leti innovation for industry

Physical Compact Model of a CBRAM cell

Marina Reyboz, Santhosh Onkaraiah, Giorgio Palma and Elisa Vianello.

CEA-LETI Grenoble, France

Physical Compact Model of a CBRAM cell

I Introduction

1- Resistive memories
2- CBRAM cell

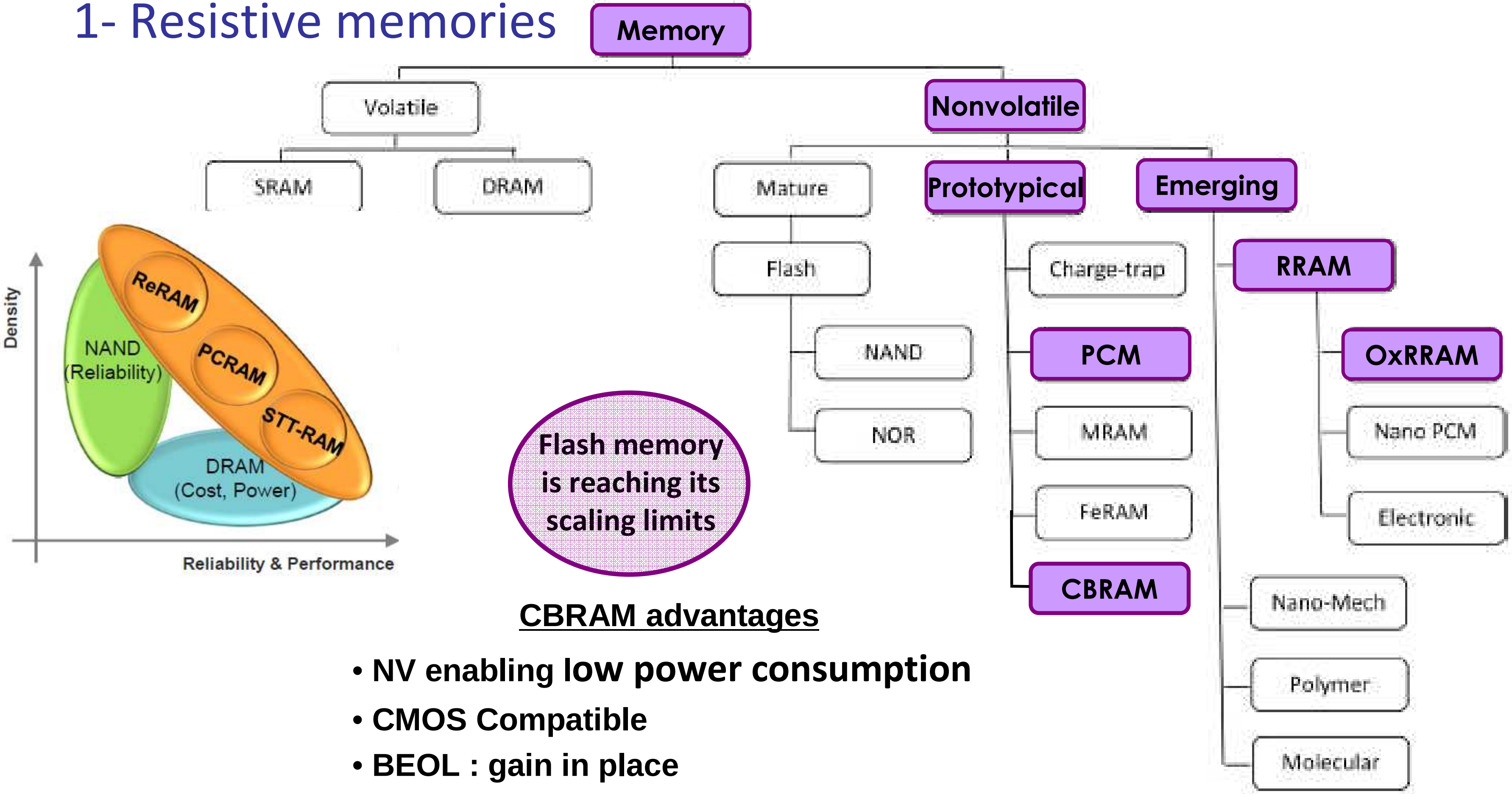
II Modelling

1- Physical modelling
2- Compact modelling
3- Calibration and validation on measurements
4- Validation in circuit design

III Conclusion and prospects

I Introduction

1- Resistive memories



Flash memory is reaching its scaling limits

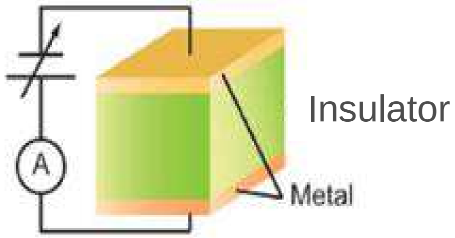
CBRAM advantages

- **NV enabling low power consumption**
- **CMOS Compatible**
- **BEOL : gain in place**
- **Fast written**
- **Scaling till 8 nm node (ITRS 2010)**
- **Multilevel**
- **Low cost (simple process)**

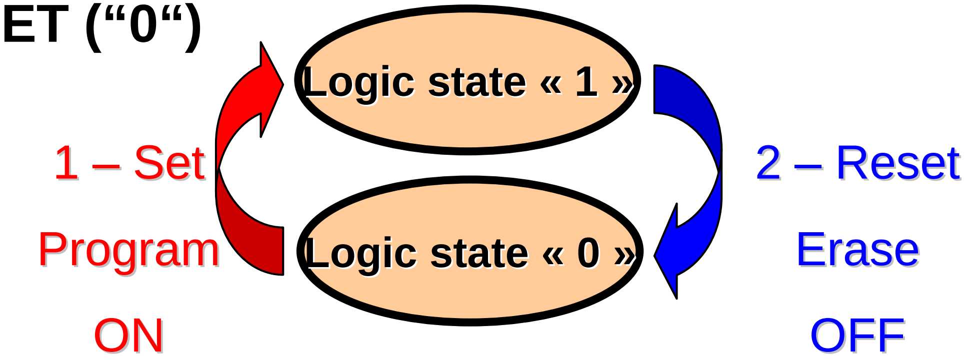
I Introduction

1- Resistive memories

- MIM structure: Metal / Insulator / Metal



-At least 2 resistive states (or more) depending on the applied voltage: SET (“1“) and RESET (“0“)



1 – Set

Program

ON

Logic state « 1 »

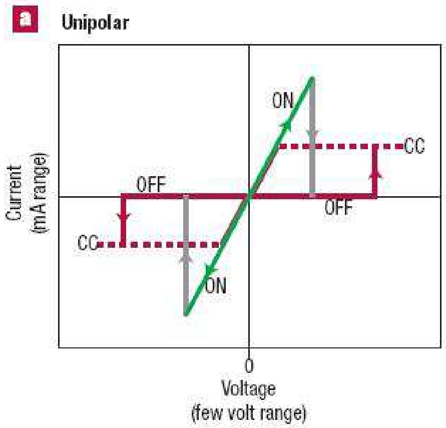
Logic state « 0 »

