UNIMORE RRAM MODEL V1.0.0 USER GUIDE

Authors:

F. M. Puglisi, T. Zanotti, and P. Pavan

Summary

1 RRAM model description

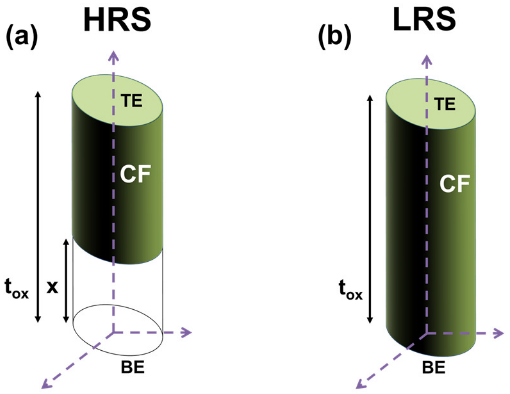


Fig. 1 - Schematic picture of the device in HRS (a) and in LRS (b). When the device is in HRS a dielectric barrier of thickness x exists between the top (TE) and bottom (BE) electrodes.

The RRAM compact model provided is designed to simulate the behavior of bipolar metal oxide Resistive RAM devices. The model is based on the physics of these devices and includes non-ideal effects (i.e. SET/RESET variability and Random Telegraph Noise) which can be enabled or disabled through model and simulation parameters [1] [2] [3] [4] [5]. As shown in section 5, the model can reproduce both the DC and pulsed characteristics even when using very short pulses (i.e. 10 ns) with a single set of parameters.

The model equations consider both the quasi-ohmic charge transport in the conductive filament (CF) and the trap-assisted tunneling transport in the dielectric barrier. The dielectric barrier dynamics is modelled with a set of differential equations which consider the field-driven oxygen ion drift during RESET (i.e. barrier growth) and the field- and temperature- accelerated bond breakage during SET (i.e. barrier collapse). The temperature dynamics of the CF and the barrier are likewise modelled with two differential equations, which enable accurate predictions also when the device is driven with very short pulses.

The device SET and RESET variability are obtained by adding a white gaussian noise on the CF cross-section and on the barrier thickness during SET and RESET events, respectively.

1.1 List of RRAM model equations

(1) $$R_{LRS} = \frac{\rho \cdot t_{ox}}{S}$$

(2) $$R_{CF} = R_{LRS} \cdot \frac{t_{ox} - x}{t_{ox}} \cdot [1 + \alpha \cdot (T_{CF} - T_{meas})]$$

(3) $$R_{Bar} = R_{LRS} \cdot \beta \cdot \left(e^{\frac{x}{l}} - 1\right) \cdot e^{\frac{E_a}{k_B T_{Bar}}}$$

(4) $$R = R_{CF} + R_{Bar}$$

(5) $$I = \frac{V_0}{R} sinh\left(\frac{V}{V_0}\right)$$

(6) $$\frac{dx}{dt} = (1 unit\, length)\, c_0 e^{-\frac{E_{ad} - (g - a\, x^b)\frac{|V|}{t_{ox}}}{k_B T_{CF}}} \qquad (reset)$$

(7) $$\frac{dx}{dt} = -x c_0 e^{-\frac{E_{ag} - g g \frac{V}{x}}{k_B T_{CF}}} \qquad (set)$$

(8) $$V_{CF} \cong V \cdot \frac{R_{CF}}{R_{CF} + \frac{R_B}{0.5 \cdot e^{\frac{|V|}{V_0}}}}$$

(9) $$V_{Bar} \cong V \cdot \frac{\frac{R_{Bar}}{0.5 \cdot e^{\frac{|V|}{V_0}}}}{R_{CF} + \frac{R_{Bar}}{0.5 \cdot e^{\frac{|V|}{V_0}}}}$$

(10) $$\frac{dT_{CF}}{dt} = C_{pCF}^{-1}[V_{CF} \cdot I - k_{CF}(T_{CF} - T_0) - k_{EX}\,(T_{CF} - T_{Bar})]$$

(11) $$\frac{dT_{Bar}}{dt} = C_{pBar}^{-1}[V_{Bar} \cdot I - k_{Bar}(T_{Bar} - T_0) - k_{EX}\,(T_{Bar} - T_{CF})]$$

