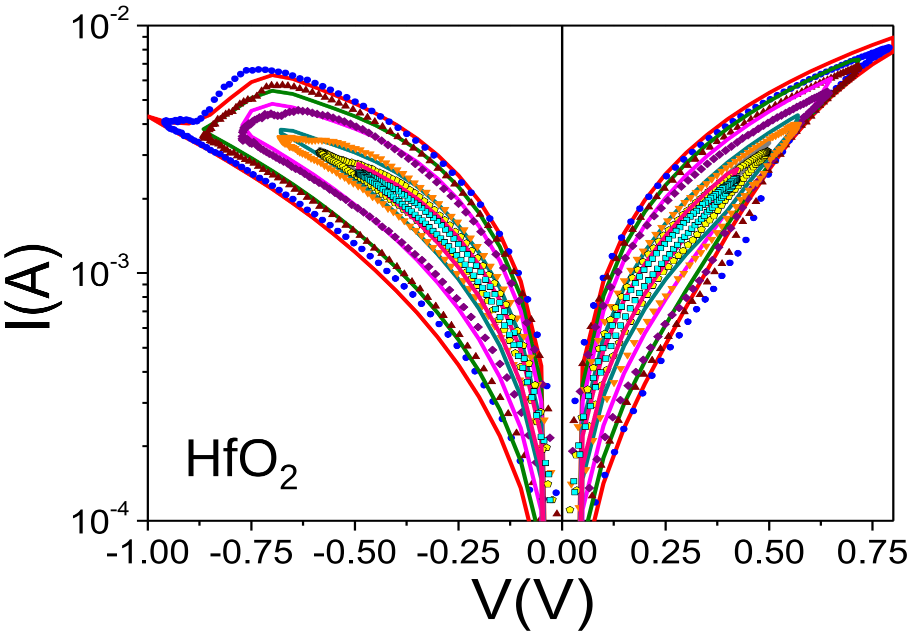


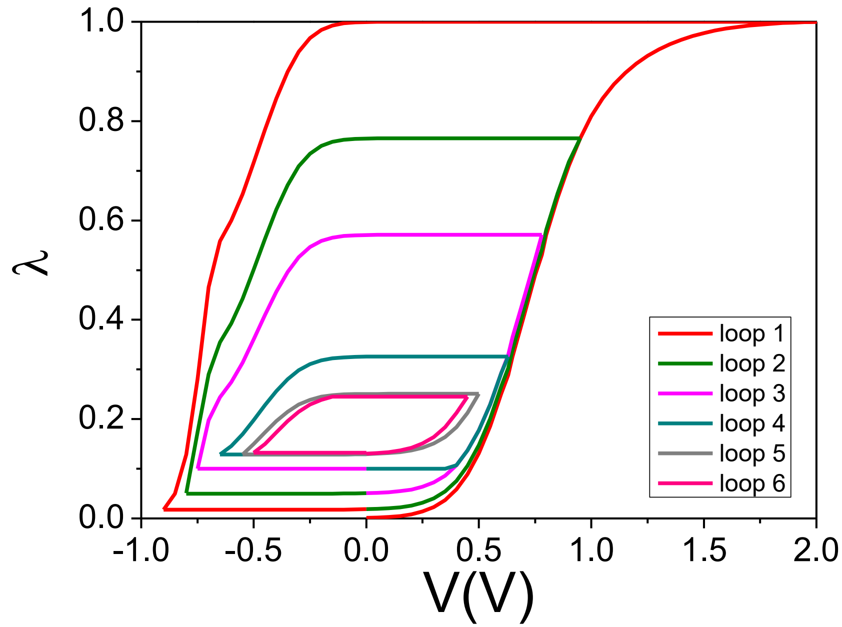


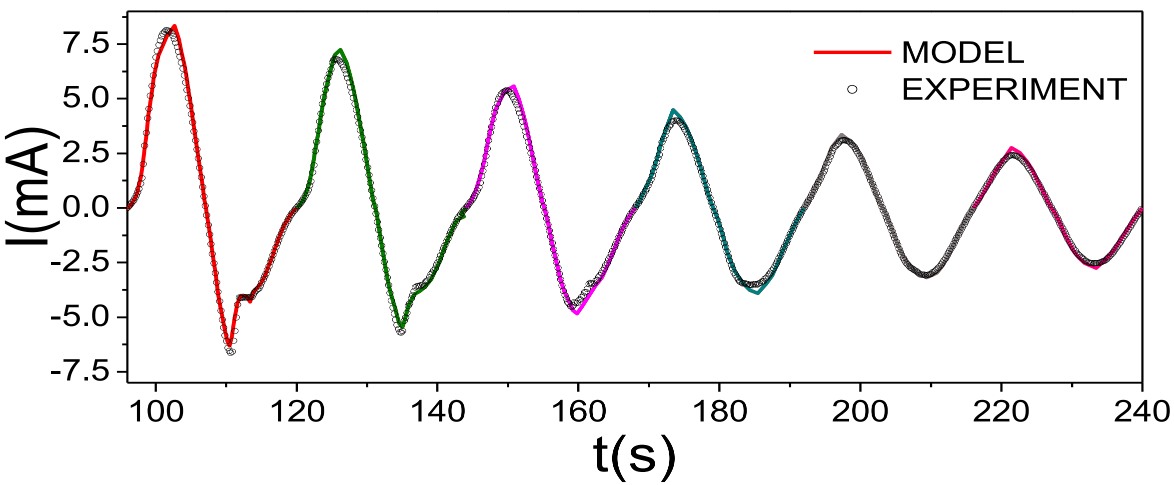


J. Blasco, UAB PhD Thesis, 2017

Superposition of hysterons: *super-hysteron*







$$S(V) = \sum_{i=1}^{3} \gamma_i \Gamma_i(V)$$

$$\sum \gamma_i = 1$$

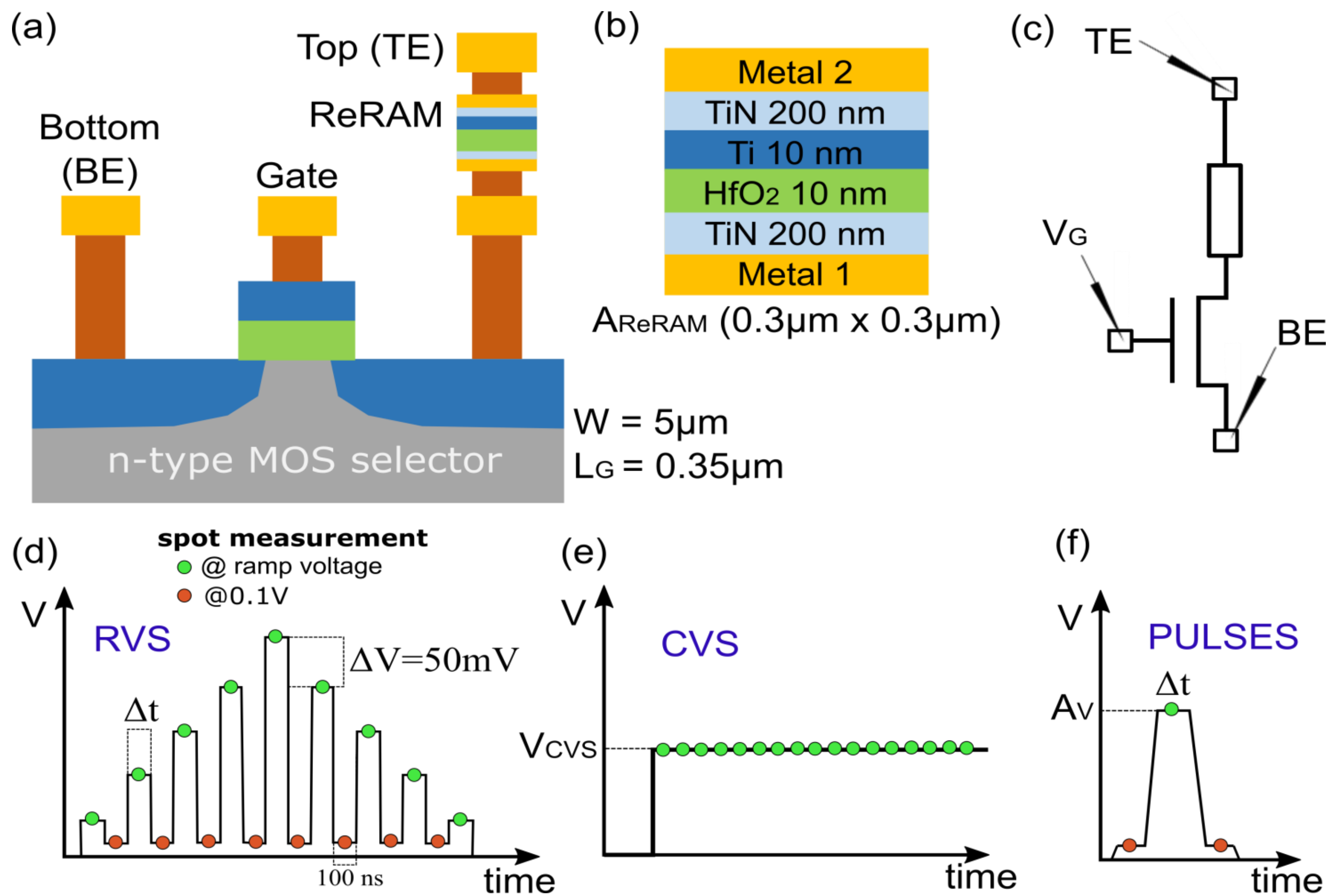
Γ: sigmoidal hysterons

γ: weight coefficients

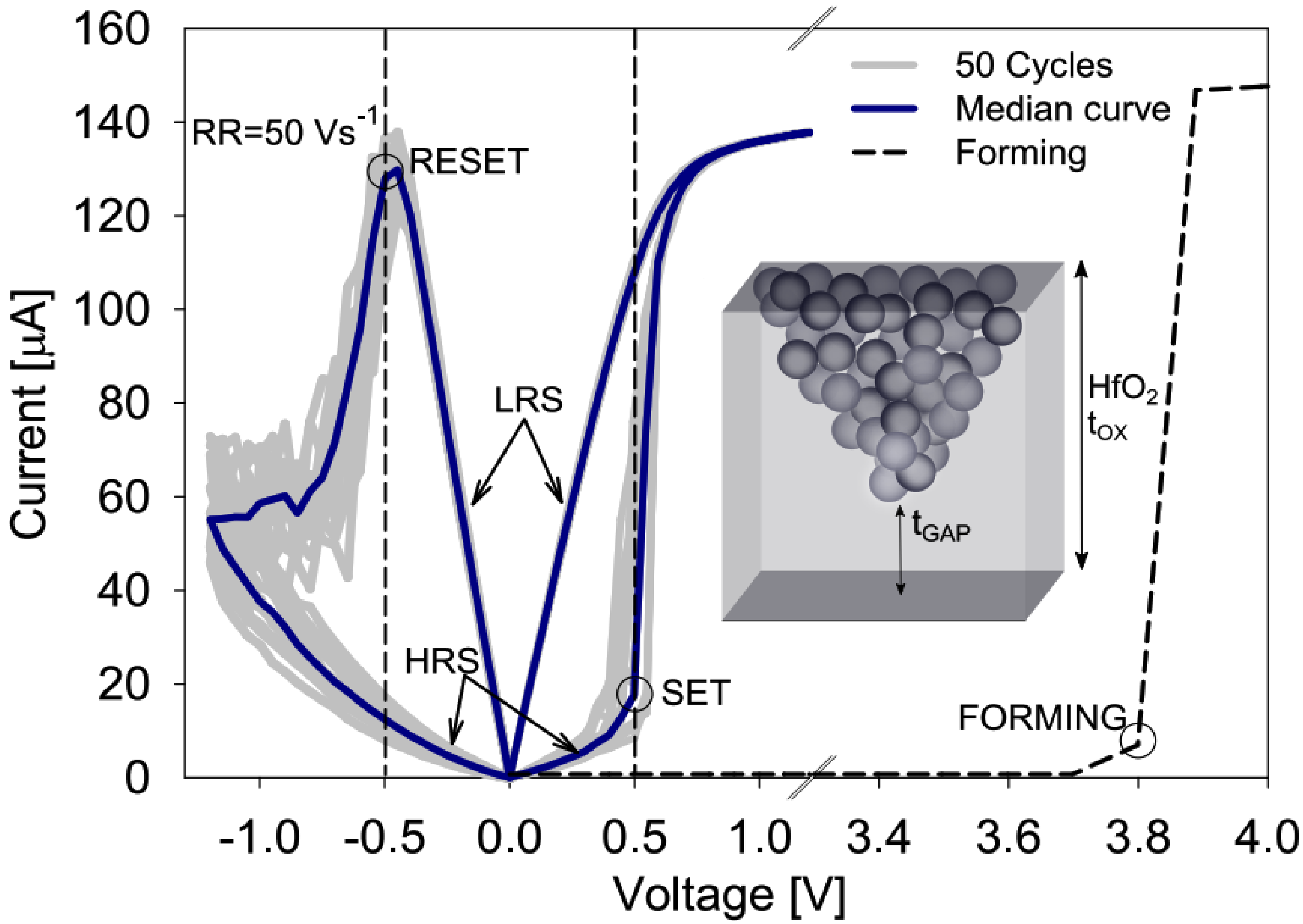
J. Blasco, UAB PhD Thesis, 2017