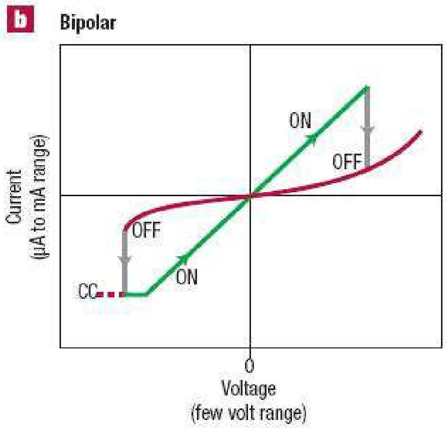
2 – Reset

Erase

OFF

- Electrical behaviours

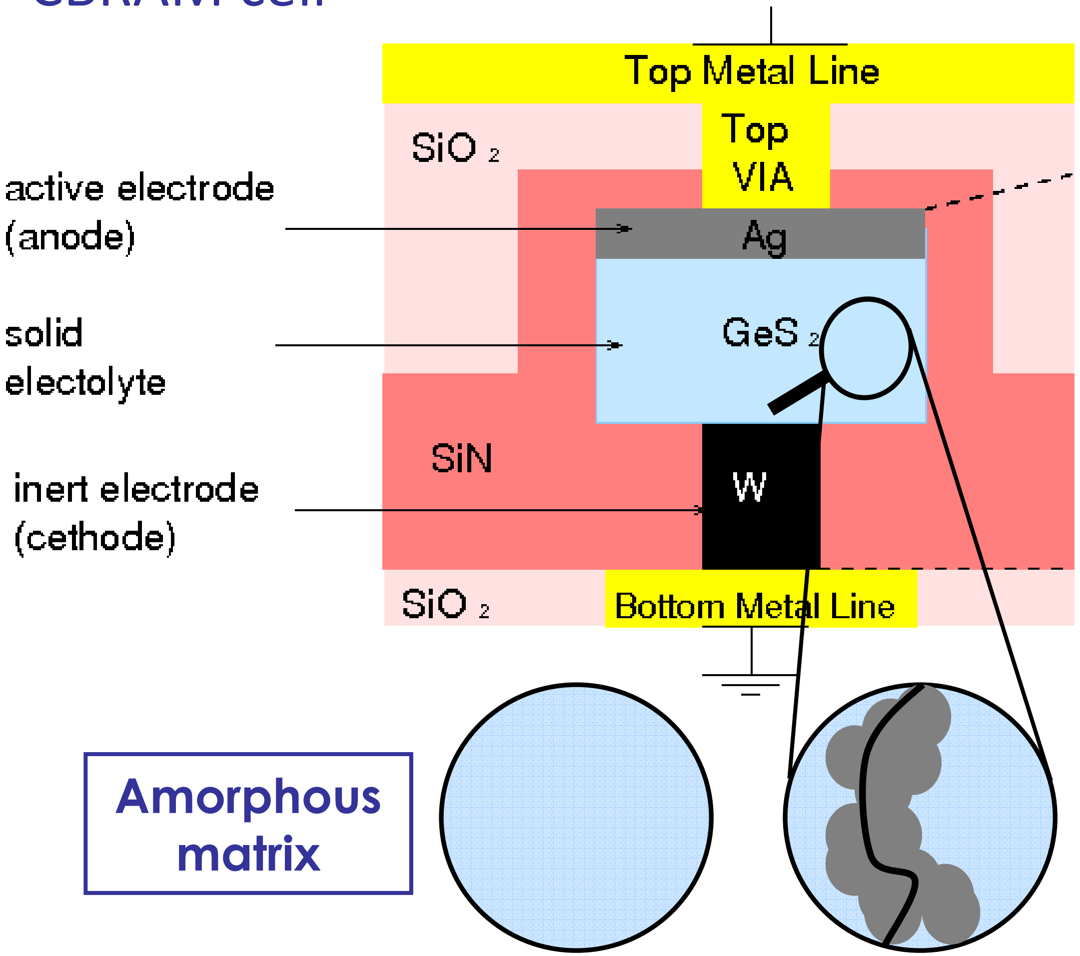




R. Waser *et al.*, *Advanced Materials*, vol. 21, 2009.

I Introduction

2- CBRAM cell



Amorphous matrix

OFF

ON

Creation of a conductive filament (CF) in the amorphous matrix

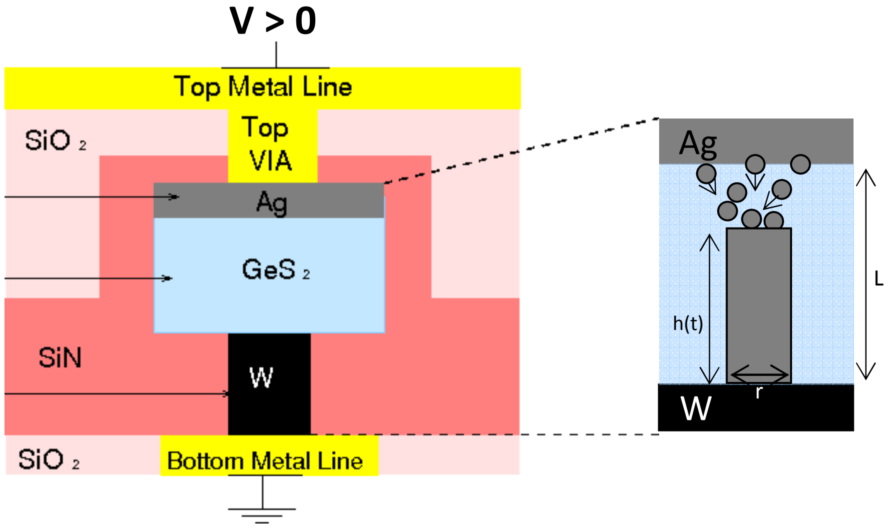
II Modelling

V > 0

1- Physical modelling: SET definition

- ✓ **Vertical growth of the conductive filament to SET the resistive RAM (h=L). No horizontal increase of the filament is taken into account as it is negligible.**

1D MODEL



- ✓ **The diffusion of Ag ions is modelled as a Mott-Gurney ionic hopping current**

$$\frac{dh}{dt} = v_h \, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\alpha q (V - \Delta^{*})}{kT}\right) \Rightarrow h = h_0 + v_h \, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\alpha q (V - \Delta^{*})}{kT}\right) t$$

v_h is vertical velocity, Ea the activation energy, k Boltzmann constant, T temperature, α vertical electric field dependence, q the elementary charge, V the applied voltage and h_0 the initial height

Time of the pulse

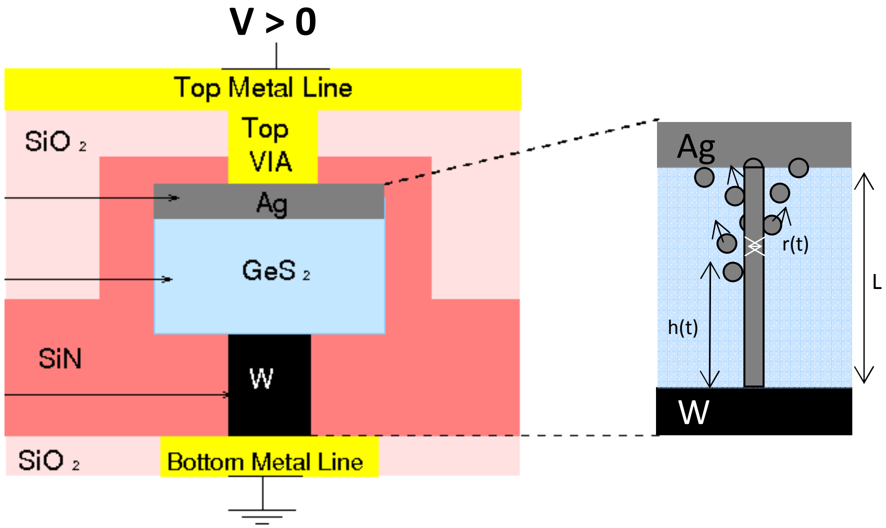
*, G. Palma *et al.* « Experimental investigation and empirical modeling of the set and reset kinetics of Ag-GeS2 Conducting Bridge Memories », IMW 2012.