1.2 RRAM model parameters description

Parameter Name	Description	Unit
rho	Oxide material resistivity	Ω ▪ nm
t_ox	Oxide layer thickness	nm
S0	Initial conductive filament section	nm^2
Ea	Activation energy of the trap assisted tunneling	eV
T0	Ambient temperature	K
l	Typical tunneling length	nm
V0	HRS current non-linearity factor	V
alpha	Resistivity temperature coefficient	1/K
beta	Barrier resistance fitting parameter	NA
c0	Bond vibration frequency	Hz
Cpb	Barrier thermal capacity	J/K
Cpcf	CF thermal capacity	J/K
kbar	Barrier thermal conductivity	W/K
kcf	CF thermal conductivity	W/K
kex	Barrier/CF mutual thermal conductivity	W/K
Ead	Diffusion activation energy of oxygen ions	eV
g	Field enhancement factor for oxygen ions diffusion	e ▪ nm
a	RESET curve slope fitting parameter	e ▪ nm
b	RESET curve curvature fitting parameter	NA
Eag	Bond breaking activation energy	eV
gg	Field enhancement factor for bond breaking	e ▪ nm
Auxiliary model parameters		
xinit	Initial barrier thickness	nm
Tinit	Initial device temperature	K
Tmeas	Temperature at which R_{LRS} is measured (see section 3.3)	K
min_time_step_vpos	Minimum time step (for positive applied voltages)	s
min_time_step_vneg	Minimum time step (for negative applied voltages)	s
tstep_param	Adaptive time step parameter	NA
Variability model parameters (effective only in transient noise analysis)		
th_set	SET event detection threshold on the barrier derivative	nm/s
dx	Maximum variation allowed on the barrier thickness (=3σ)	nm
ds	Maximum variation allowed on the CF cross-section (=3σ)	nm^2
S0var	CF cross-section at which the measured ds is obtained	nm^2
Fmax	Maximum frequency of the noise for transient noise analysis	Hz
ddt_x_clip_th	RESET event detection threshold on the barrier derivative	nm/s

2 RTN model description

RTN is a phenomenon that causes fluctuations in the device current which can lead to errors during the reading of the device state. Two different physical mechanisms are believed to be responsible for RTN when the device is in HRS or LRS [2] [4]. When the device is in HRS, RTN current fluctuations are caused by (de-)trapping of charge in slow defects (supposedly oxygen interstitial atoms) which do not participate to the charge transport but cause the temporary de-activation of V_O^+ defects that assist charge transport when active. In LRS, RTN is caused by electron trapping and de-trapping in defects located in the proximity of the CF (i.e. within one Debye length). Charges trapped at such defects perturb the potential in their surroundings causing a screening effect on the portion of the CF close to them, which induces a resistance change. Further details on the modelling of RTN can be found in [2] [4].

The model distributes defects along the barrier and around the CF when the barrier is respectively growing or collapsing. To each defect is associated a random vertical distance from the bottom electrode, a resistance variation, an initial state (empty or filled) and emission and capture times. To consider voltage and temperature variations, the capture and emission times are constantly updated. The state transition is modelled using a random variable with a transition probability directly proportional to the time elapsed from the last state transition. The RTN current contribution due to the such defects is then added to the RRAM model current.

2.1 List of RTN model equations

HRS equations

(12) $$N_O = x \cdot S \cdot O_{Density}$$

(13) $$n\ sampled\ from\ a\ Poisson\ distribution\ with\ mean\ N_O$$

(14) $$E_{rel O_i} = E_{rel0_O} + U(-\Delta E_{rel_O}, \Delta E_{rel_O})$$

(15) $$E_{t O_i} = E_{t0_O} + U(-\Delta E_{t_O}, \Delta E_{t_O})$$

(16) $$pos_i = x \cdot U(0,1)$$

(17) $$\Delta R_i = R_{Bar} \cdot var_{ln} \quad with \quad var_{ln} = e^{v_n} \quad , v_n \sim \mathcal{N}(\Delta R_{HRS_{mean}}, \Delta R_{HRS_{std}})$$

(18) $$\tau_{e_i} = \left[const_0 \cdot N_C\, e^{-\frac{x - pos_i}{\lambda_e}} \cdot e^{-\frac{E_{relO_i}}{4 k_B T_{CF}}}\right]^{-1}$$

(19) $$\tau_{c_i} = \left[const_0 \cdot N_C\, e^{-\frac{pos_i}{\lambda_c}} \cdot e^{-\frac{\left[E_{relO_i} - \left(E_{ti} - \phi + V \frac{pos_i}{x}\right)\right]^2}{4 E_{relO_i} k_B T_{CF}}}\right]^{-1}$$

LRS equations

(20) $$N_V \cong t_{ox} \cdot \pi \cdot \left[r_t^2 + 2 \cdot r_t \cdot \sqrt{\frac{S}{\pi}}\right] \cdot V_{Density}$$

(21) $$n\ sampled\ from\ a\ Poisson\ distribution\ with\ mean\ N_V$$

(22) $$E_{rel V_i} = E_{rel0_V} + U(-\Delta E_{rel_V}, \Delta E_{rel_V})$$

(23) $$E_{t V_i} = E_{t0_V} + U(-\Delta E_{t_V}, \Delta E_{t_V})$$

(24) $$pos_i = t_{ox} \cdot U(0,1)$$

(25) $\Delta \mathrm{R}_i = R_{LRS} \cdot var_{ln} \quad with \quad var_{ln} = e^{v_n} \;, \; v_n \sim \mathcal{N}\left(ln\left(\frac{1}{2 + \frac{2\, t_{ox}\, S}{r_t^3}} \right), \Delta \mathrm{R_{LRS}}_{\mathrm{std}} \right)$

(26) $\tau_{e_{O_i}} = \left[const_0 \cdot N_C\, e^{-\frac{t_{ox} - pos_i}{\lambda_e}} \cdot e^{-\frac{E_{relO_i}}{4\, k_B T_{CF}}} \right]^{-1}$

(27) $\tau_{c_{O_i}} = \left[const_0 \cdot N_C\, e^{-\frac{pos_i}{\lambda_c}} \cdot e^{-\frac{\left[E_{relO_i} - \left(E_{t_i} - \phi + V \frac{pos_i}{x}\right)\right]^2}{4\, E_{relO_i} k_B T_{CF}}} \right]^{-1}$