EU project PANACHE 2014-2017

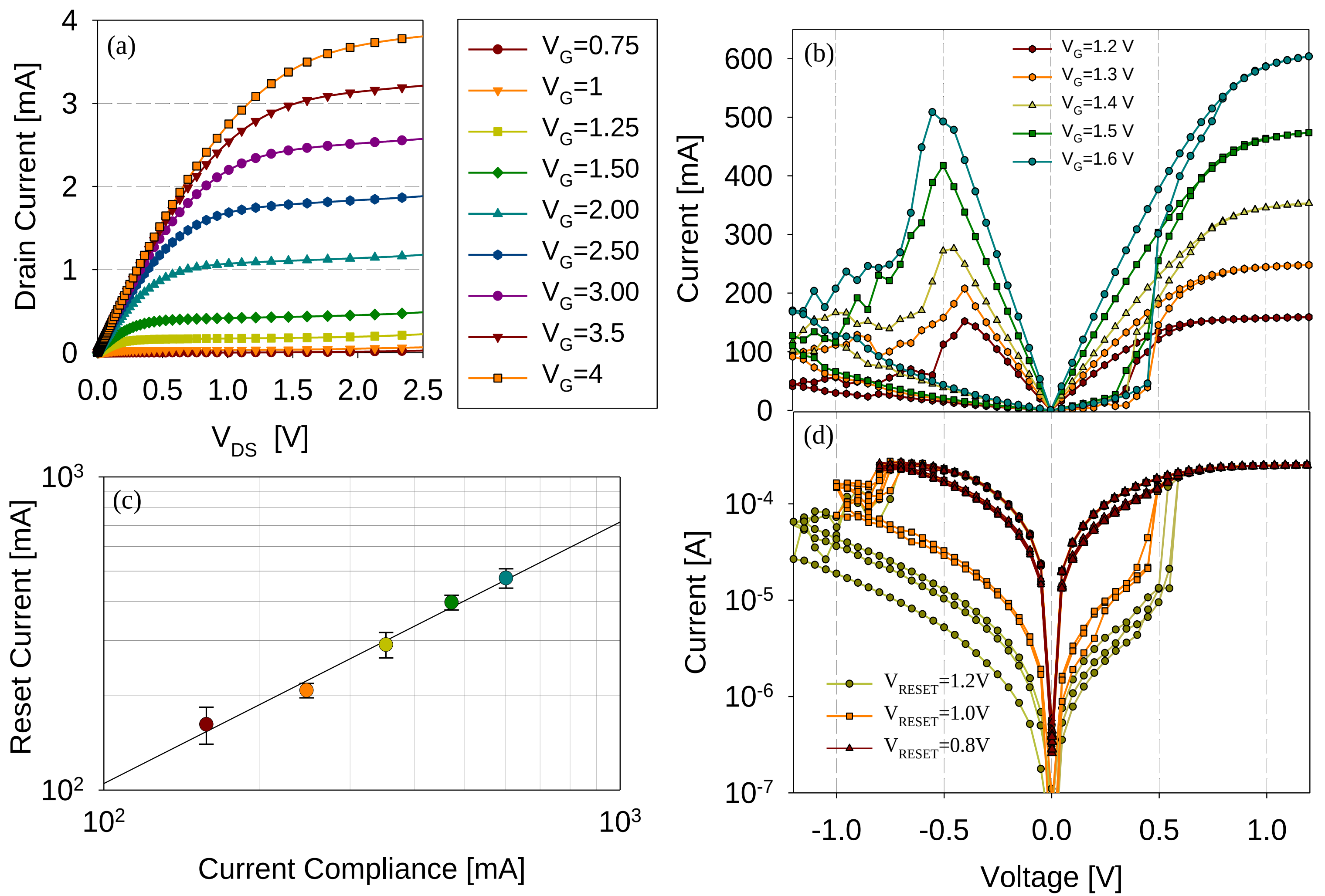
Pilot line for Advanced Nonvolatile memory technologies for Automotive microControllers, High security applications and general Electronics



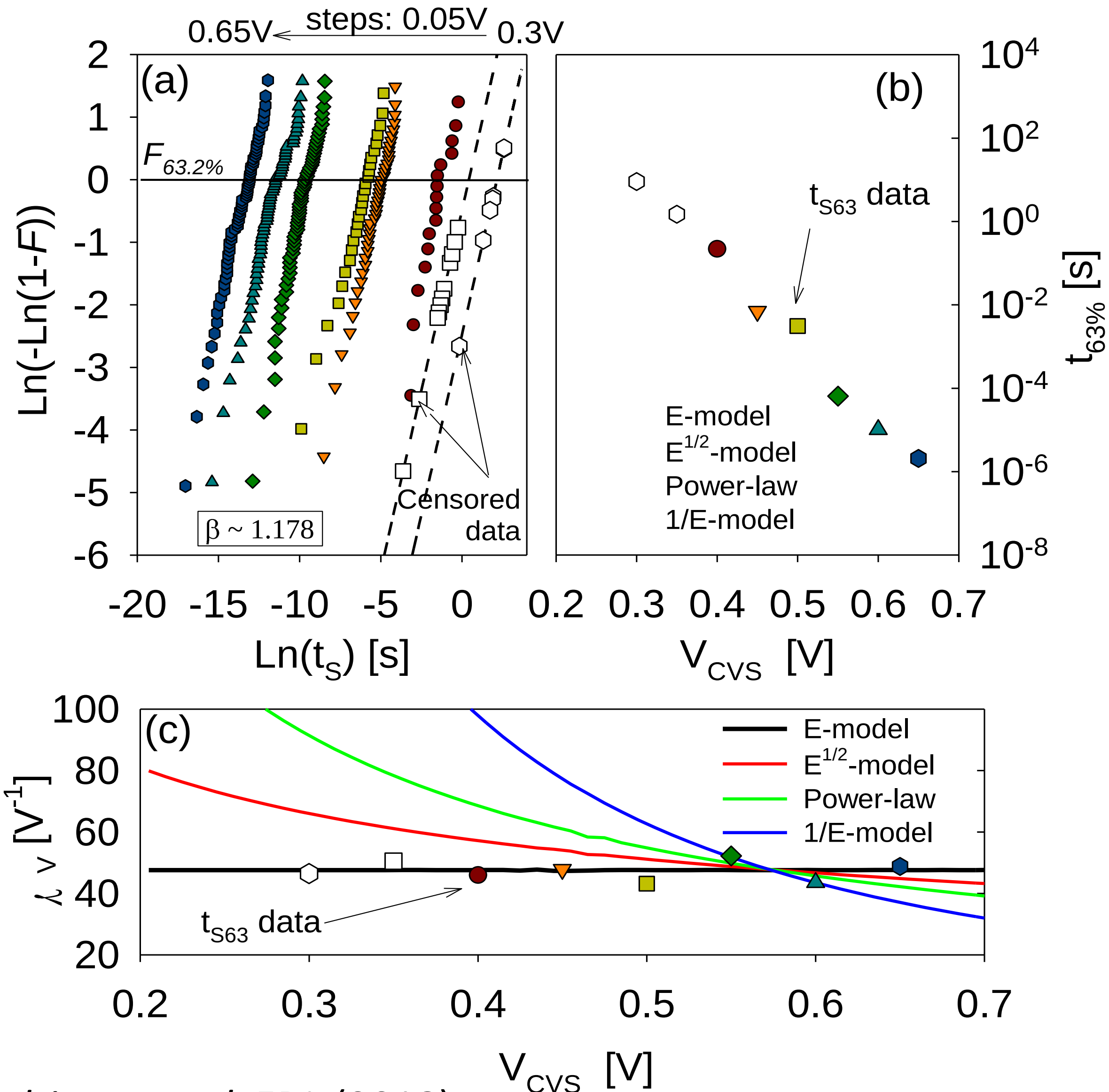
Typical switching behavior



Transistor as selector



Set statistics: accurate determination of acceleration law



Constant voltage stress experiments

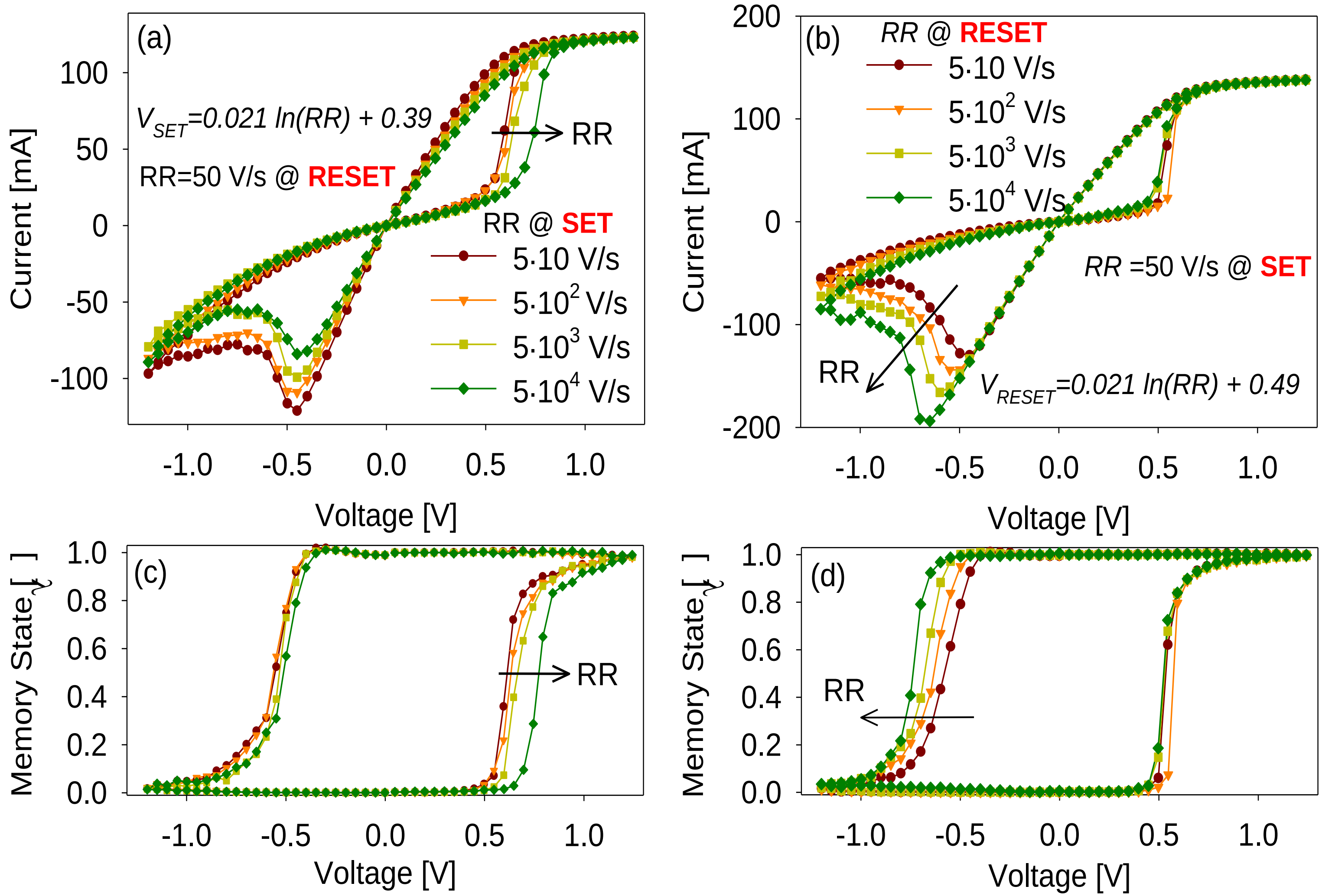
E-model:

$$\tau = \tau_0 e^{-\gamma V}$$

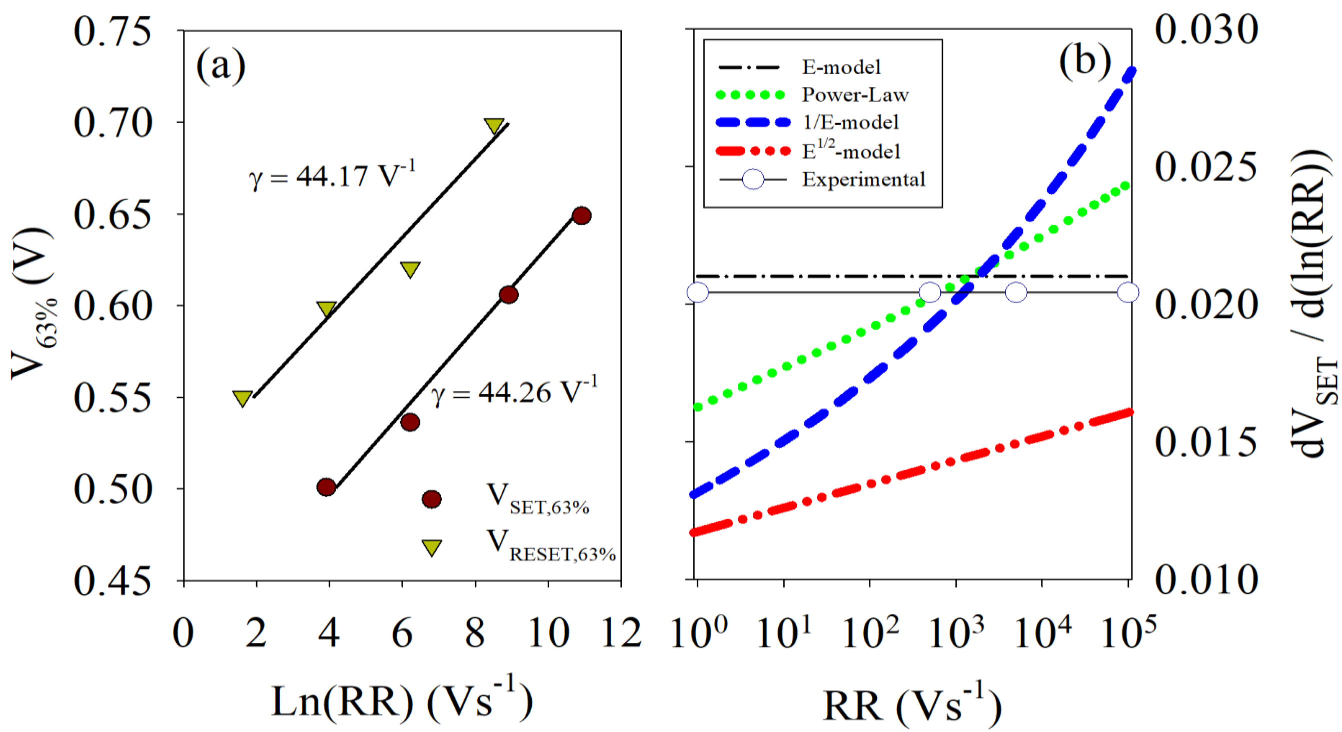
Experimental results for CVS confirm this model for the switching time

A. Rodriguez et al, EDL (2018)

Pulsed measurements with different ramp rates



Pulsed measurements with different ramp rates



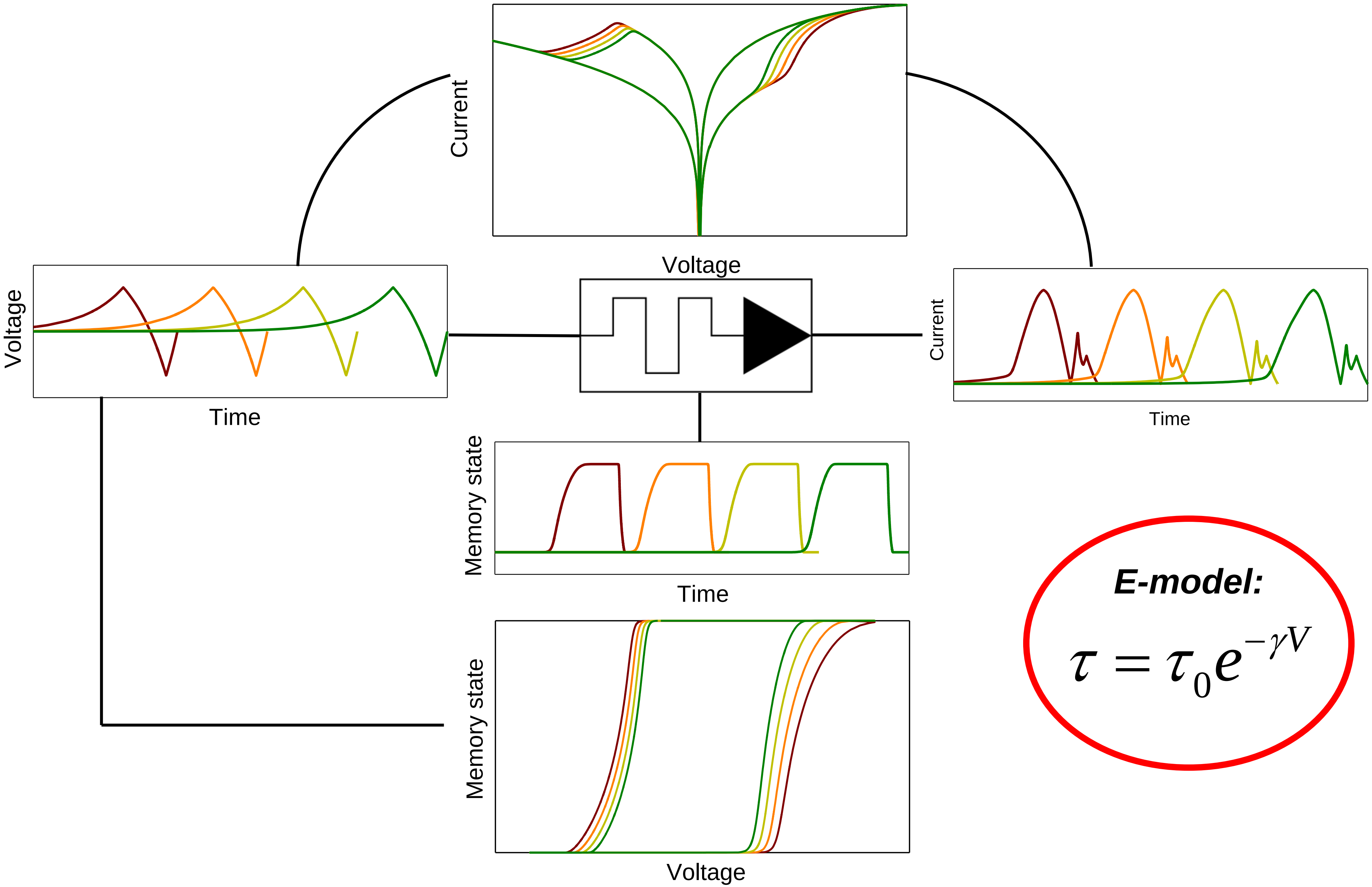
Ramped voltage stress experiments

Experimental results for RVS confirm this model for the switching time

E-model:

$$\tau = \tau_0 e^{-\gamma V}$$

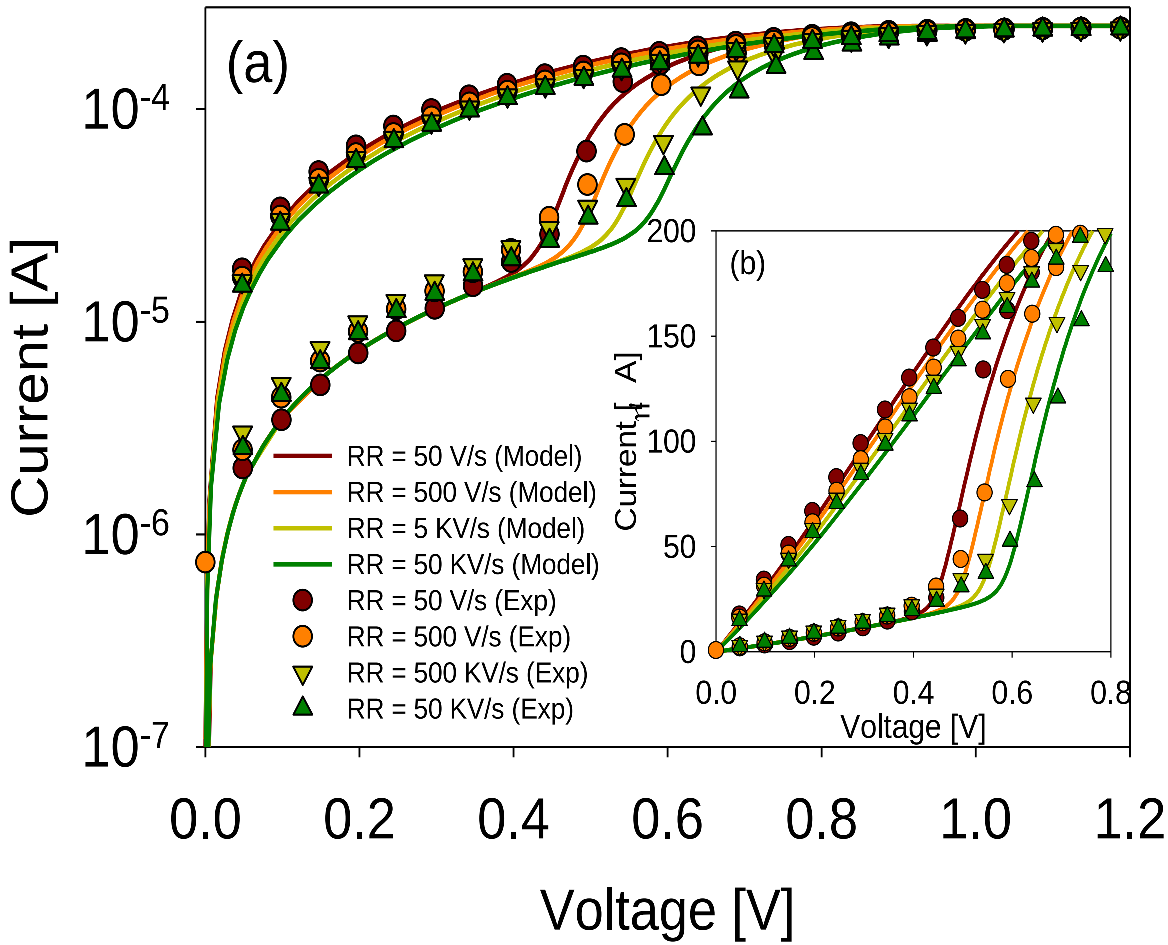
Time-dependent model



E-model:

$$\tau = \tau_0 e^{-\gamma V}$$

Effect of ramp rate: experimental and model results



I_{max} = 1.3e-4 A

I_{min} = 3.5e-5 A

α_{max} = 3.5 V^{-1}

α_{min} = 1 V^{-1}

del = Δt_{exp}

γ_{RESET} = 70 V^{-1}

γ_{SET} = 50 V^{-1}

τ_{RESET} = 5e+19s

τ_{SET} = 1e+7s

R_S = 500Ω

Outline

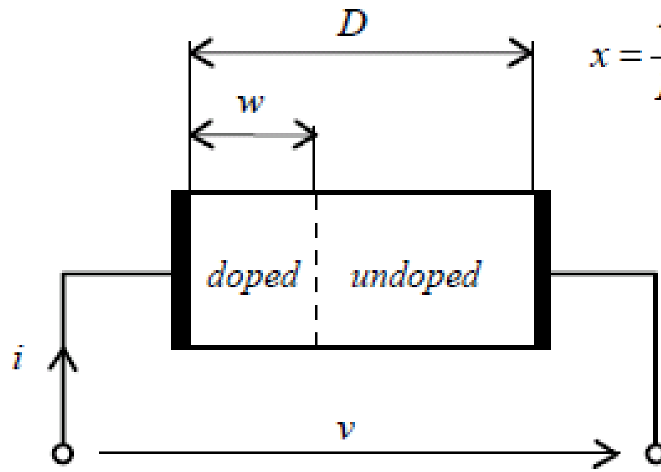
- Introduction to filamentary-type ReRAM
- Physical models and quantum limit
- The circuital approach
- Model implementation
- The problem of variability
- Final comments