II Modelling

V < 0

1- Physical modelling: RESET definition

- ✓ **Lateral decrease of the radius of the filament till r≈0.**



- ✓ **The diffusion of Ag ions is modelled by a Mott-Gurney ionic hopping current**

Time of the pulse

$$\frac{dr}{dt} = v_r\, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\beta q (V-\overset{*}{\Delta})}{kT}\right) \Rightarrow r = r_0 + v_r\, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\beta q (V-\overset{*}{\Delta})}{kT}\right) t$$

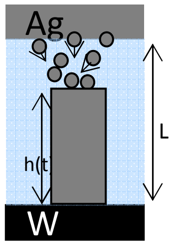
v_r is lateral velocity, β lateral electric field dependence and r_0 the initial radius

- ✓ **Electrochemical reaction processes are neglected**

***, G. Palma *et al.* « Experimental investigation and empirical modeling of the set and reset kinetics of Ag-GeS2 Conducting Bridge Memories », IMW 2012.**

II Modelling

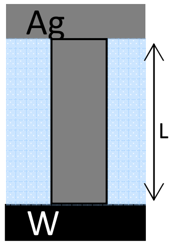
1- Physical modelling: resistance and current derivations



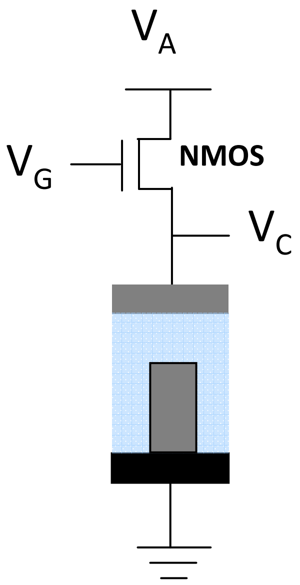
- Resistance derivation before SET occurs

$$R_{SET} = \frac{\rho_{on}\, h + \rho_{off}\,(L - h)}{\pi\, r^2}$$

ρ_{on} is the CF resistivity and ρ_{off} the electrolyte resistivity

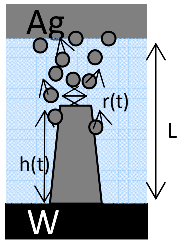


- Resistance derivation after SET : the current is limited by a compliance current thanks to a transistor



$$R_{ON} = \frac{C}{I_{comp}}$$

C is a fitting parameter



- Resistance before RESET

$$R_{RESET} = \frac{\rho_{on}\, L}{\pi\, r^2}$$

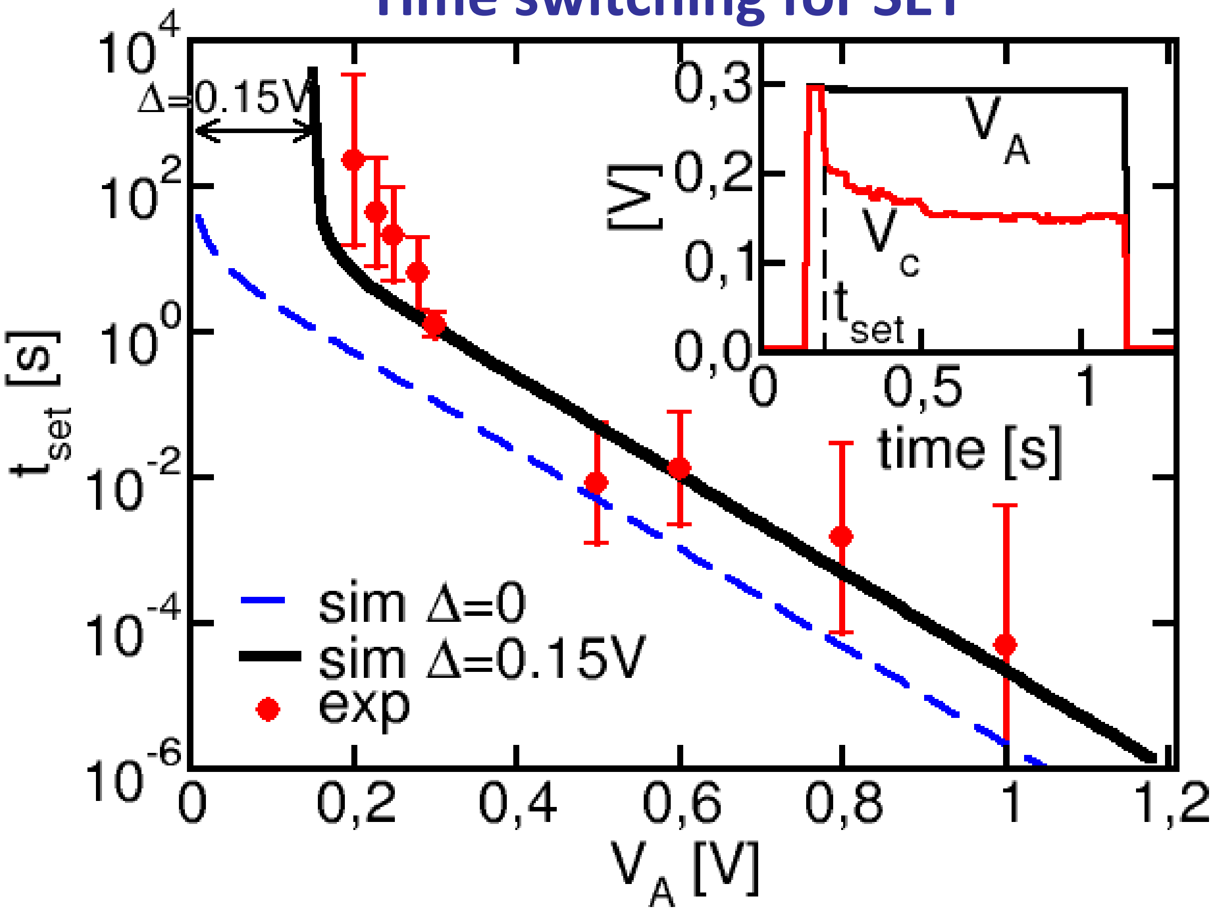
- Current through the CBRAM cell

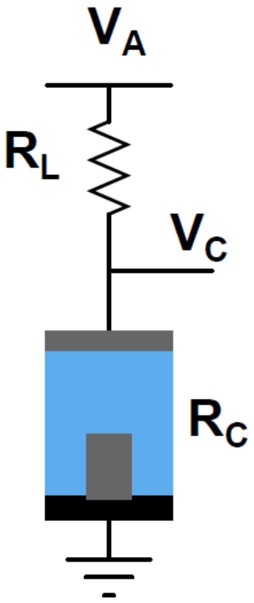
$$I_{CBRAM} = \frac{V_{CBRAM}}{R_{CBRAM}}$$