(28) $\tau_{e_{V_i}} = \left[const_0 \cdot N_C\, e^{-\frac{t_{ox} - pos_i}{\lambda_e}} \cdot e^{-\frac{E_{relV_i}}{4\, k_B T_{CF}}} \right]^{-1}$

(29) $\tau_{c_{V_i}} = \left[const_0 \cdot N_C\, e^{-\frac{pos_i}{\lambda_c}} \cdot e^{-\frac{\left[E_{relV_i} - \left(E_{tV_i} - \phi + V \frac{pos_i}{t_{ox}}\right)\right]^2}{4 E_{relV_i} k_B T_{CF}}} \right]^{-1}$

Output current update

(30) $\wp(\text{transition})_i = 1 - e^{-\frac{t_i}{\tau_i}}$

(31) $\Delta \mathrm{R} = \sum_{\substack{i=1 \\ State_i = active}}^{n} \Delta \mathrm{R}_i$

(32) $\Delta I_{RTN} = \frac{\Delta \mathrm{R}}{\mathrm{R}}\, \mathrm{I}$

2.2 RTN model parameters description

Parameter Name	Description	Unit
const0	Capture and emission times constant	J ▪ m^3/s
Nc	Density of states at the bottom of the conduction band	1/(J▪m^3)
phi	Energy barrier for injected electrons	eV
lambda_c	Typical tunneling length (capture)	m
lambda_e	Typical tunneling length (emission)	m
maximum_number_of_defects	Maximum number of defects that can be generated	NA
Erel0_O	Nominal oxygen ions relaxation energy	eV
Et0_O	Nominal oxygen ions thermal ionization energy	eV
Erel0_V	Nominal oxygen vacancies relaxation energy	eV
Et0_V	Nominal oxygen vacancies thermal ionization energy	eV
Delta_Erel_O	Spread of the oxygen ions relaxation energy distribution	eV
Delta_Et_O	Spread of the oxygen ions thermal ionization energy distribution	eV
Delta_Erel_V	Spread of the oxygen vacancies relaxation energy distribution	eV
Delta_Et_V	Spread of the oxygen vacancies thermal ionization energy distribution	eV
DeltaR_dist_HRS_mean	Mean of the normal distribution associated to the logNormal distribution of the R_{HRS} due to RTN. For further information see [2] [3]	NA
DeltaR_dist_HRS_std	Standard deviation of the normal distribution associated to the logNormal distribution of the R_{HRS} due to RTN. For further information see [2] [3]	NA

DeltaR_dist_LRS_std	Standard deviation of the normal distribution of the R_{LRS} due to RTN. For further information see [2] [3]	NA
rt	Screening length of trapped charge in a defect [2]	m
O_ions_density	Oxygen ions density in the barrier	m^{-3}
V_density	Oxygen vacancies density around the CF	m^{-3}
Auxiliary model parameters		
RTN_ON	Parameter used to switch on the RTN module (0=OFF; 1=ON)	NA
rand_seed_ini	Initial random seed value	NA
dxdt_th	Threshold on the barrier derivative to randomly re-assign defects positions	m/s

3 Parameter calibration

Experimental data of real devices (I-V curves and possibly the response to fast RESET pulses) are required to calibrate the model. A qualitative analysis of the effect of each parameter relevant for the model calibration is shown in section 3.2.

3.1 Default parameter set

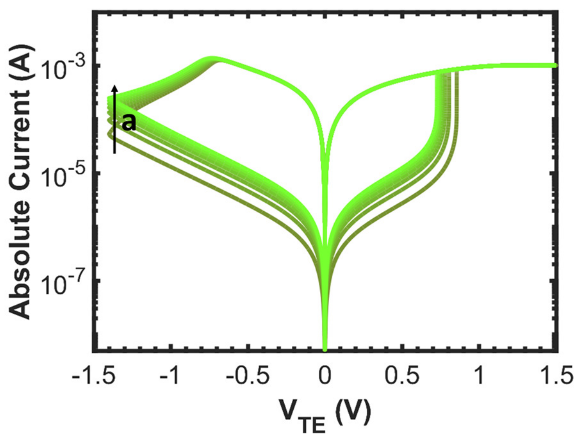
The following parameters are calibrated to reproduce experimental data in the literature [6].