Memristor simulation using SPICE

- It is of great benefit for circuit designers to be able to model memristive devices in SPICE-type simulators

$$R_{mem}(x) = R_{on}x + R_{off}(1-x) = R_{off} - (R_{off} - R_{on})x$$

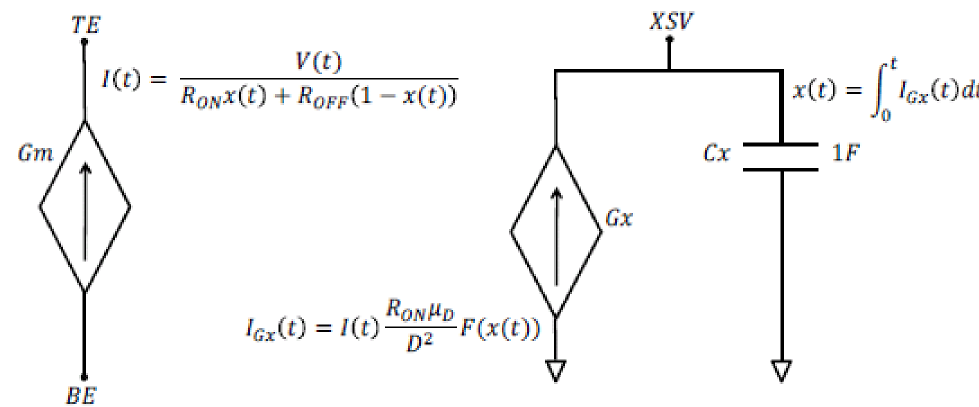
$$\frac{dx}{dt} = ki(t)f(x) \; , \; k = \frac{\mu_v R_{on}}{D^2}$$



$$x = \frac{w}{D} \in (0,1)$$

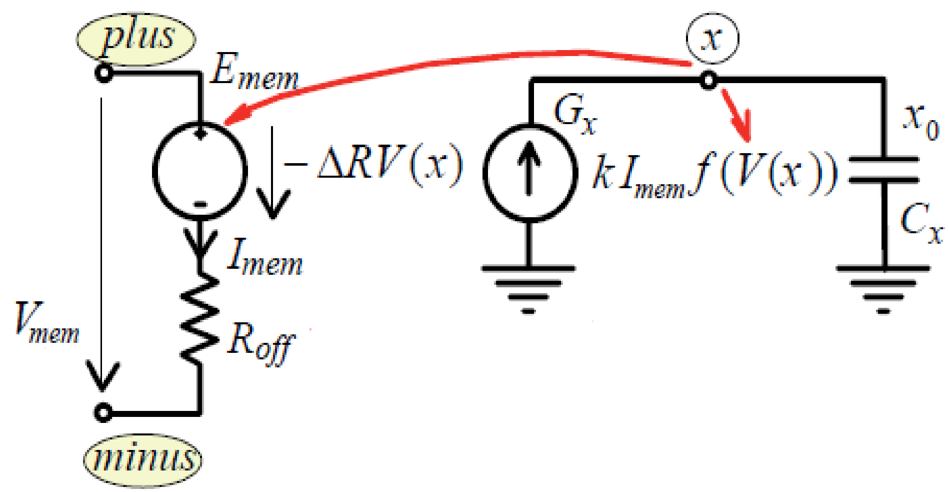
Implementation of the variable state equation

Two-port equation

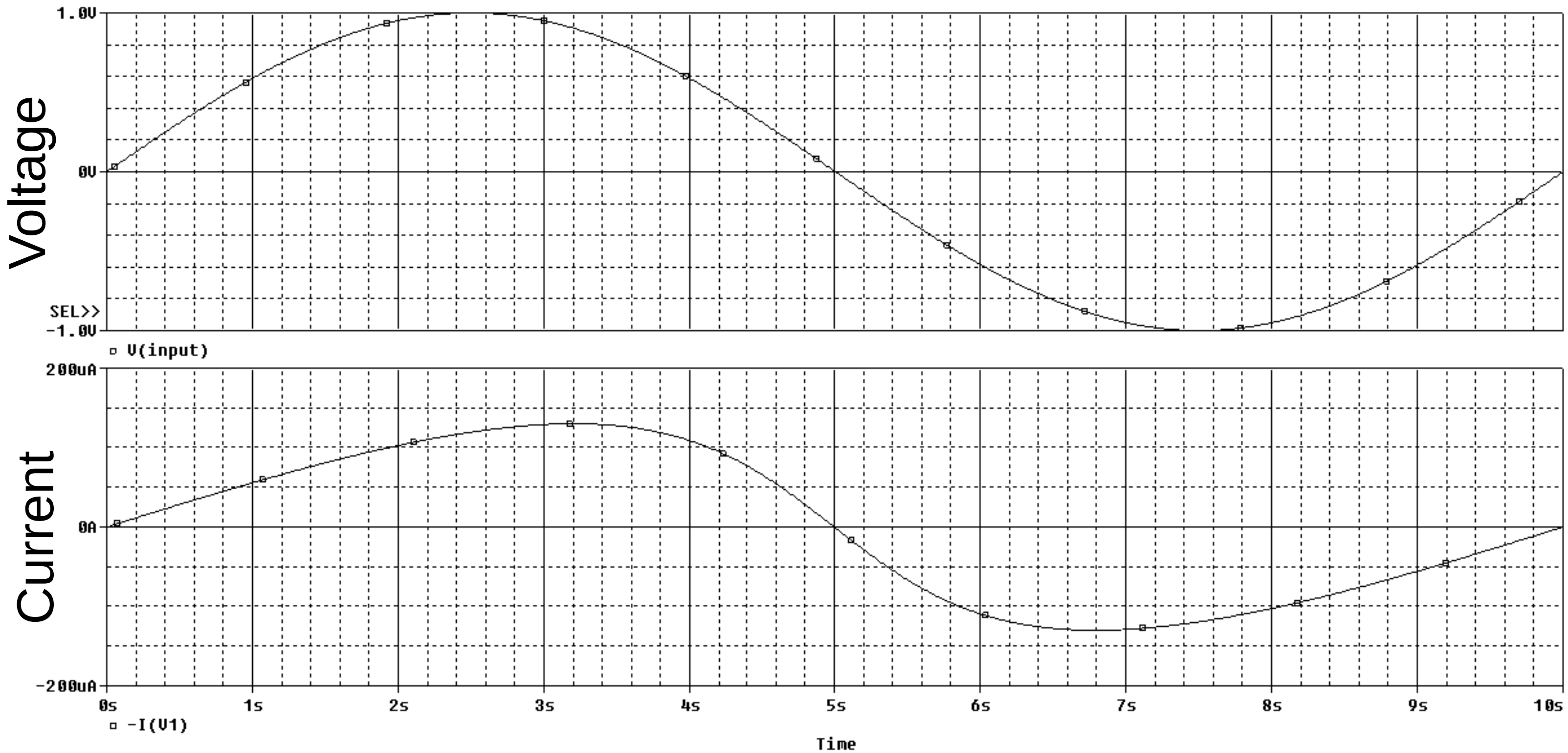


Memristor simulation using PSPICE

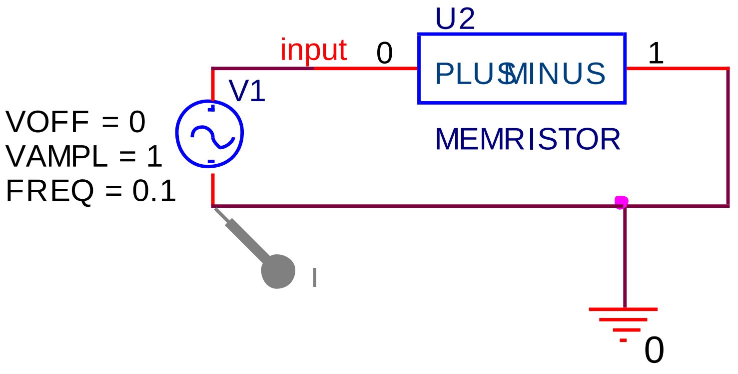
```
.SUBCKT memristor Plus Minus PARAMS:
+ Ron=1K Roff=100K Rinit=80K D=10N uv=10F p=1
***********************************************
* STATE EQUATION MODELING *
Gx 0 x value={ I(Emem)*uv*Ron/D^2*f(V(x),p)}
Cx x 0 1 IC={(Roff-Rinit)/(Roff-Ron)}
Raux x 0 1G
***********************************************
* RESISTIVE PORT MODELING *
Emem plus aux value={-I(Emem)*V(x)*(Roff-Ron)}
Roff aux minus {Roff}
********************************
* WINDOW FUNCTION MODELING *
.func f(x,p)={1-(2*x-1)^(2*p)}
.ENDS memristor
```



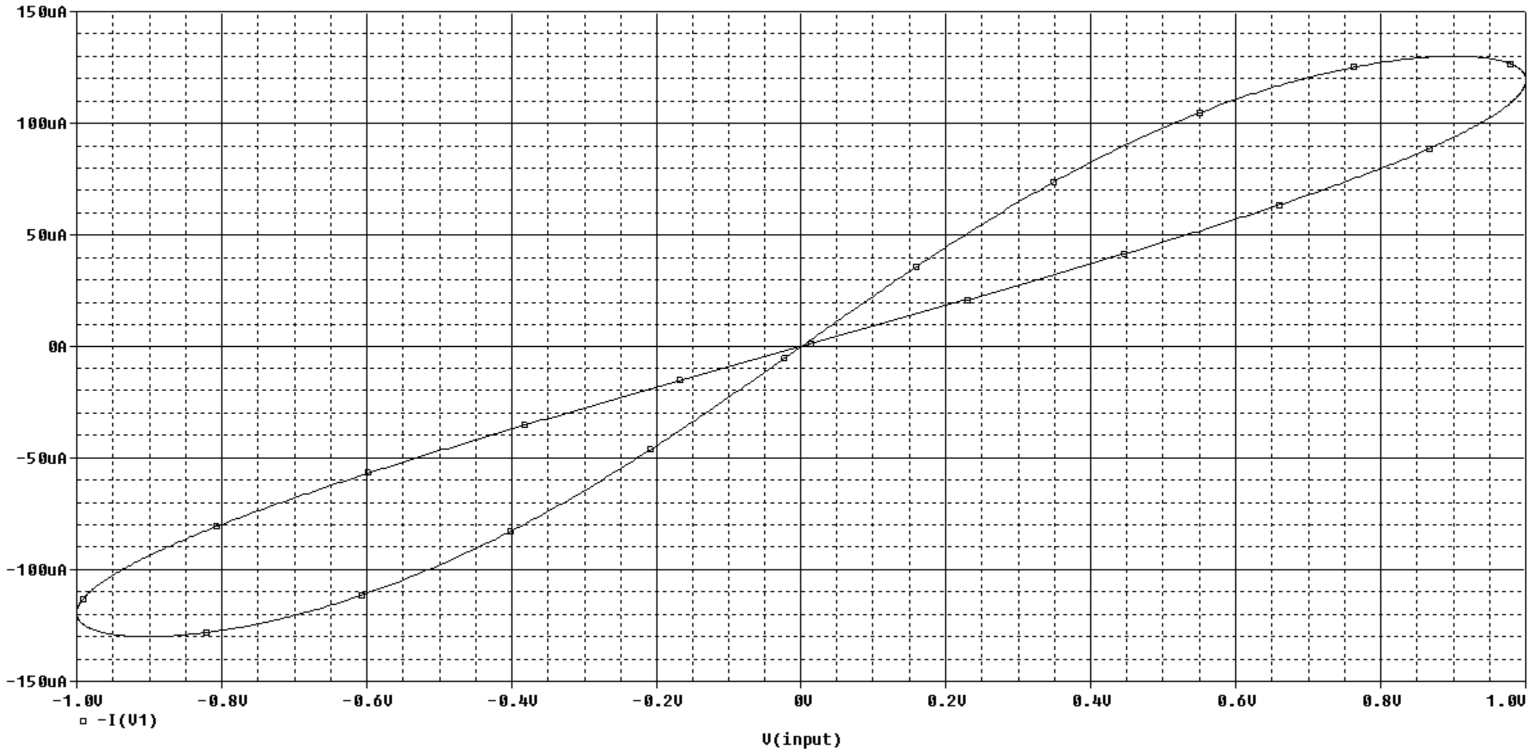
Memristor simulation using PSPICE



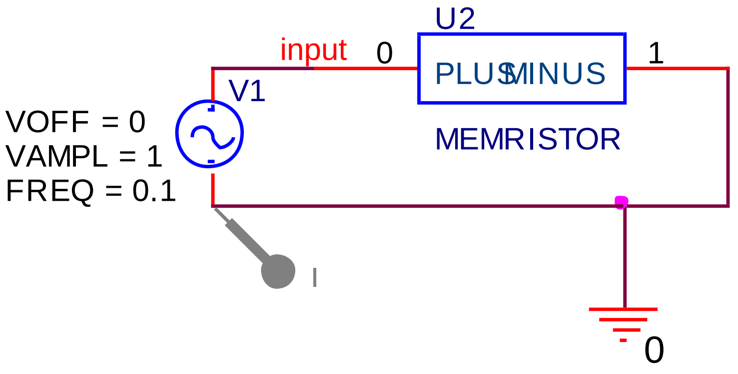
The figures show how this memristor model reacts to a simple sinusoidal input voltage