II Modelling

1- Physical modelling: validation on measurements

Time switching for SET

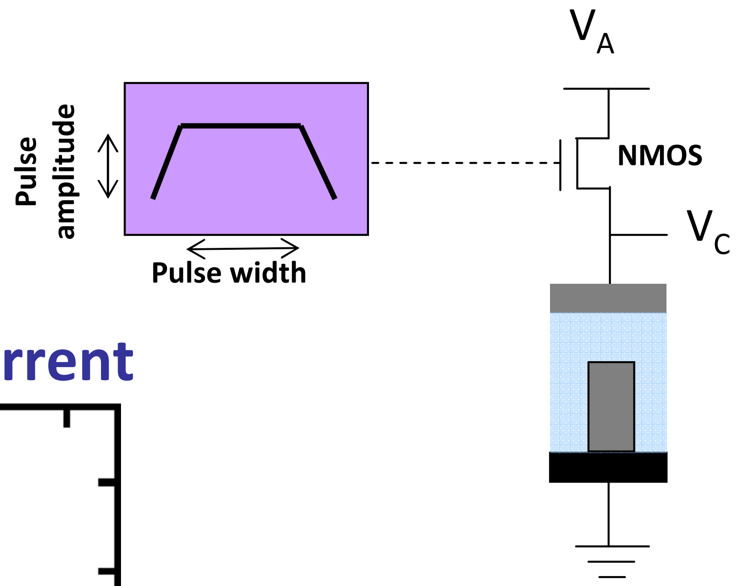




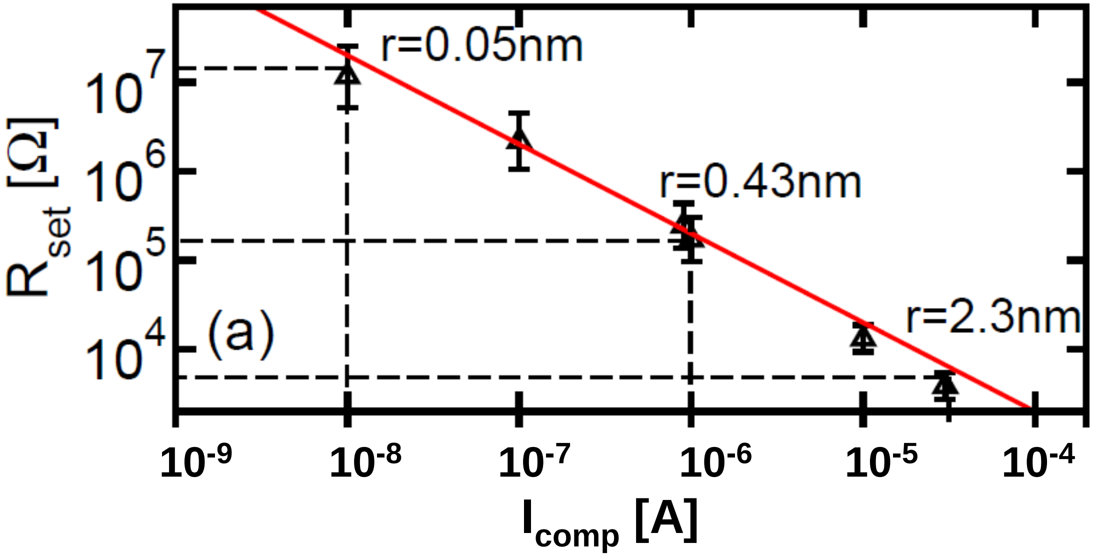
G. Palma *et al.* « Experimental investigation and empirical modeling of the set and reset kinetics of Ag-GeS2 Conducting Bridge Memories », IMW 2012.

II Modelling

1- Physical modelling: validation on measurements



SET resistance versus compliance current

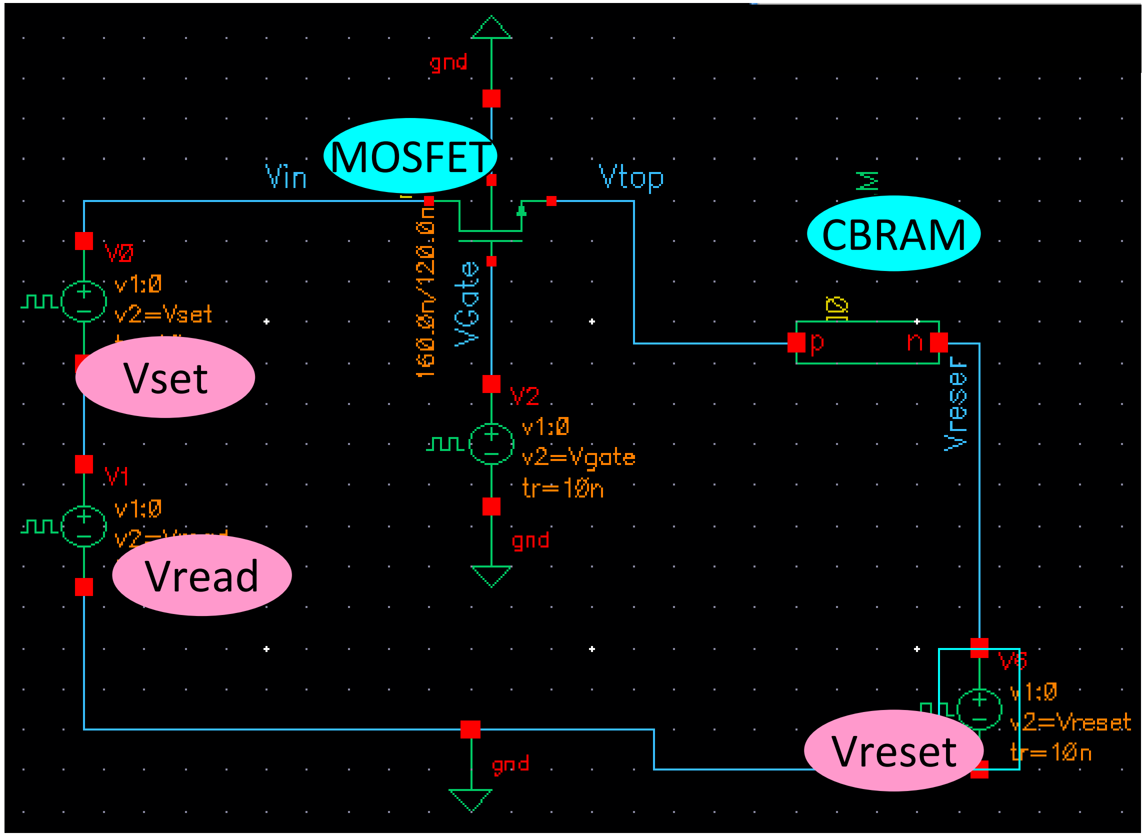


G. Palma *et al.* « Experimental investigation and empirical modeling of the set and reset kinetics of Ag-GeS2 Conducting Bridge Memories », IMW 2012.

II Modelling

2- Compact modelling : generalities

- **Implemented using Verilog-A**
- **Simulation using ELDO**
- **MOSFET to program the cell**



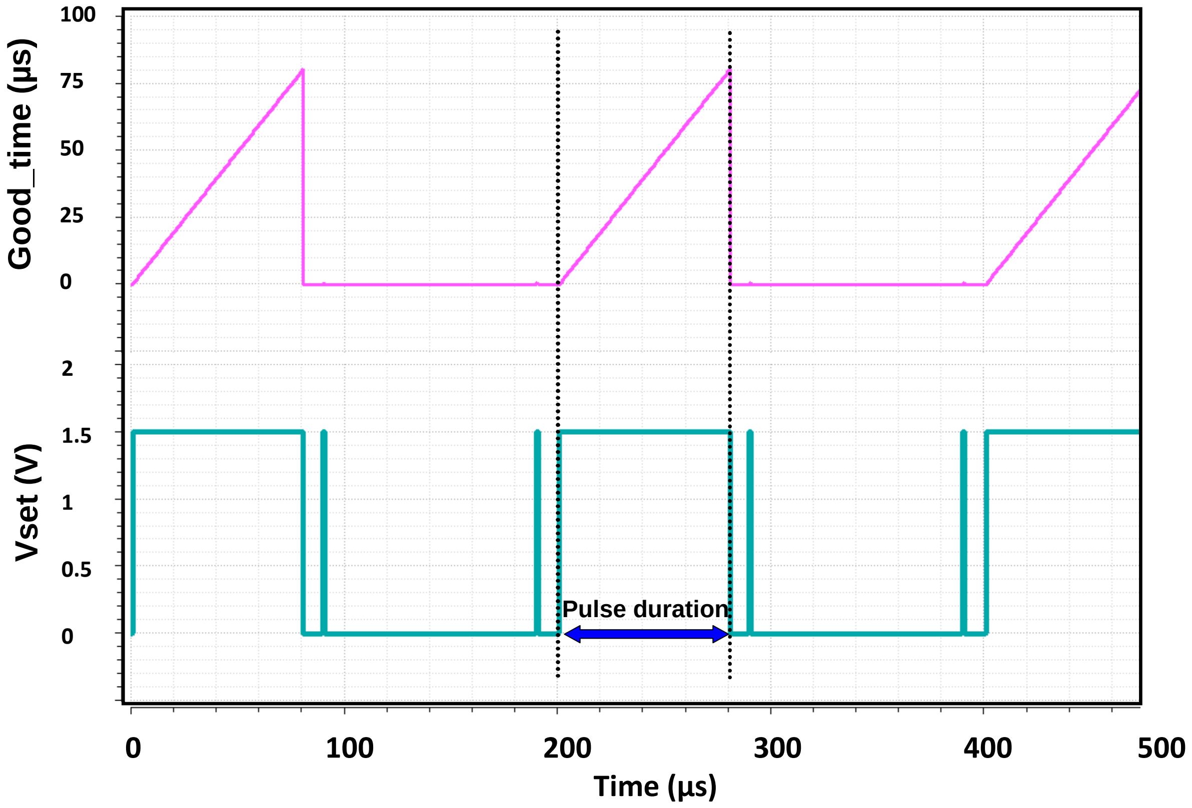
II Modelling

2- Compact modelling : time derivation

- Need to derive the vertical and lateral growth.

- Definition of a function (« good_time ») using $abstime to return the time of pulse.