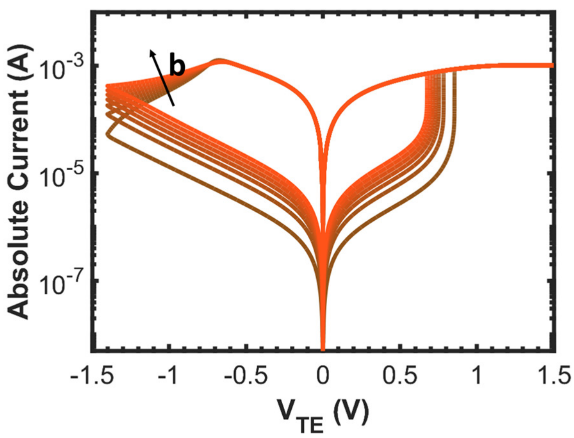
Parameter Name	Default value	Unit
rho	3000	Ω ▪ nm
t_ox	12	nm
S0	72	nm^2
Ea	0.12	eV
T0	300	K
l	0.42	nm
V0	0.32	V
alpha	0.002	1/K
beta	1e-3	NA
c0	5e13	Hz
Cpb	4e-9	J/K
Cpcf	5e-13	J/K
kbar	5e-5	W/K
kcf	1e-6	W/K
kex	0	W/K
Ead	4.4	eV
g	54	e ▪ nm
a	14	e ▪ nm
b	0.4	NA
Eag	1.2	eV
gg	1.75	e ▪ nm
Auxiliary model parameters		
xinit	0	nm
Tinit	300	K
Tmeas	300	K
min_time_step_vpos	1e-13	s
min_time_step_vneg	1e-13	s
tstep_param	1e2	NA
Variability model parameters (effective only in transient noise analysis)		

th_set	10	nm/s
dx	0.8	nm
ds	20	nm^2
S0var	72	nm^2
Fmax	1000	Hz
ddt_x_clip_th	1e-5	nm/s
RTN model parameters		
const0	4.19e-32	J ▪ m^3/s
Nc	2.42e45	1/(J▪m^3)
phi	2.1	eV
lambda_c	2e-10	m
lambda_e	2e-10	m
maximum_number_of_defects	100	NA
Erel0_O	2.67	eV
Et0_O	2.3	eV
Erel0_V	1.19	eV
Et0_V	2.1	eV
Delta_Erel_O	0.4	eV
Delta_Et_O	0.5	eV
Delta_Erel_V	0.4	eV
Delta_Et_V	0.5	eV
DeltaR_dist_HRS_mean	ln(0.5)	NA
DeltaR_dist_HRS_std	0.6	NA
DeltaR_dist_LRS_std	0.3	NA
rt	1.7e-9	nm
O_ions_density	1e26	m^{-3}
V_density	2e27	m^{-3}
Auxiliary RTN model parameters		
RTN_ON	0	NA
dxdt_th	1e-10	m/s
rand_seed_ini	0	NA

3.2 Examples of parameter variations

In the following figures the value of a single parameter is varied at a time and its effect on quasi-static I-V SET/RESET curves is shown. The arrow indicates the direction of increasing parameter values. The same information is also encoded in the shades of the curves color.





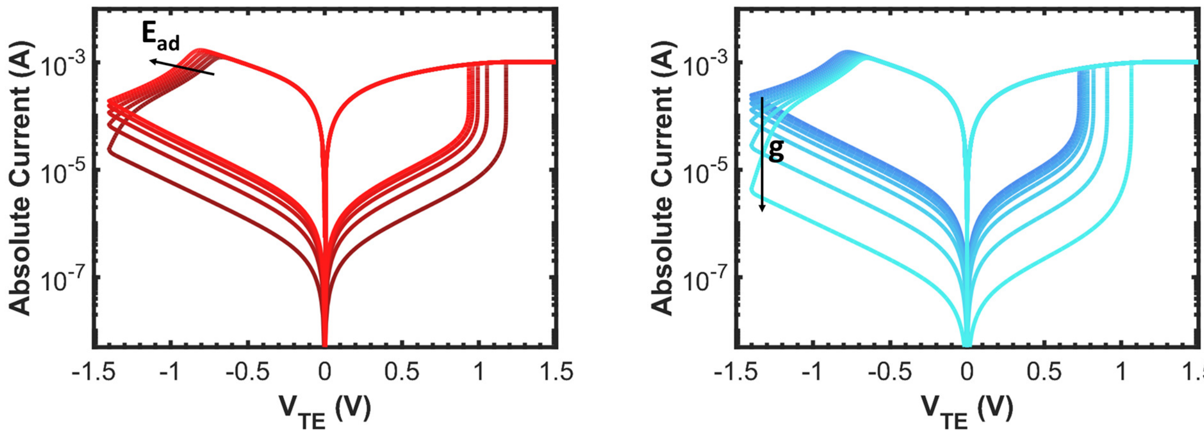


Fig. 2 - Parameters which mainly influence the RESET curve. Increasing values of E_{ad} decrease the voltage at which the barrier starts to grow. Rising the value of g boosts the effects of the applied voltage, thus leading to faster barrier growth. The parameters a and b model the relation between the barrier growth rate, the applied voltage and the barrier thickness. The RESET curve slope and curvature are influenced by parameter a and b, respectively.