Memristor simulation using PSPICE

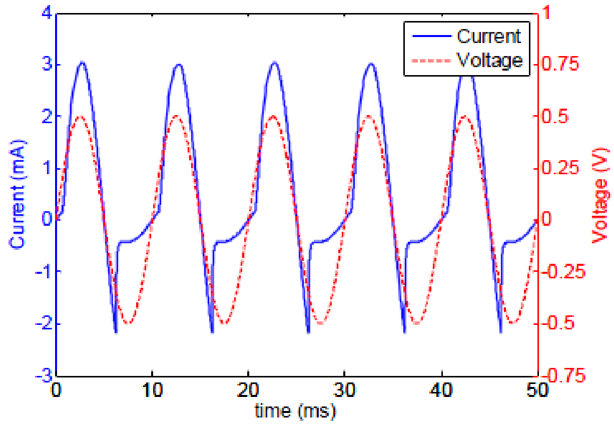


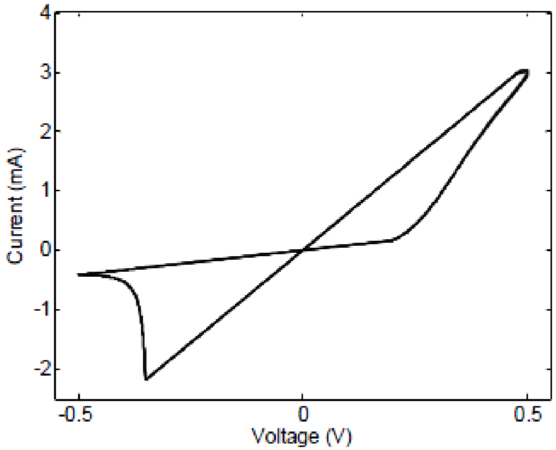
The figure shows that the memristor current is not only related to the applied voltage but also to the history of the device as expected for a hysteretic system



Memristor models in LTSPICE (free software)

```
* Code for memristor model proposed by Dr. Pino et al.

* Connections:
* TE:  Top electrode
* BE:  Bottom electrode
* RSV: External connection to plot resistance
*      that is not used otherwise

.SUBCKT MEM_PINO TE BE RSV

* Ron:      Minimum device resistance
* Roff:     Maximum device resistance
* Th:       Positive voltage threshold
* Tl:       Negative voltage threshold
* Kh1, Kh2: Fitting params for pos voltage
* Kl1, Kl2: Fitting params for neg voltage

.params Ron=160 Roff=1200 Th=0.2 Tl=-0.35 Kh1=5.5e6 Kh2=-20
+Kl1=4e6 Kl2=20

* Fits the change in resistance to characterization data
.func Rt(V1, V2) = IF( V1 <= Th, IF(V1 >= Tl, 0, IF(V2 <
+Roff, Kl1*exp(Kl2*(V1-Tl)), 0) ), IF(V2 > Ron, -
+Kh1*exp(Kh2*(V1-Th)), 0) )

* Circuit to integrate to find resistance
Gx 0 RSV value={Rt(V(TE,BE),V(RSV))}
Cx RSV 0 {1}
.ic V(RSV) = Roff

* Current source representing memristor
Gmem TE BE value = {V(TE,BE)/V(RSV)}

.ENDS MEM_PINO
```



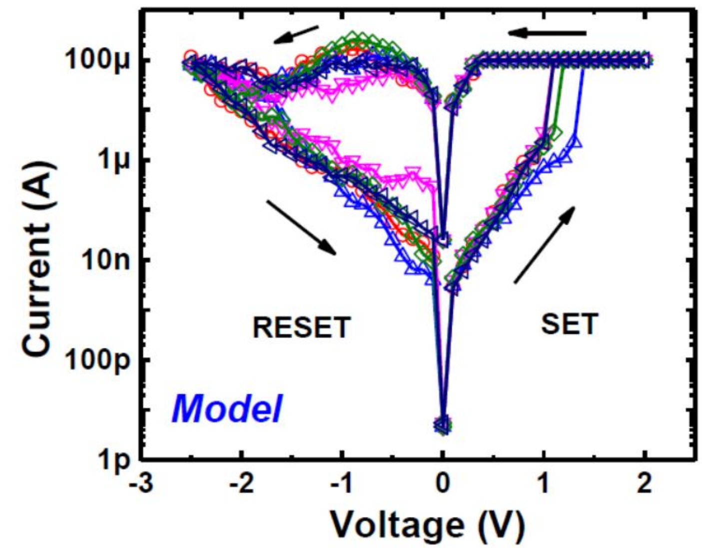


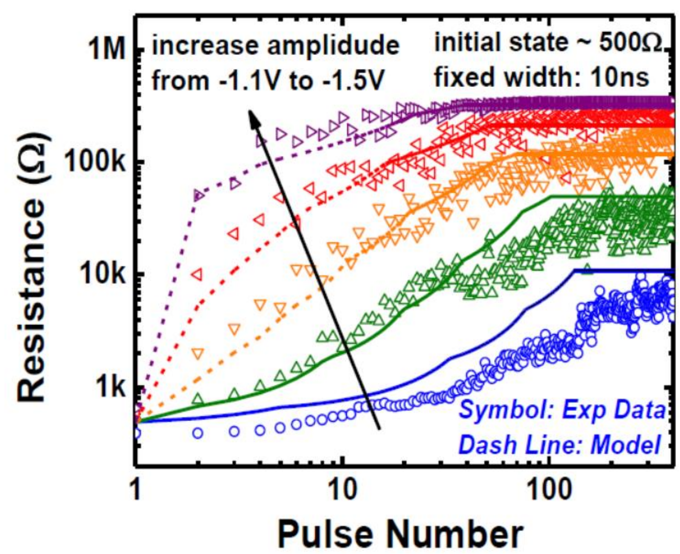
A complete library of memristor models in LTSPICE can be found in:
"MEMRISTOR DEVICE MODELING AND CIRCUIT DESIGN FOR READ OUT INTEGRATED CIRCUITS, MEMORY ARCHITECTURES, AND NEUROMORPHIC SYSTEMS",
PhD Thesis, Chris Yakopcic, University of Dayton, May 2014

Memristor models in Verilog-A

- Industry standard modeling language for analog circuits (subset of Verilog-AMS)

```
////////////////////////////////////////////////////
// VerilogA model for memristor
//
// kerentalis@gmail.com
// Dimafliter@gmail.com
// skva@tx.technion.ac.il
//
// Technion - Israel institute of technology
// EE Dept. December 2011
//
////////////////////////////////////////////////////

`include "disciplines.vams"
`include "constants.h"

// define meter units for w parameter
nature distance
  access = Metr;
  units = "m";
  abstol = 0.01n;
endnature

discipline Distance
  potential distance;
enddiscipline

/////////////Linear Ion Drift model /////////////

if (model==0) begin // Linear Ion Drift model

    dwdt =(uv*Ron/D)*I(p,n);

     //change the w width only if the
     // threshhold_voltage permits!
       if(abs(I(p,n))<threshhold_voltage/R) begin
            w=w_last;
        dwdt=0;
       end

    // No window
    if ((window_type==0)|| (window_type==4)) begin

        w=dwdt*dt+w_last;

    end // No window

  // Jogelkar window
     if (window_type==1) begin

        if (sign(I(p,n))==1) begin
            sign_multply=0;
            if(w==0) begin
            sign_multply=1;
            end
        end
        if (sign(I(p,n))==-1) begin
                sign_multply=0;
                if(w==D) begin
```





Z. Jiang *et al*, SISPAD (2014)

Memristor models in MODELICA

MODELICA LIBRARY: MEMRISTORS

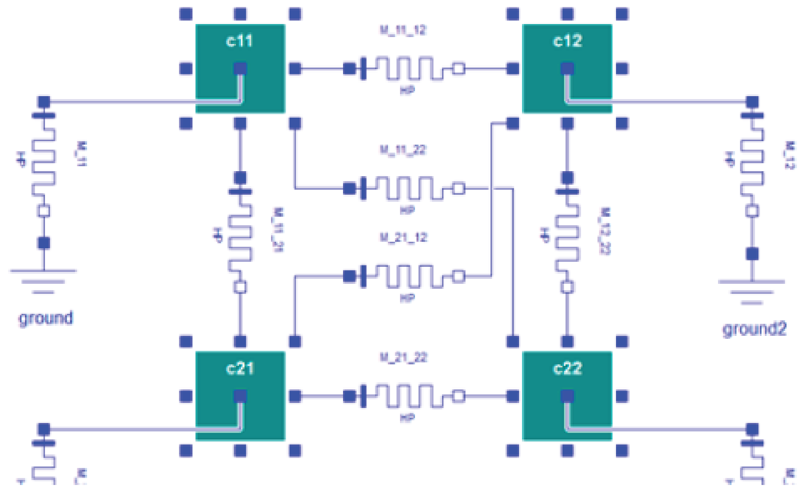
The Library

- Includes all the current memristor models
- Provides extendable application examples
- Can be used flexibly by linking to other physical domains
- Is available in the modern, object-oriented language of Modelica

The Benefits for You

- Open and easily extendable library
- Models of various degrees of abstraction
- Valid parameterization already integrated in models
- Extensive collection of examples to test the memristor in analog circuits and cellular non-linear networks

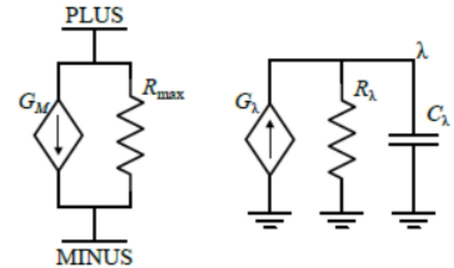
Fraunhofer Institute for Integrated Circuits IIS Design Automation Division EAS

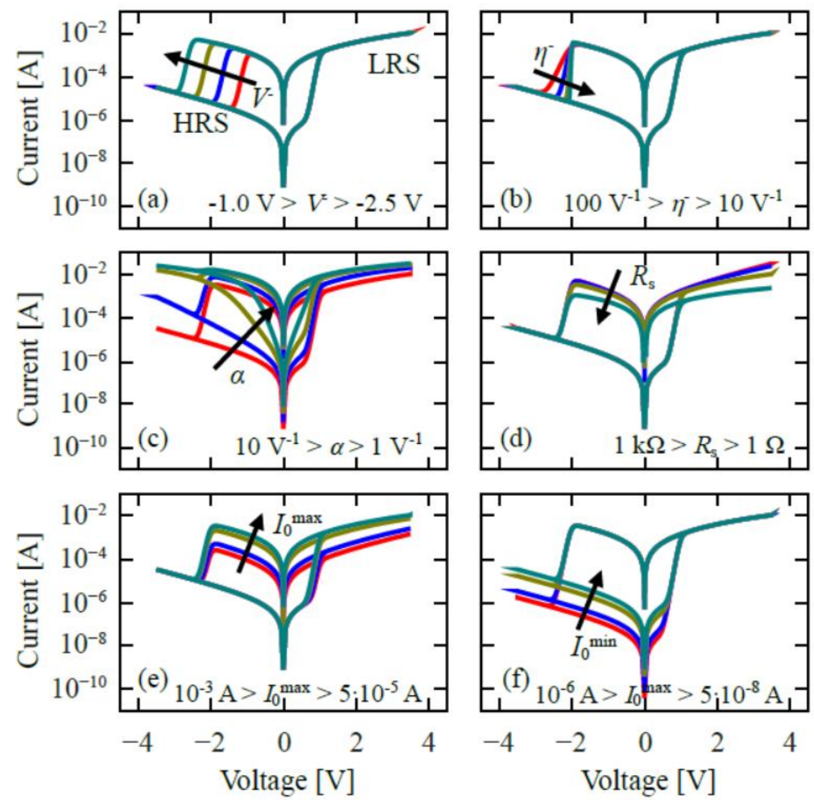


Open-source Modelica-based modeling and simulation environment intended for industrial and academic usage (https://www.openmodelica.org/)
(free software)