Example for positive voltages



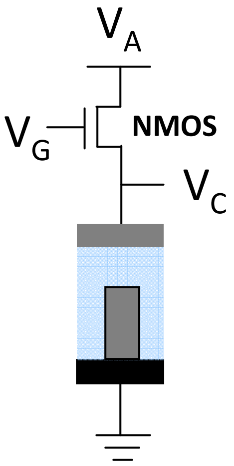
II Modelling

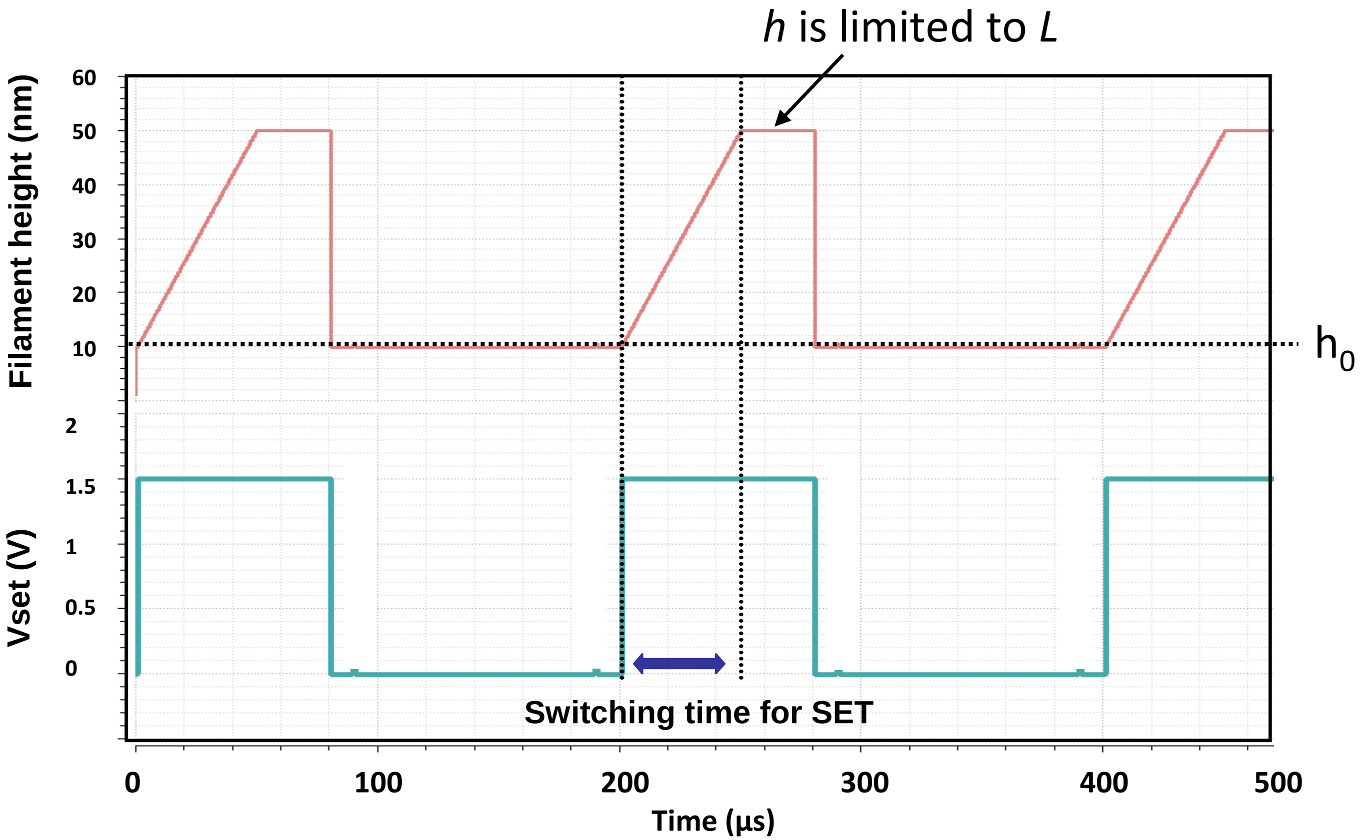
2- Compact modelling: height derivation

V > 0

$$\frac{dh}{dt} = v_h\, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\alpha\, q\,(V-\Delta^{*})}{kT}\right) \Rightarrow h = h_0 + v_h\, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\alpha\, q\,(V-\Delta^{*})}{kT}\right) t$$

h_0 is equal to 10 nm, L to 50 nm




h is limited to *L*

Switching time for SET

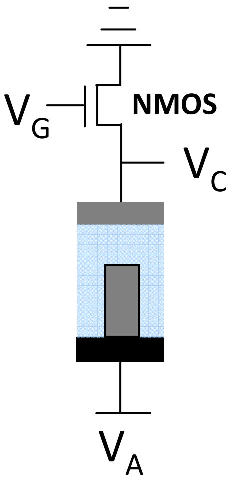
II Modelling

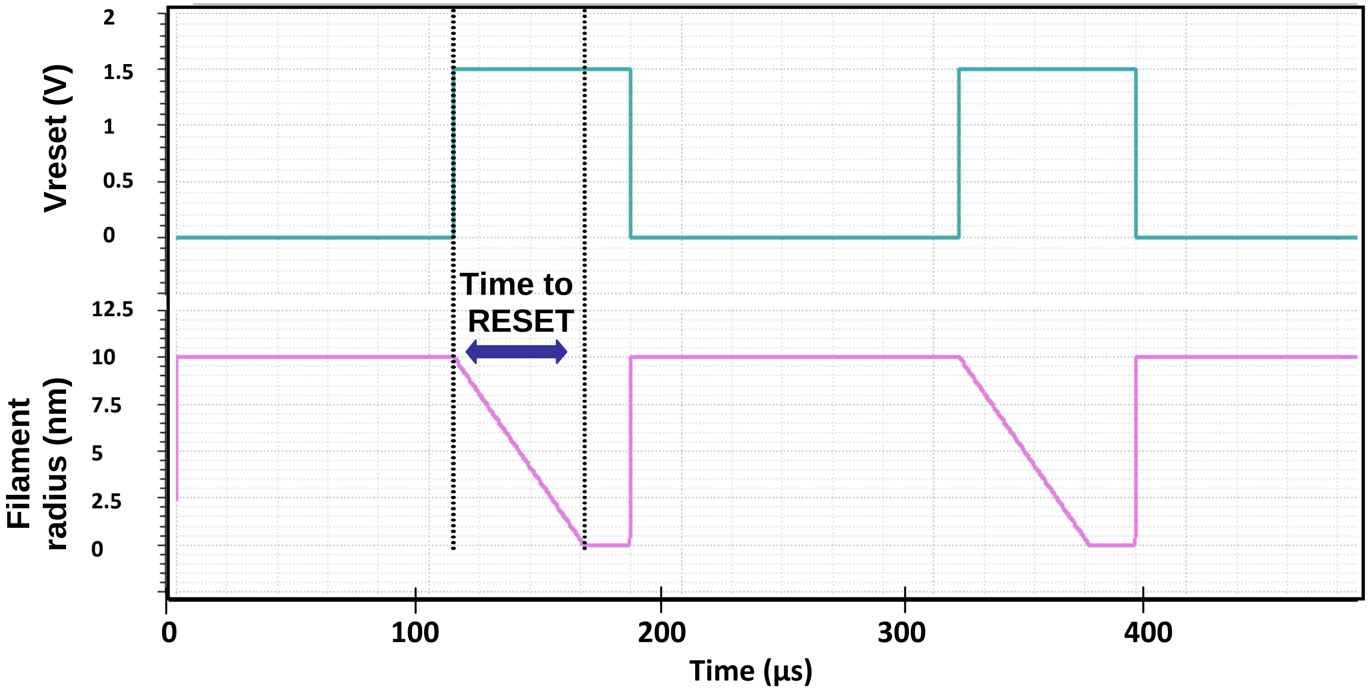
2- Compact modelling: radius derivation

V < 0

$$\frac{dr}{dt} = v_r\, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\beta q (V - \Delta^*)}{kT}\right) \Rightarrow r = r_0 + v_r\, e^{\left(\frac{-Ea}{kT}\right)} \sinh\left(\frac{\beta q (V - \Delta^*)}{kT}\right) t$$