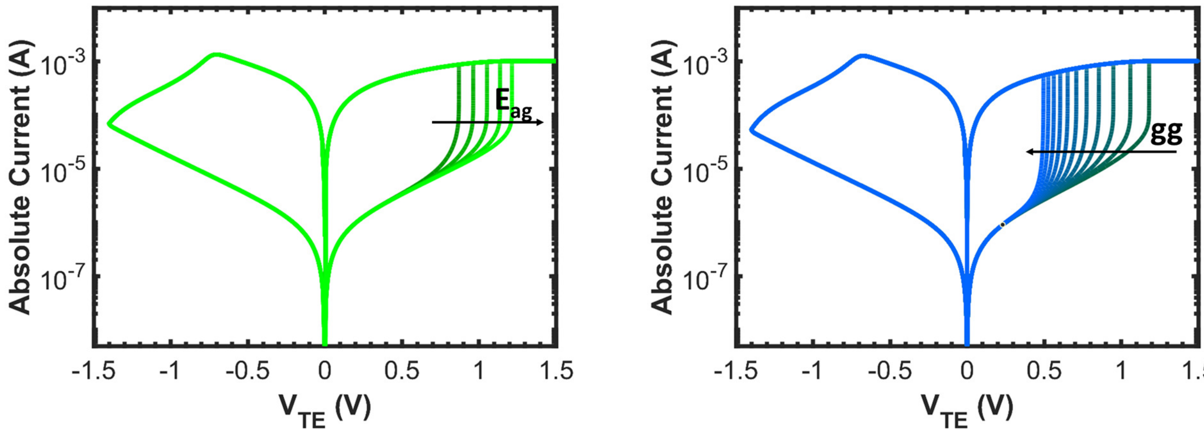


Fig. 3 - Parameters which influence the SET process. Higher E_{ag} increases the SET voltage (at the same HRS resistance), while increasing gg enhances the field dependence of the SET process.

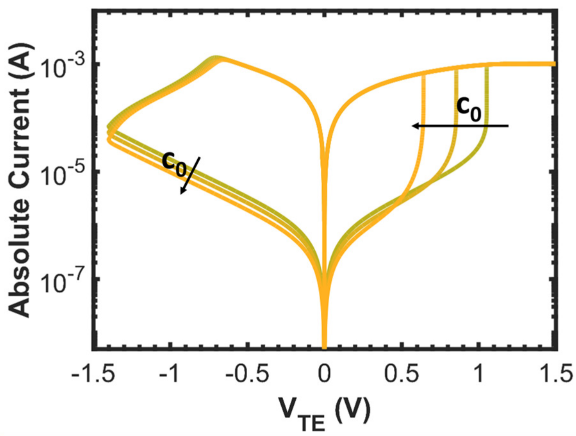


Fig. 4 - c_0 affects the barrier variation rate. Thus, higher values of c_0 cause greater HRS resistances and lower SET voltages.

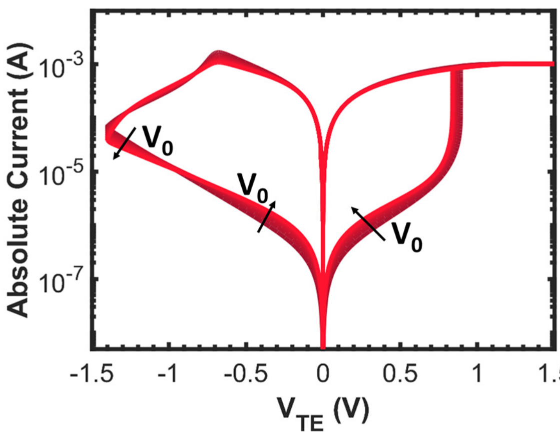


Fig. 5 - V_0 affects the I-V non-linearity in HRS.

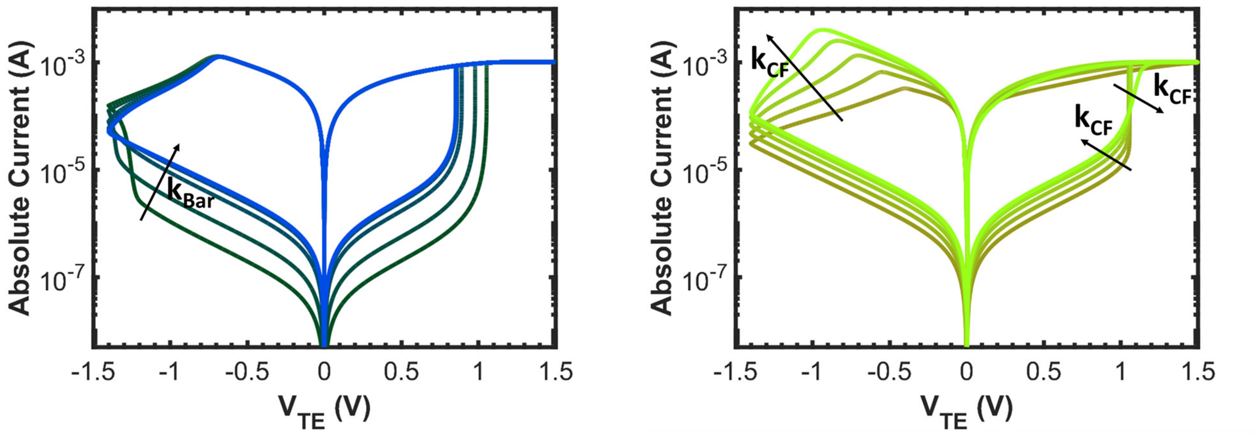


Fig. 6 – k_{Bar} and k_{CF} influence the temperature dynamics, leading to smaller temperature variations when increased. Lower temperatures lead to smaller barriers and smoother SET transitions.