Memdiode model in LTSPICE

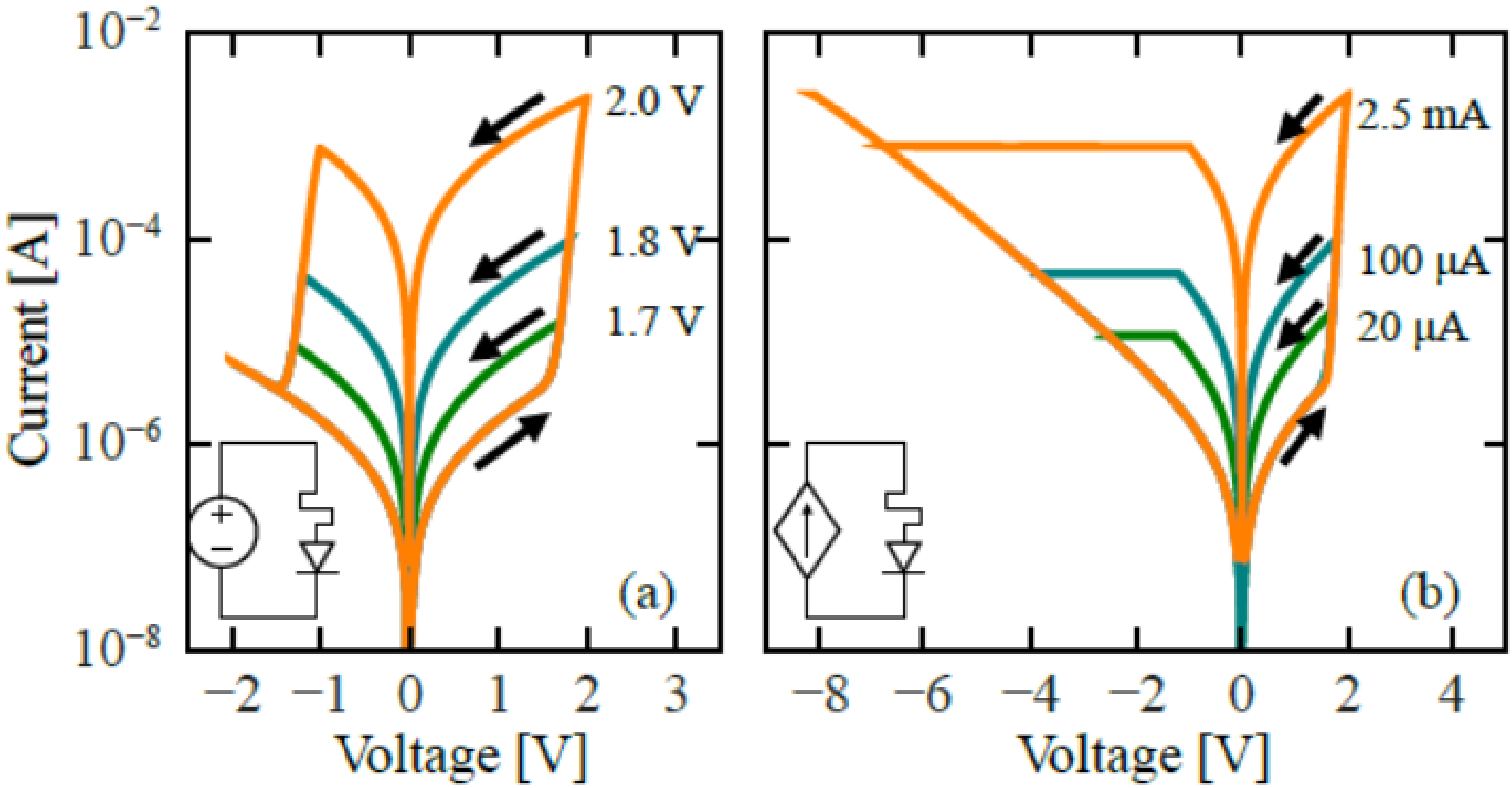
```
.subckt memdiode + -
.params
ion=1e-2 aon=3 ron=100 ioff=1e-4 aoff=1 roff=100
+ nset=10 vset=0.5 nres=10 vres=-0.5 CH0=1e-4 H0=0
****************************************
* STATE EQUATION MODELING *
BH 0 H I=min(R(V(+,-)),max(S(V(+,-)),V(H))) Rpar=1
CH H 0 {CH0} ic={H0}
****************************************
* RESISTIVE PORT MODELING *
BR + - I=sgn(V(+,-))*(1/(a(V(H))*RS(V(H)))*w(a(V(H))*
+ RS(V(H))*I0(V(H))*exp(a(V(H))*(abs(V(+,-))+RS(V(H))*
+ I0(V(H)))))-I0(V(H))) Rpar=1e10
****************************************
* AUXILIARY FUNCTIONS *
.func w(x)=log(1+x)*(1-(log(1+log(1+x)))/(2+log(1+x)))
.func I0(x)=ion*x+ioff*(1-x)
.func a(x)=aon*x+aoff*(1-x)
.func RS(x)=ron*x+roff*(1-x)
.func S(x)=1/(1+exp(-nset*(x-vset)))
.func R(x)=1/(1+exp(-nres*(x-vres)))
.ends memdiode
```





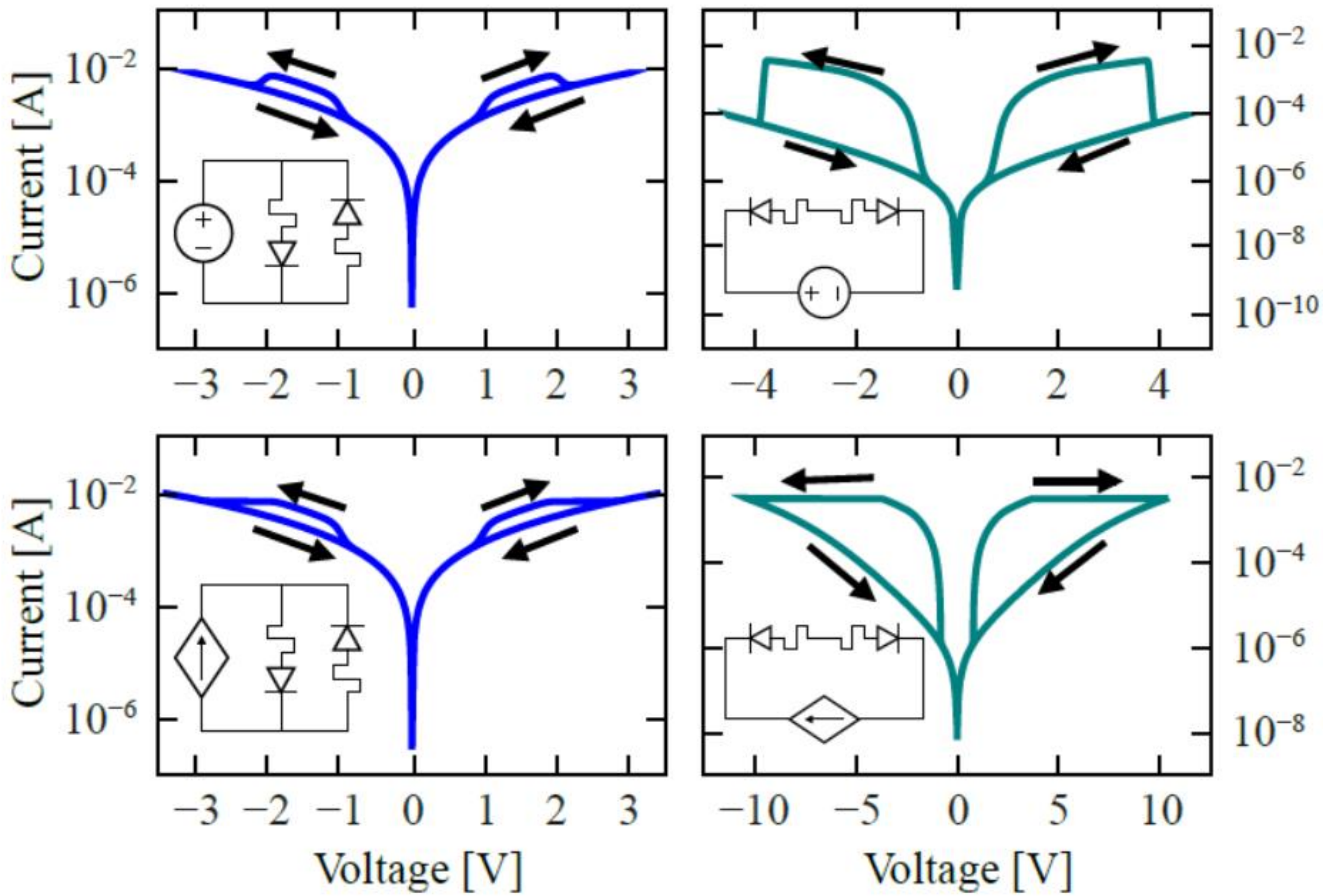
G. Patterson *et al*, IEEE Trans Comp Aided Design, 2017

Simple circuits with memdiodes



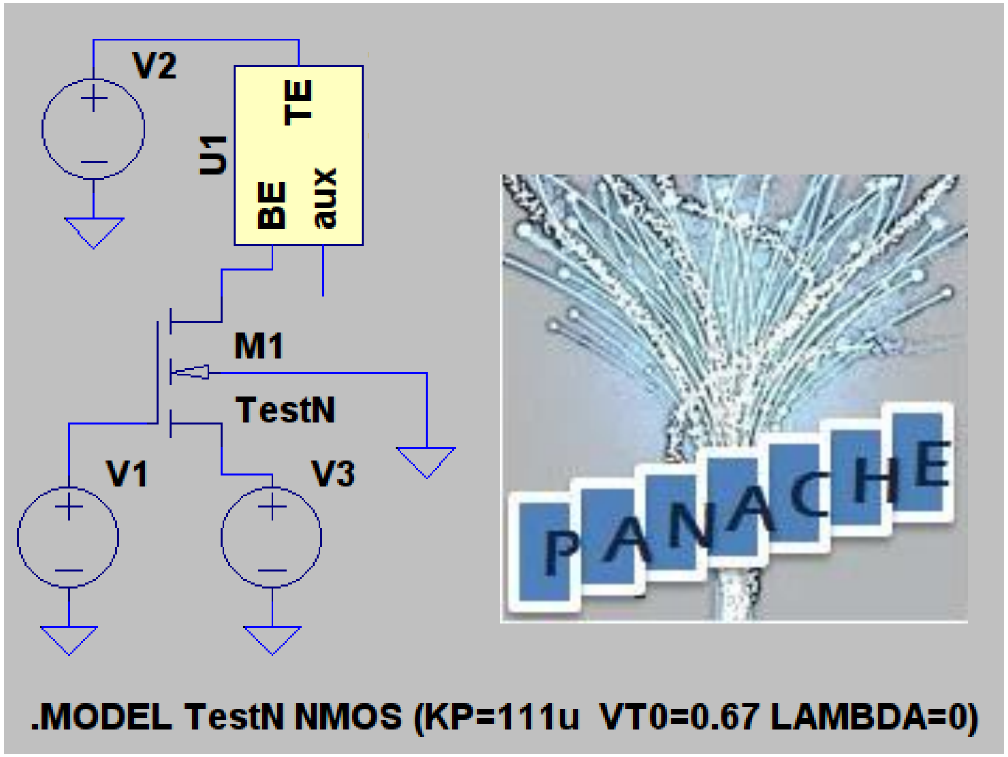
Memdiodes driven by voltage and current sources