r_0 is assumed 10 nm





II Modelling

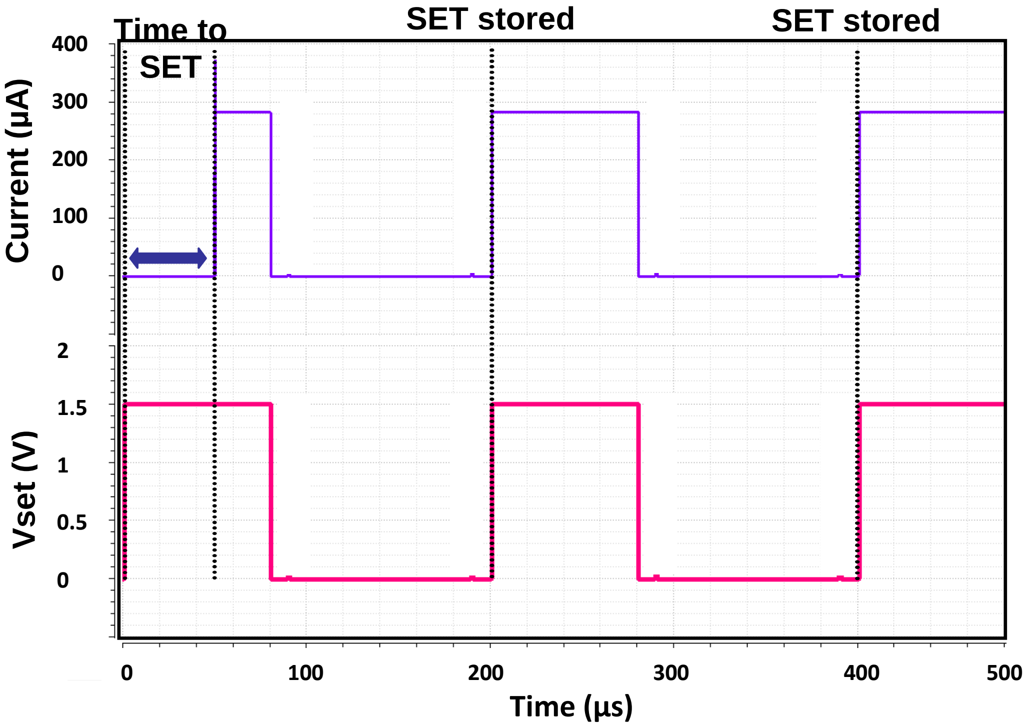
2- Compact modelling: information storage

Definition of a storage variable (« store ») to keep the state of the cell:

« store » = 1 if height of the CF is equal to L

« store » = 0 if radius of the CF is less than r_{min}

Example for the SET state:

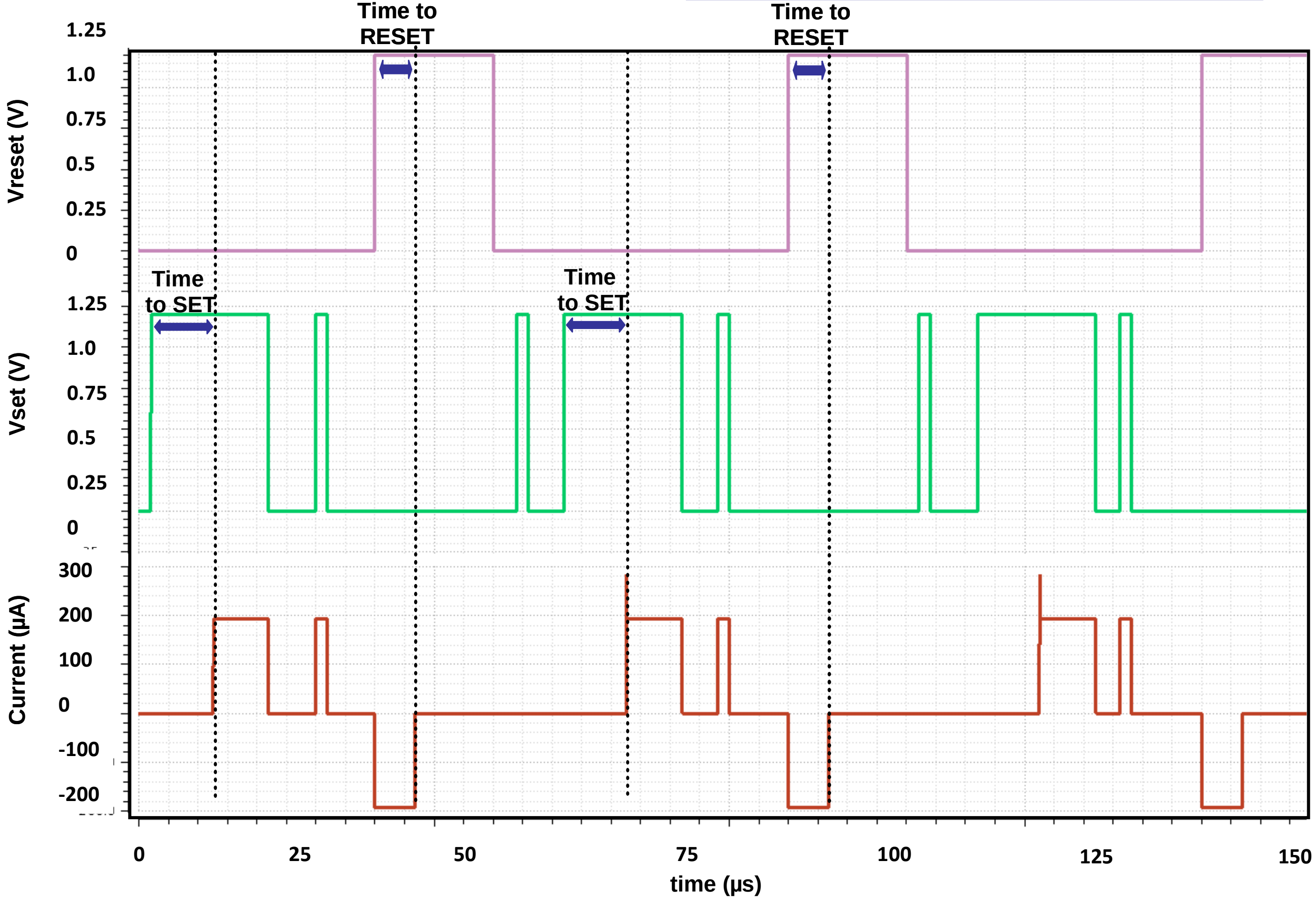


II Modelling

2- Compact modelling: resistance and current derivations

For continuity of the model, we use:

$$R = \left(R_{ON} - R_{OFF}\right)\left(1 + e^{\left(\frac{store - 0.5}{0.05}\right)}\right) + R_{ON}$$