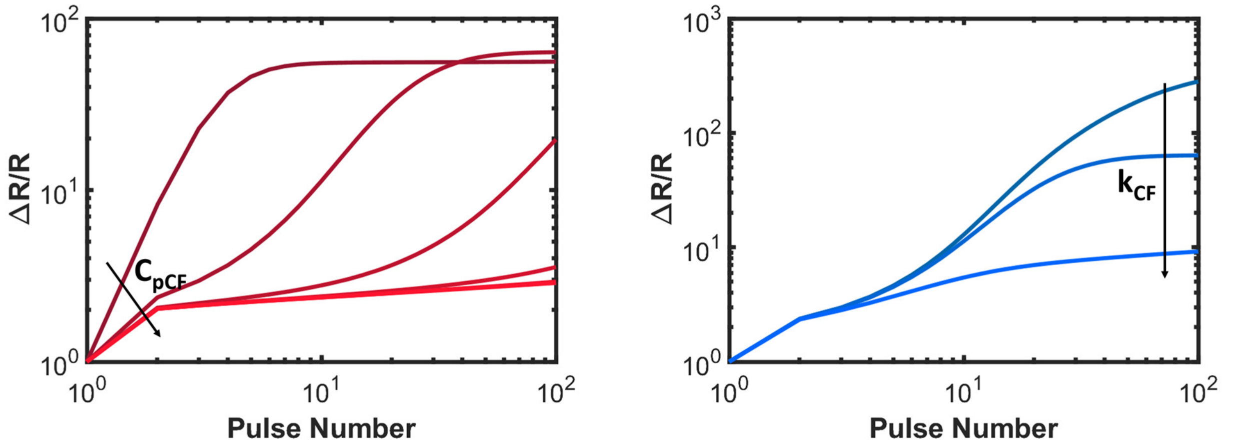


Fig. 7 - Pulsed RESET response at different C_{pCF} and k_{CF}. As these two parameters are increased, the CF temperature dynamics becomes slower.

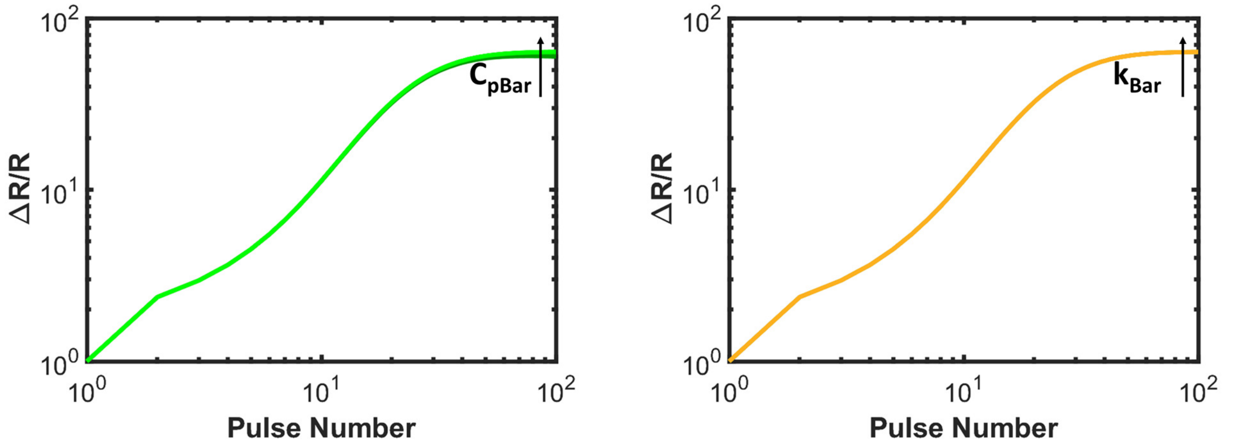


Fig. 8 - Pulsed RESET response and variation of C_{pBar} and k_{Bar}. As these two parameters are increased, the barrier temperature dynamics becomes slower. The effect should become more relevant with smaller CF cross-section.

3.3 Auxiliary parameters calibration

tstep_param	The parameter allows to adapt the time step based on the barrier thickness derivative, so that during a SET event the time resolution is increased. When *tstep_param* is equal to 0 the time step adaption is disabled and managed by the solver. Otherwise, the effect of the parameter can be approximated with the formula: $$\Delta t \cong \frac{1}{\left\lvert\frac{dx}{dt}\right\rvert}\frac{0.1}{tstep\_param}$$ Where $\frac{dx}{dt}$ is in nm/s.
th_set	This parameter is the threshold used for detecting the SET event. If the user needs to modify this value, it can be set by looking at the variable *ddt_x* during a SET transition.
dxdt_th	In the current implementation, the RTN module is conceived to be used in reading conditions only (i.e. when a small and constant bias is applied). When relatively large voltages are used RTN fluctuations might be exceedingly large. This parameter can be used to limit this phenomenon during RESET/SET sweeps. Must be set to a small enough value.
dx	*dx* can be estimated from the R_{HRS} distribution.
ds, S0var	*ds* can be estimated as three time the standard deviation of the R_{LRS} distribution divided by $\rho\, t_{ox}$. *S0var* must be set equal to the cross-section at which the desired *ds* is obtained. The SET variability then scales as inversely proportional to the CF cross-section.
Fmax	*Fmax* must be set equal to the *noisefmax* parameter of the transient noise simulation. In this way the model automatically scales the variability white noise power parameter to obtain the desired *ds* and *dx*.
ddt_x_clip_th	This threshold determines the interval wherein the RESET variability is injected. The value, typically larger than *dxdt_th*, can be set by performing a parametric analysis and observing the resulting I-V curves.
Tmeas	The model accounts for two temperature effects in LRS. One is the device self-heating that accounts for the difference between the temperature of the CF and the ambient temperature and the other considers the R_{LRS} temperature dependence (see equations (1, 2)). *Tmeas* can differ from the ambient temperature (*T0*) and represents the temperature at which R_{LRS} is measured. For example, if R_{LRS} is equal to 1kΩ at 300K than *Tmeas* is set to 300K. Then if *T0* is set to a different temperature R_{LRS} scales accordingly.