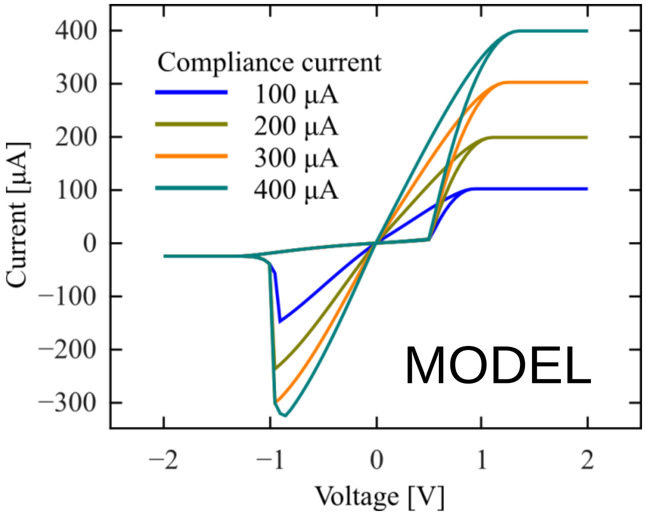
Simple circuits with memdiodes

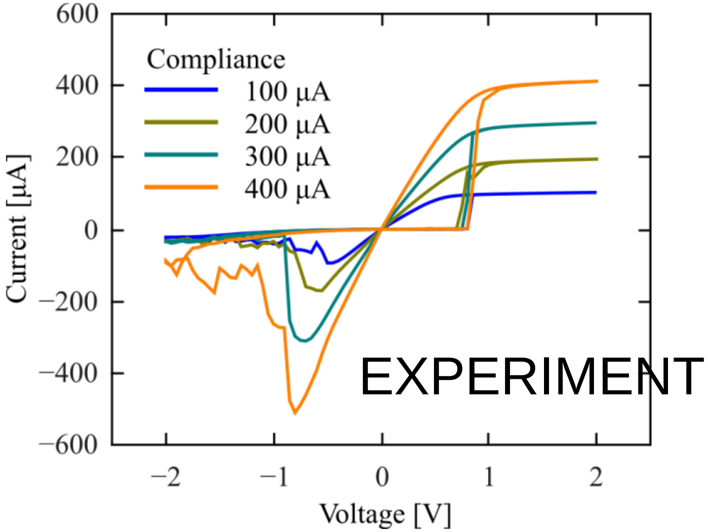


Parallel and series memdiodes driven by voltage and current sources

Simulations of 1T1R structures (EU Project PANACHE)



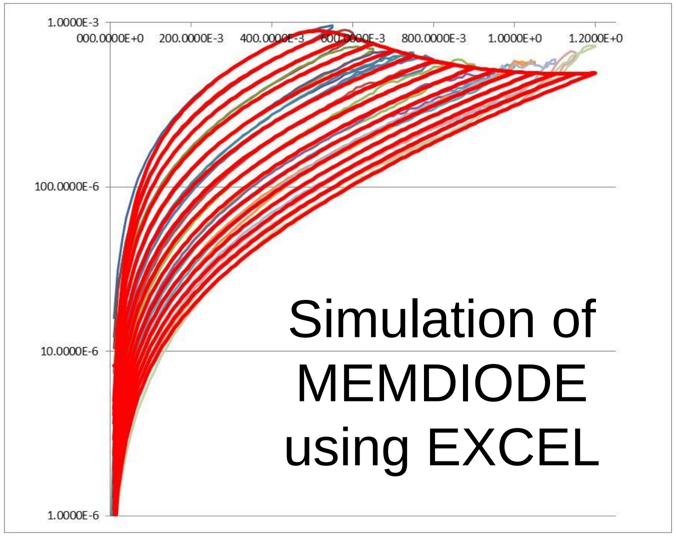


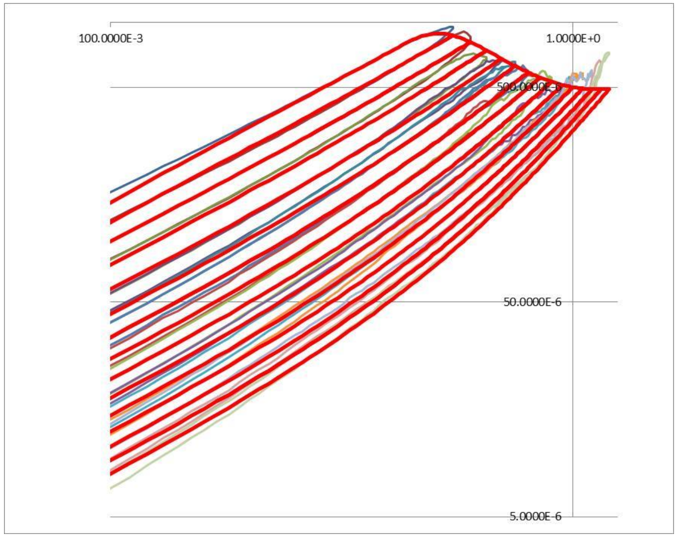


Memdiode controlled by access transistor

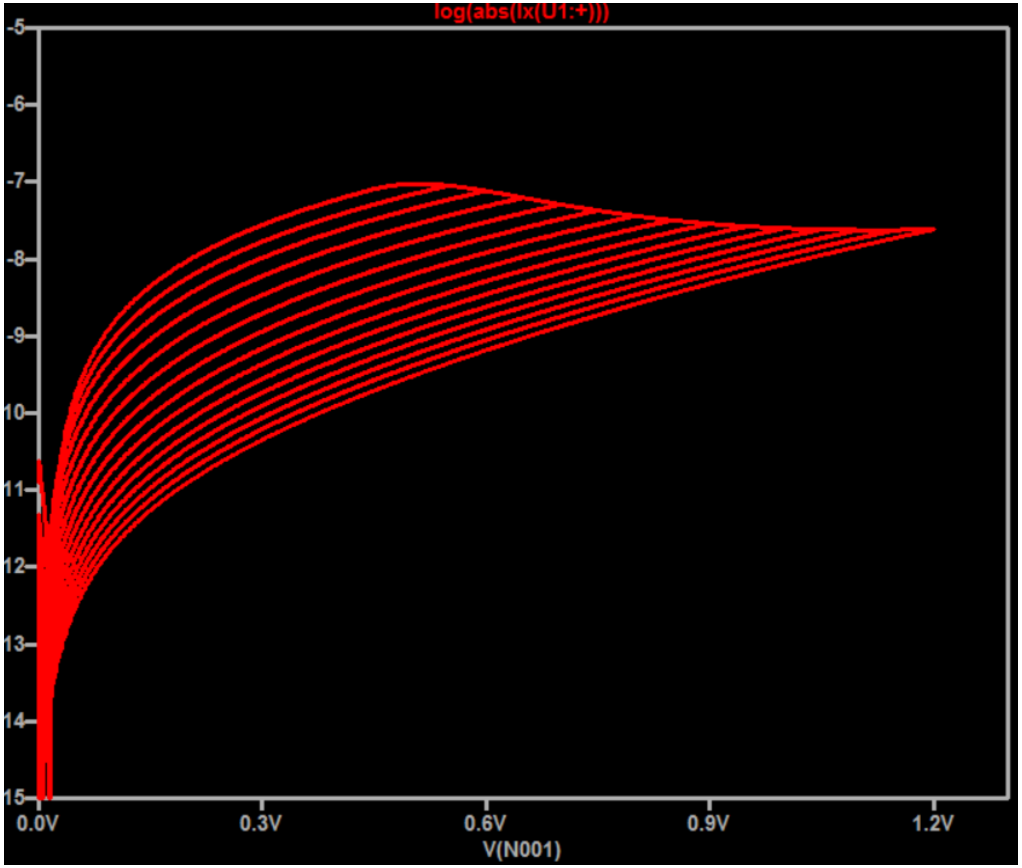
In collaboration with LETI, France

Model and simulation results for SiO_x





Simulation of MEMDIODE using LTSpice



Modeling multi-level conduction

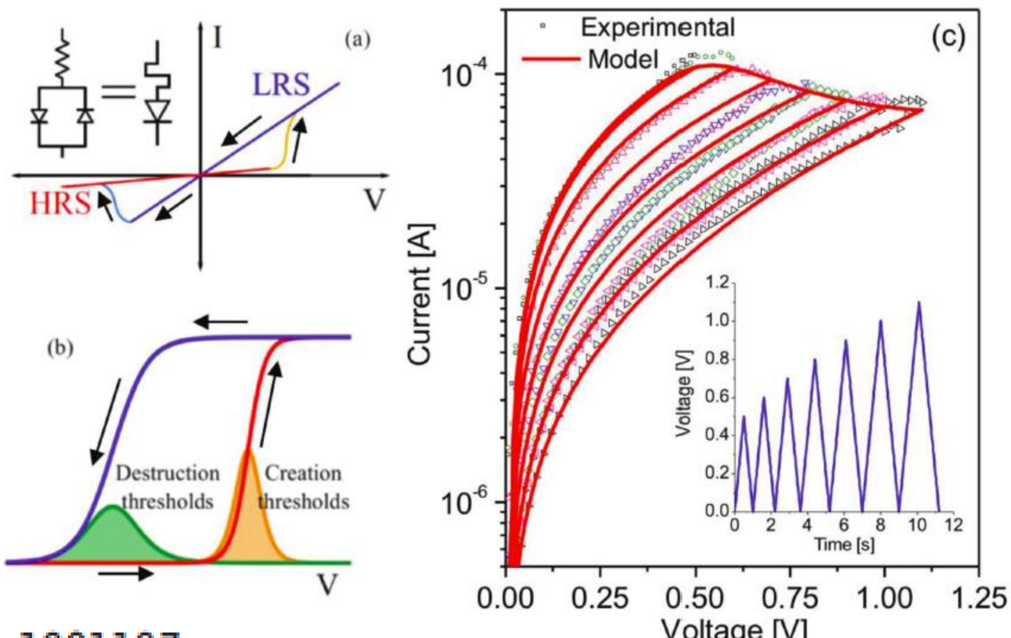
In collaboration with UCL, UK

ADVANCED MATERIALS

www.advmat.de

Silicon Oxide (SiO_x): A Promising Material for Resistance Switching?

Adnan Mehonic, Alexander L. Shluger, David Gao, Ilia Valov, Enrique Miranda, Daniele Ielmini, Alessandro Bricalli, Elia Ambrosi, Can Li, J. Joshua Yang, Qiangfei Xia, and Anthony J. Kenyon**

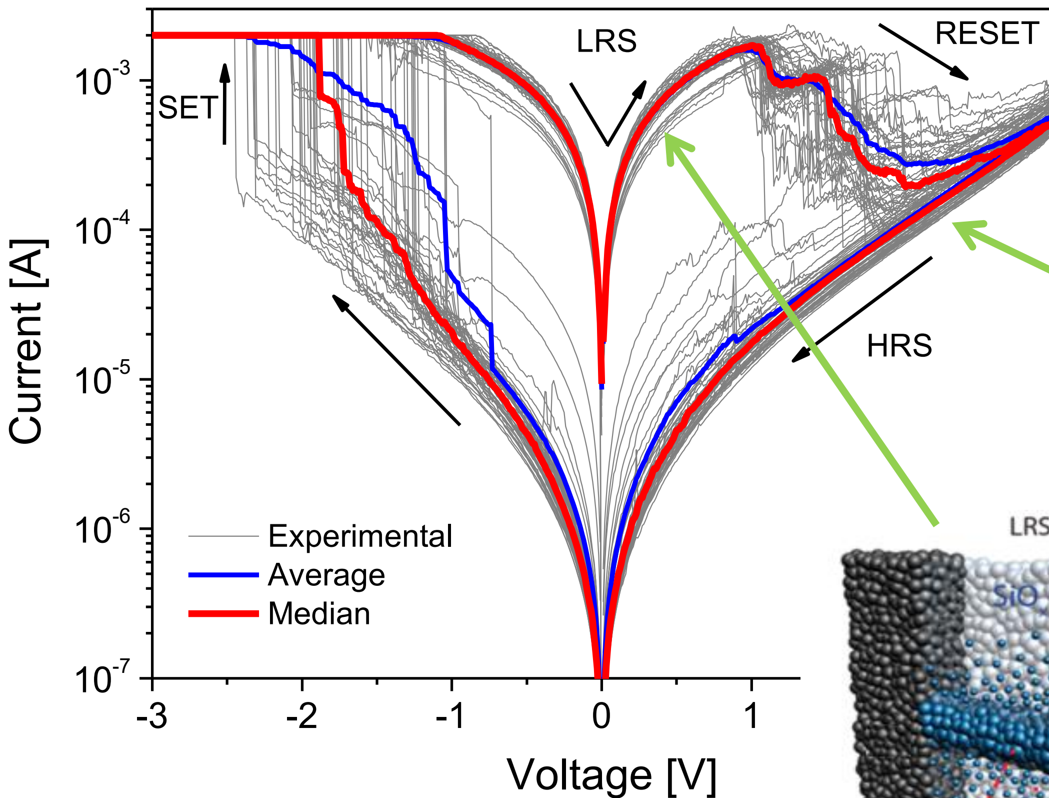


Adv. Mater. **2018**, 1801187

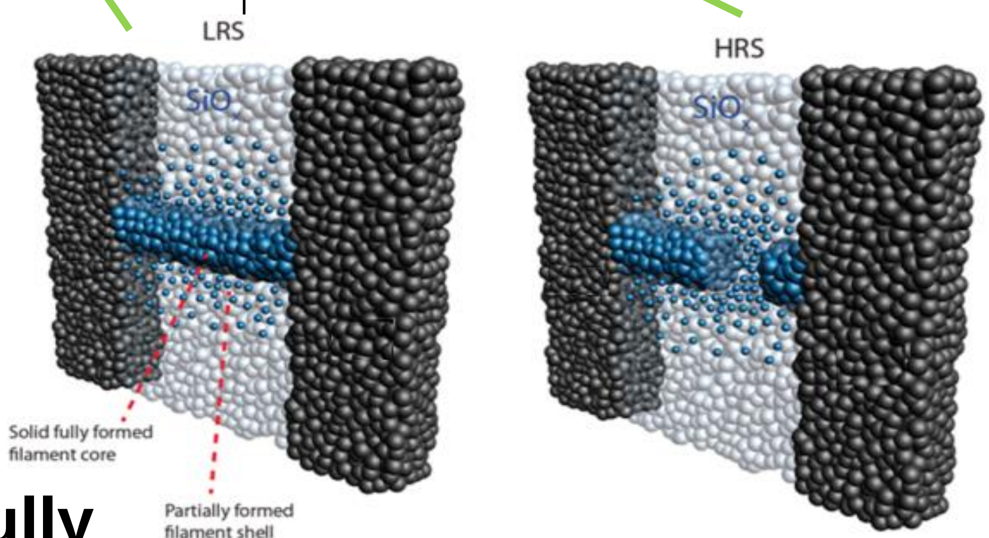
Outline

- Introduction to filamentary-type ReRAM
- Physical models and quantum limit
- The circuital approach
- Model implementation
- The problem of variability
- Final comments