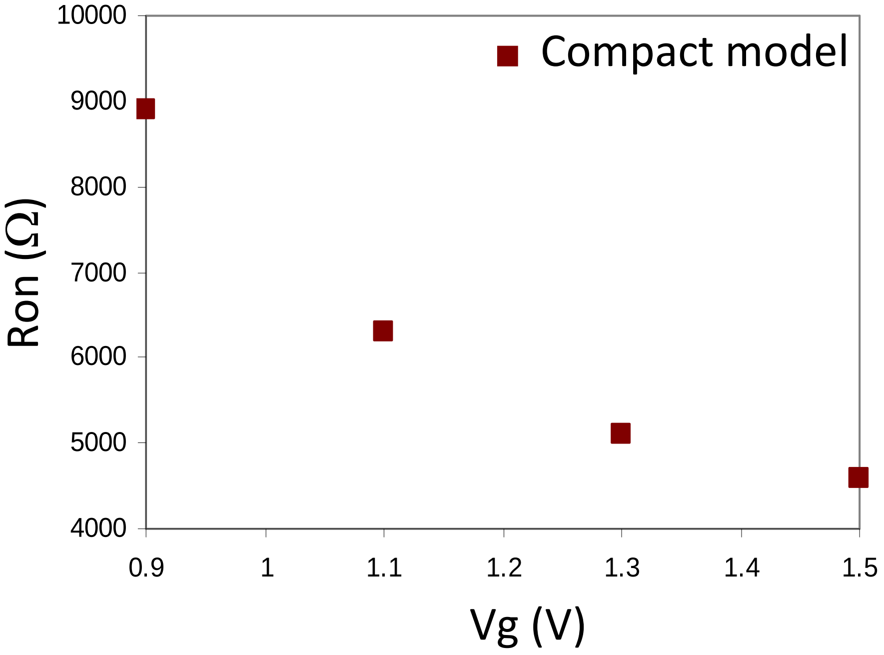
II Modelling

2- Compact modelling: compliance current effect

Using a polynomial function

$$R_{on} = \frac{R_{on0}}{V^{6}}$$

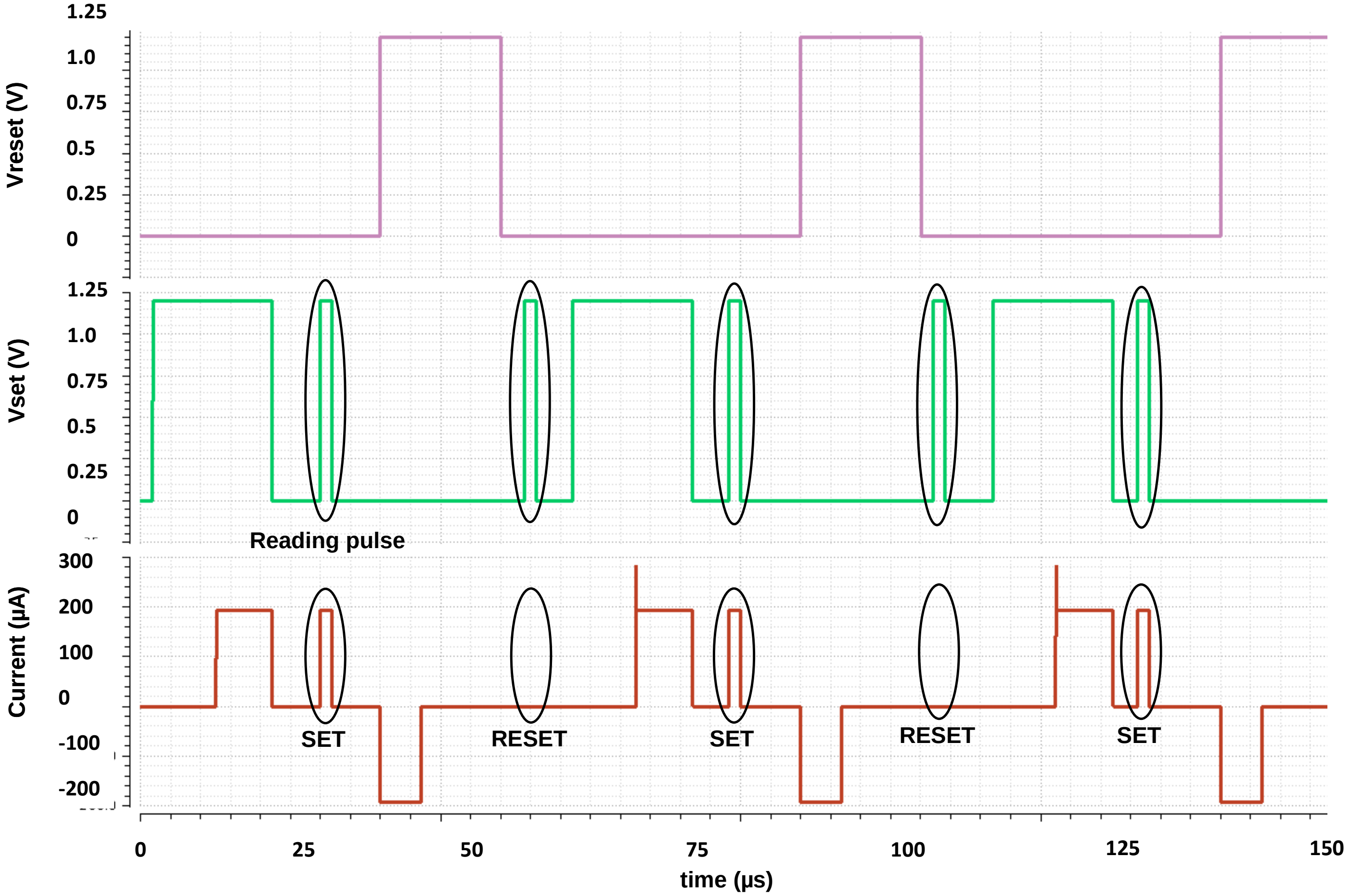
R_{on0} is a fitted parameter and *V* the voltage of the CBRAM



II Modelling

2- Compact modelling: reading

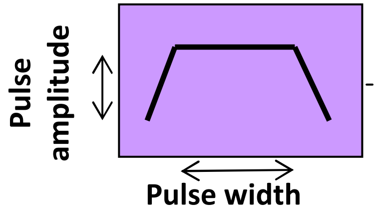
Reading is done at V_g = 1.5V for very short pulses, not to program the cell.



II Modelling

3- Calibration and validation on measurements

The model is calibrated on measurements. Parameters are given in the following table:



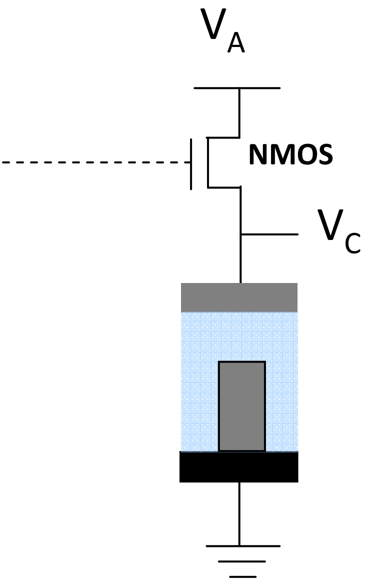
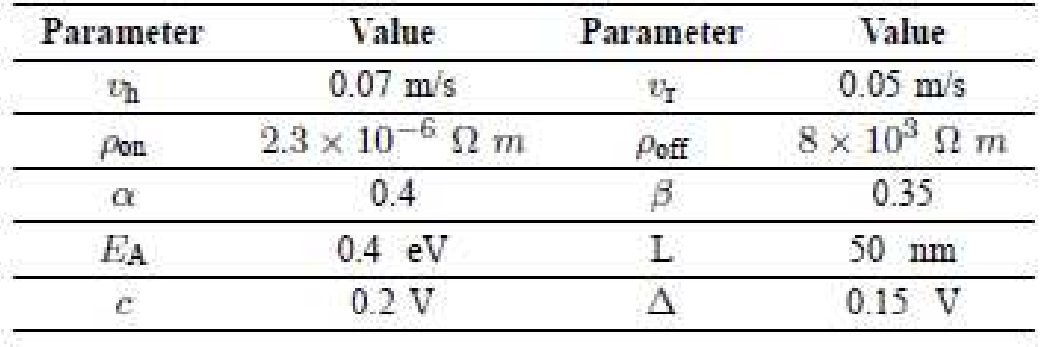