4 Using the Model

The model is designed to be used in transient simulation. To instantiate the model in a netlist, first the following line of code must be included (tested using Cadence Spectre):

```
ahdl_include "UNIMORE_RRAM_model_1_0_0.va"
```

The file "UNIMORE_RRAM_model_additional_disciplines_v1_0_0.va" must also be present in the same folder of the Verilog-A model file. This file includes additional natures and disciplines used in the model for relaxing the tolerances on the temperature and barrier related variables. To instantiate a device the following code can be used:

```
RR0 (TE BE) UNIMORE_RRAM_model_1_0_0 rho=3000 t_ox=12 S0=72 kb=8.6e-05 \
    Ea=0.12 T0=300 l=0.42 V0=0.32 alpha=0.002 beta=1e-3 c0=5e+13 Cpb=4e-09 \
    Cpcf=5e-13 kbar=5e-05 kcf=1e-06 kex=0 Ead=4.4 g=54 gg=1.75 Eag=1.2 \
```

*xinit=0 Tinit=300 Tmeas=300 min_time_step_vpos=1e-13 *

*min_time_step_vneg=1e-13 tstep_param=100 a=14 b=0.4 th_set=10 *

*dx=0.8 ds=20 S0var=72 Fmax=1000 ddt_x_clip_th=1e-05 *

*rand_seed_ini=0 RTN_ON=0 const0=4.19e-32 Nc=2.42e+45 phi=2.1 *

*lambda_c=2e-10 lambda_e=2e-10 maximum_number_defects=100 *

*Delta_Erel_O=0.4 Delta_Et_O=0.5 Delta_Erel_V=0.4 Delta_Et_V=0.5 *

*DeltaR_dist_HRS_mean=-0.693147 DeltaR_dist_HRS_std=0.6 *

*DeltaR_dist_LRS_std=0.3 rt=1.7e-09 O_ions_density=1e+26 *

*V_density=2e+27 Erel0_O=2.67 Et0_O=2.3 Erel0_V=1.19 Et0_V=2.1 *

dxdt_th=1e-10

Where RR0 is the name of the device instance, TE and BE are the names used to indicate the top electrode and bottom electrode nodes. After the model name follows the list of parameters. To avoid convergence issues during the SET event a form of current limitation must be provided. This can be accomplished connecting a resistor or a properly biased MOS in series with the RRAM device (or whatever current-limiting device).

To improve the simulator convergence the following options should be included in the transient simulation configuration:

method=gear2only maxiters=10000 restart=yes

In order to save the value of internal variables (e.g. barrier, Tcf, Tbar…) the following options have to be included:

saveOptions options save=all saveahdlvars=all

To include the SET/RESET variability in the analysis a transient noise analysis must be performed including the options highlighted in bold in the example below:

tran tran stop=580m errpreset=conservative ***noisefmax=1000 noiseseed=1*** **

noisetmin=10u noiseupdate=fmax noiseon=[RR0] *maxstep=1m ic=all *

*skipdc=no write="spectre.ic" writefinal="spectre.fc" method=gear2only *

relref=pointlocal annotate=status maxiters=10000 restart=yes

The RTN module should be activated only when a low voltage read operation is simulated. If the RTN module is active during a RESET or SET operation it may cause unrealistic current profiles.

5 Spectre simulation results

In this section we show simulations results using the Spectre simulator version "*10.1.1.200.isr13*". In the simulation we employed the default model parameters, which are calibrated on data from [6]. The used Spectre netlist file for each simulation are provided in the folder '\Benchmarks', along with the MOS model used as a current limiter.

5.1 Quasi-static transient simulation: RRAM I-V characteristic

This simulation can be used to reproduce the device I-V curve, applying a triangular voltage waveform with the minimum value equal to the desired V_{RESET}, and maximum value larger than V_{SET}. Two additional devices where included in the circuit schematic: a properly biased MOSFET used as a current limiter at positive voltages and an ideal switch that closes when the applied voltage is negative to perform the reset.