Variability in SiO_x-based ReRAM devices



HRS: partially formed filament



LRS: fully formed filament

Origin of variability

VARIABILITY

EXTRINSIC

Device-to-device:

- *area*
- *thickness*
- *roughness*
- *composition*
- *contacts*
- …

MEASUREMENT

- *Cycling protocol*
- *Current limitation*
- *Ageing effects*
- *Signal excursion*

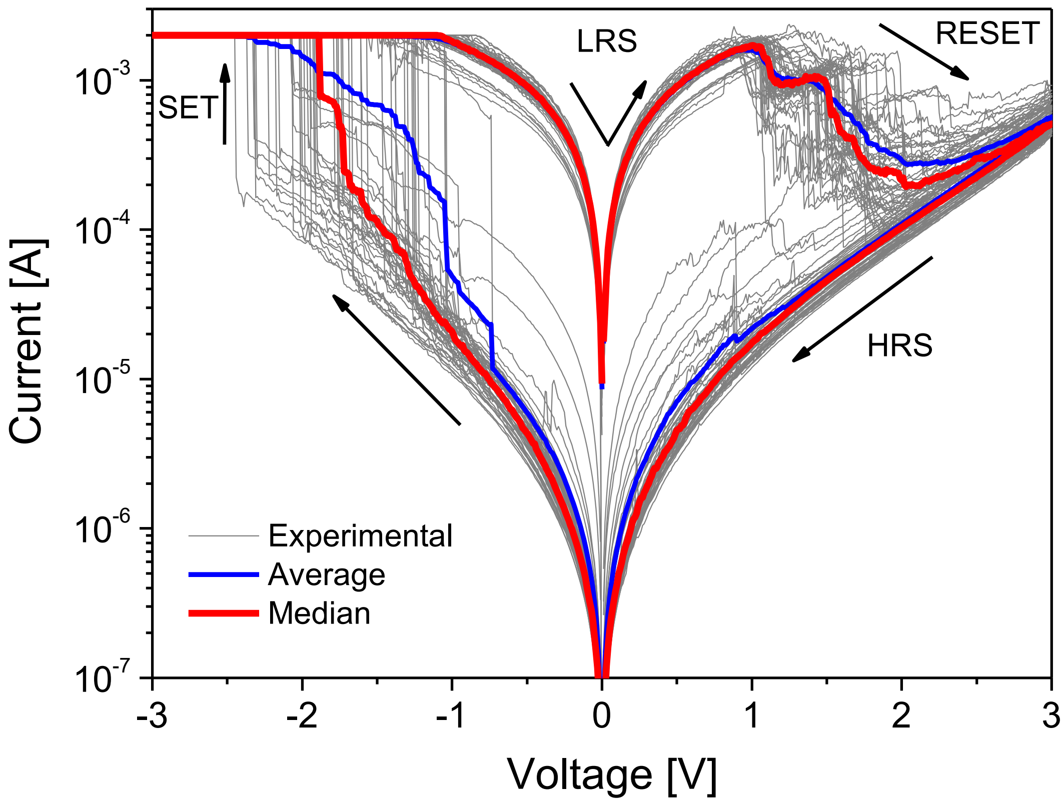
INTRINSIC

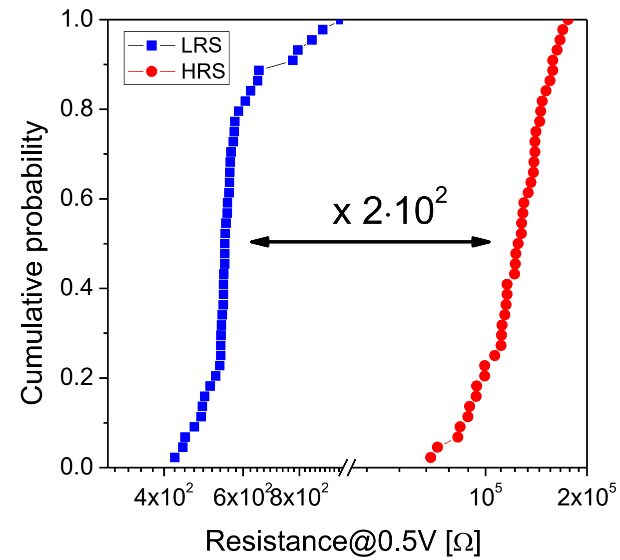
Discrete nature of the problem:

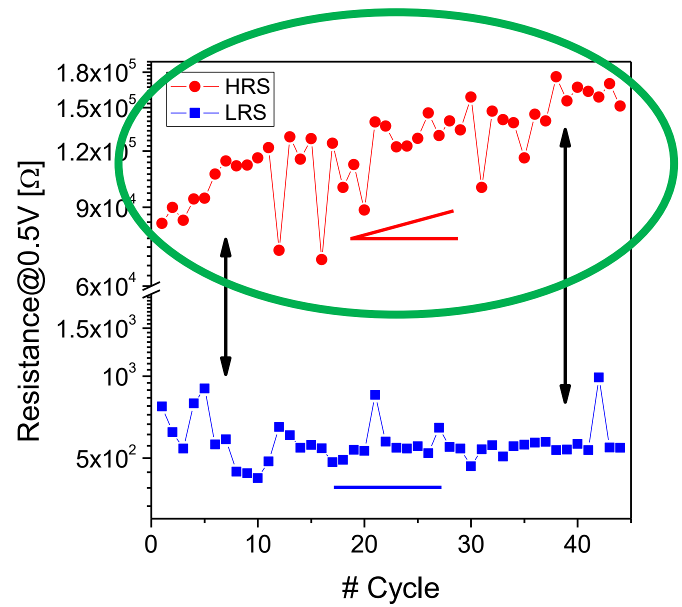
- *dopant fluctuations*
- *morfophology of the CF*
- …

Variability is also affected by the way we measure

Effects of cycling on SiO_x (C2C)

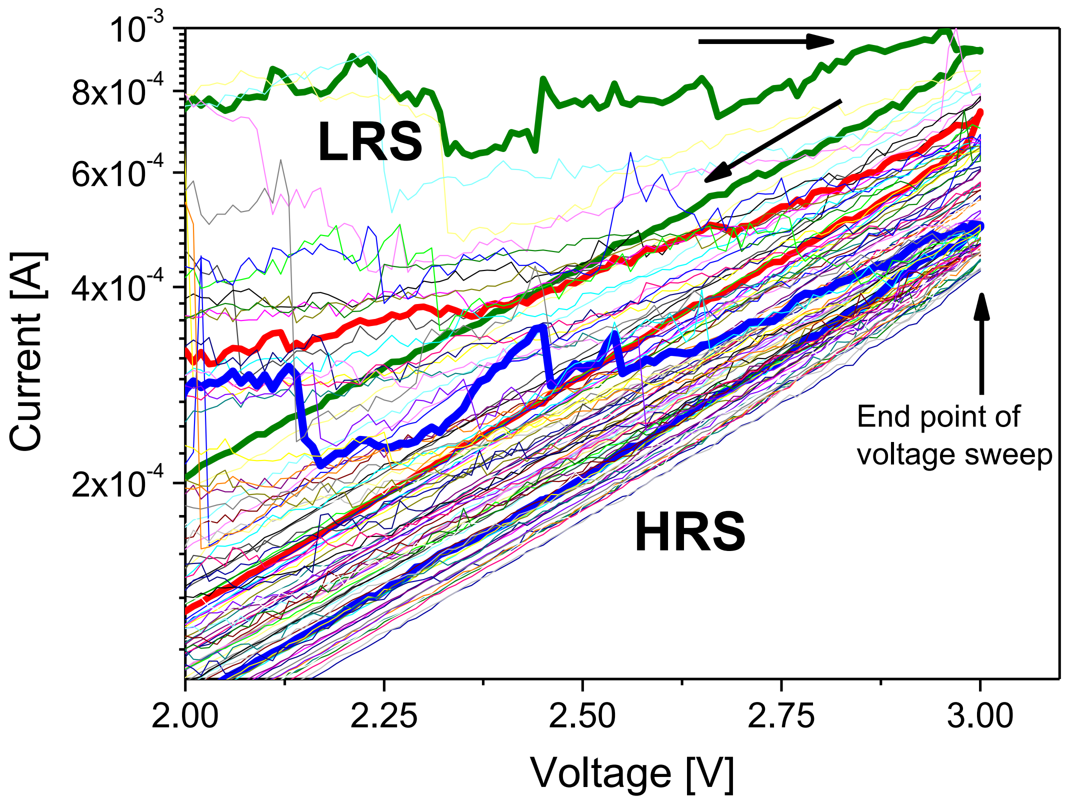


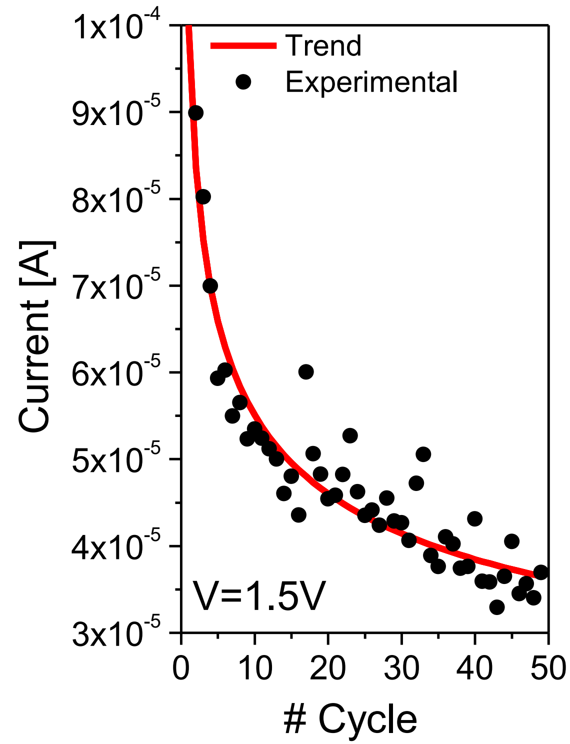




- Excellent cyclability
- Good resistance window
- **Trend in HRS**

Effects of cycling on SiO_x (C2C)





- The trend in HRS is associated with the end point of the reset curve
  - **C2C is a stochastic process: trend + volatility**

Outline

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- Final comments

Latest news:

- Fujitsu and Panasonic are jointly ramping up a second-generation ReRAM device (OxRAM)
- Crossbar is sampling a 40nm ReRAM technology (CBRAM)
- TSMC and UMC recently put ReRAM on their roadmaps
- HP has moved towards a more traditional memory scheme for the system (“The machine”) and has backed away from the memristor
- 4DS, Adesto, Micron, Samsung, Sony and others are also developing ReRAM
- GlobalFoundries is not pushing ReRAM today

Source: Semiconductor Engineering (2017)

Will ReRAM technology succeed?

- ReRAM has proven to be far more difficult to develop than anyone initially expected
- NAND has scaled farther than previously thought, causing many to delay or scrap efforts in ReRAM
- ReRAM won't replace NAND or other memories, but it is expected to find its place, particularly in embedded memory applications
- ReRAMs are well-positioned as a low-cost solution for IoT, wearable devices, and neuromorphic computing
- Today, 3D-XPoint and STT-MRAM have the most momentum

Source: Semiconductor Engineering (2017)

Muito obrigado!

Any doubt? Write me: **enrique.miranda@uab.cat**