TABLE I
PARAMETERS USED

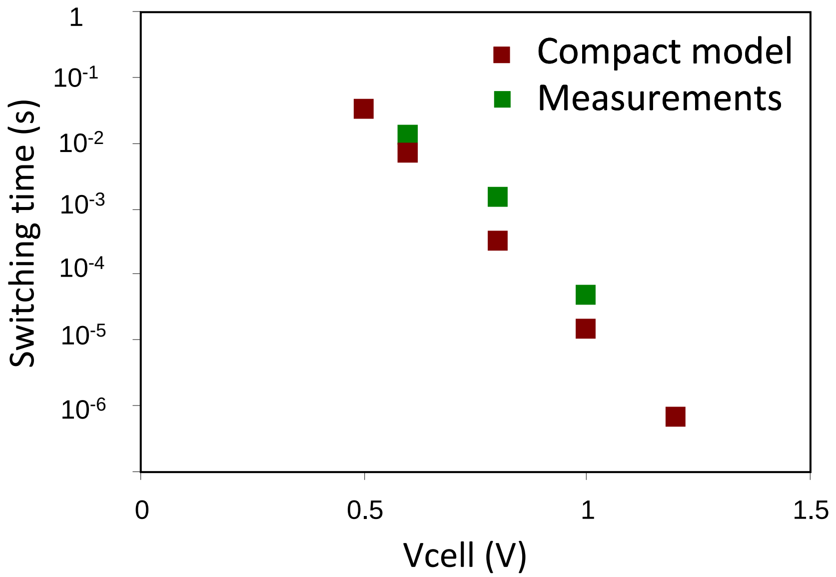


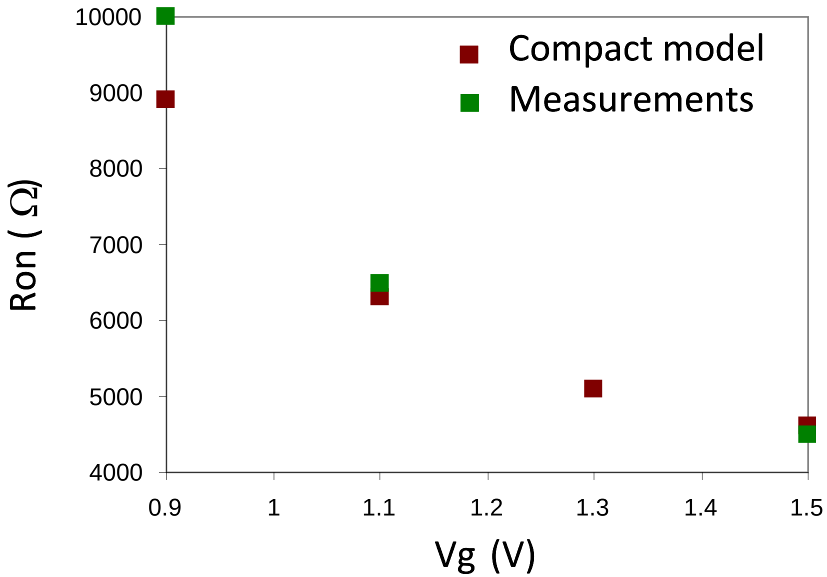
Parameter	Value	Parameter	Value
v_h	0.07 m/s	v_r	0.05 m/s
ρ_{on}	$2.3 \times 10^{-6}\ \Omega\ m$	ρ_{off}	$8 \times 10^{3}\ \Omega\ m$
α	0.4	β	0.35
E_A	0.4 eV	L	50 nm
c	0.2 V	Δ	0.15 V

G. Palma *et al.* « Experimental investigation and empirical modeling of the set and reset kinetics of Ag-GeS2 Conducting Bridge Memories », IMW 2012.

II Modelling

3- Calibration and validation on measurements





G. Palma *et al.* « Experimental investigation and empirical modeling of the set and reset kinetics of Ag-GeS2 Conducting Bridge Memories », IMW 2012.

II Modelling

4- Validation of the model in circuit design

Many circuits were done with the model as:

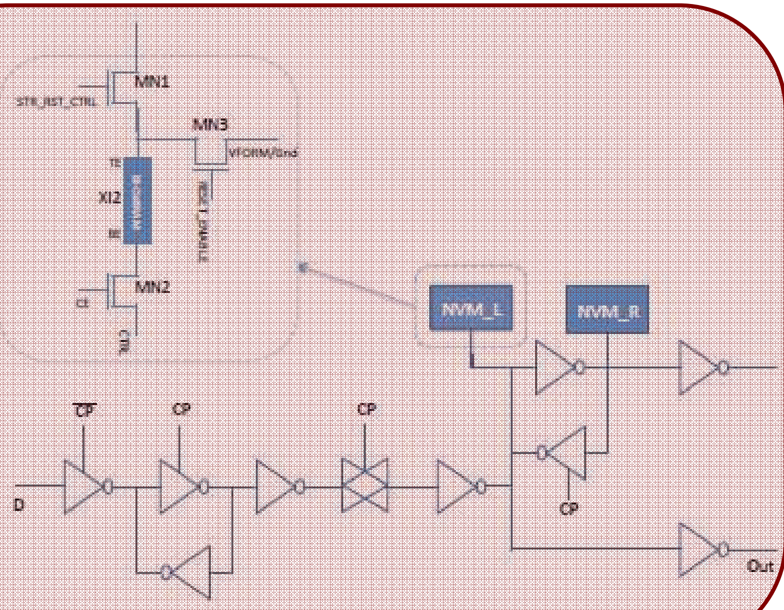
- ✓ NV SRAM
- ✓ NV Flip Flop
- ✓ NV LUT
- ✓ Neuromorphic applications
- ✓ Circuits for Imagers

It is a way to validate the compact model for memory applications because no standard test exists.

II Modelling

4- Validation of the model in circuit design

Example : a NV Flip Flop with a bipolar OxRRAM*
Same principle for CBRAM to be published.



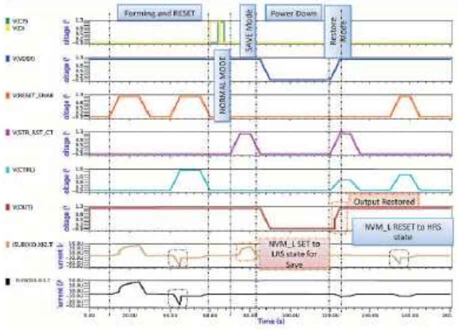


Fig. 5. Bi-RNVFF architecture with Non-volatile block based on ReRAM with ReRAMs in slave state for Data = 1

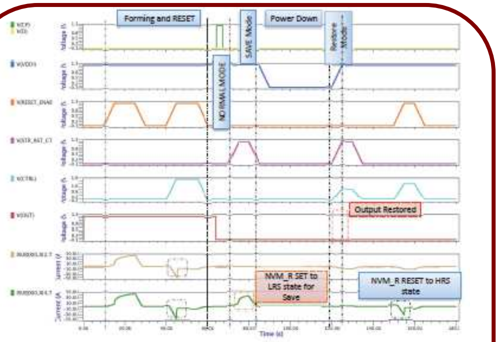


Fig. 6. Bi-RNVFF architecture with Non-volatile block based on ReRAM with ReRAMs in slave state for Data = 0

*S. Onkaraiah *et al.*, « Non-volatile Bipolar OxRRAM based Flip-flops for low-power architectures », ISCAS 2012

III Conclusion and prospects

Conclusion

- ✓A compact model of a CBRAM cell was developed.
- ✓ The model is implemented in Verilog-A.
- ✓ The model is adjusted on measurements.
- ✓ The model is validated with different circuits.

Prospects

- ✓ Improvement of the robustness of the model.
- ✓ Add more physics.

leti

LABORATOIRE D'ÉLECTRONIQUE
ET DE TECHNOLOGIES
DE L'INFORMATION

CEA-Leti
MINATEC Campus, 17 rue des Martyrs
38054 GRENOBLE Cedex 9
Tel. +33 4 38 78 36 25

www.leti.fr

Thank you for attention

cea

MINATEC®

INSTITUT
CARNOT
CEA LETI

Physical Compact Model of a CBRAM cell

Marina Reyboz, Santhosh Onkaraiah, Giorgio Palma and Elisa Vianello

Abstract:

This paper deals with the compact model of a CBRAM (Conductive Bridging Random Access Memory) cell. CBRAMs are a kind of Resistive Random Access Memories (RRAMs) fabricated in the BEOL (Back-End-Of-Line). They are a promising breakthrough for including permanent retention mechanisms (non-volatility) in embedded systems at low cost.

CBRAMs are made of a solid electrolyte sandwiches between two electrodes of which in silver. A filament can be created between these electrodes, it is the SET. The destruction of this filament is named RESET. Consequently, two states, a LRS (Low Resistive State) and a HRS (High Resistive State) are possible.

A physical compact model is proposed in order to simulate innovative circuits, particularly in the field of power management. This model is based on the Mott Gurney equation which describes the diffusion of silver ions in the solid electrolyte. Thus, this model is a dynamic model which represents the switching time and the resistances (LRS and HRS) depending of the voltages at the top and the bottom electrodes.

The compact model, written in Verilog-A is validated on electrical characterization.