5.1.1 Results without variability and RTN

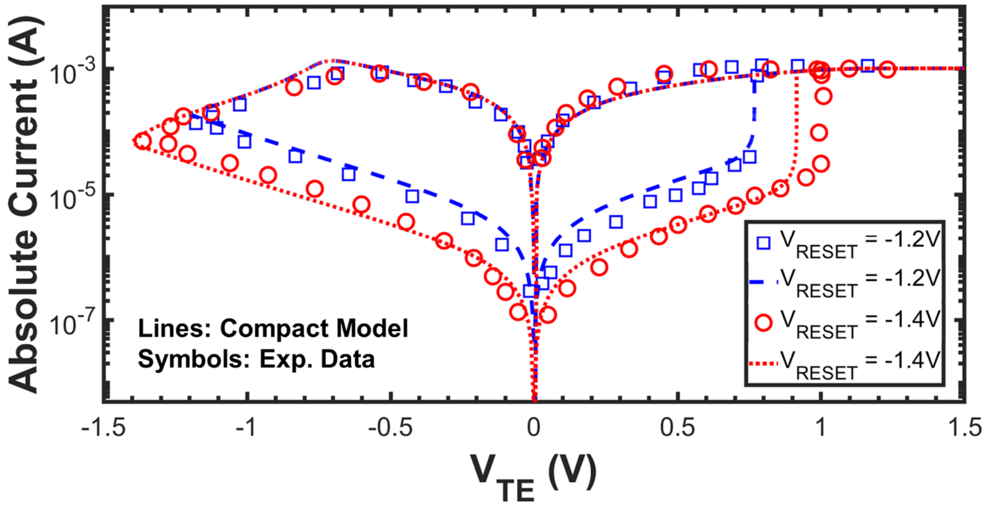


Fig. 8 - Simulated (lines) and experimental (symbols) device I-V curves at different V_{RESET}. Data from [6].

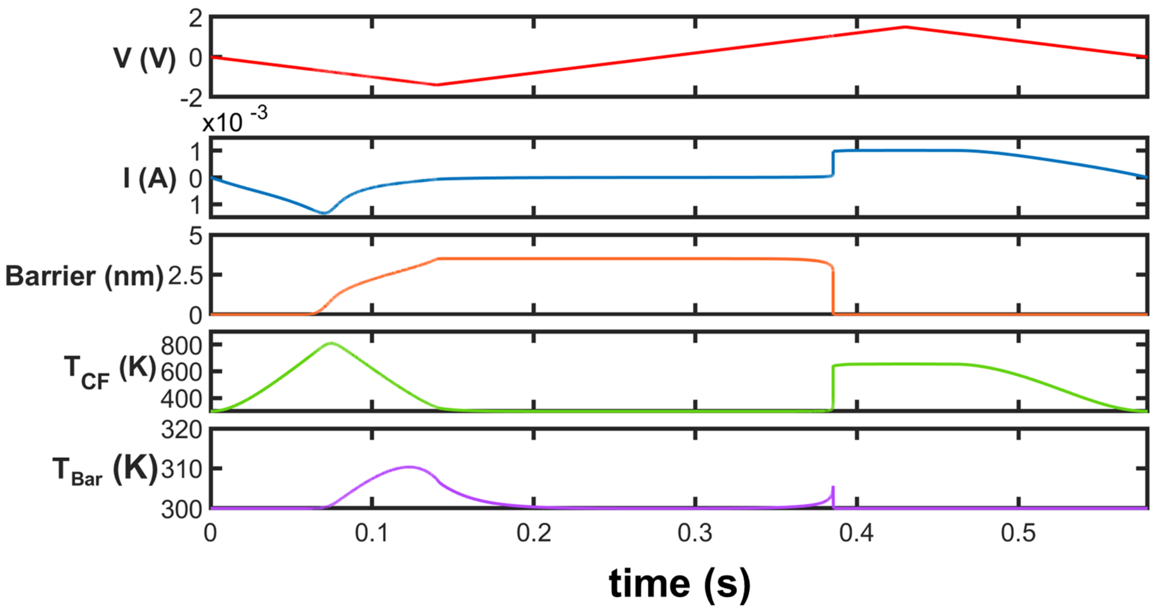


Fig. 9 - Model variables time evolution when a triangular waveform is applied which causes a RESET event followed by a SET event.

5.1.2 Results with variability included

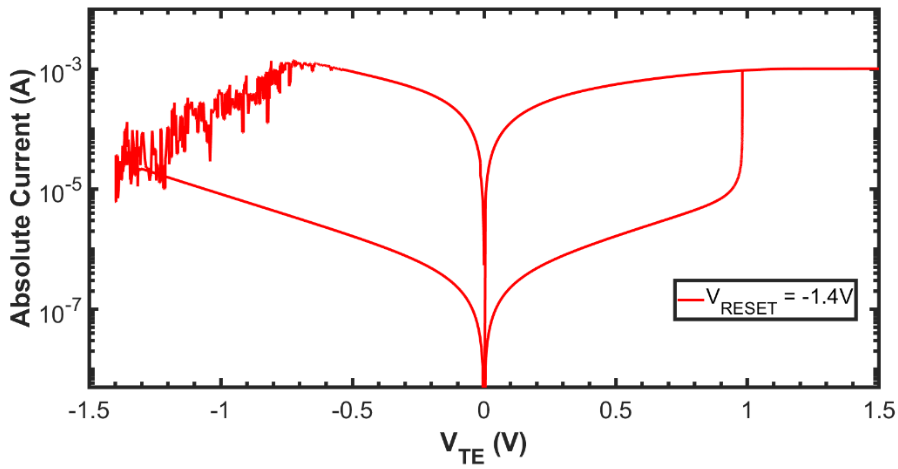


Fig. 10 – Results of the SET/RESET variability simulation considering one RESET/SET cycle using V_{RESET} = -1.4V.

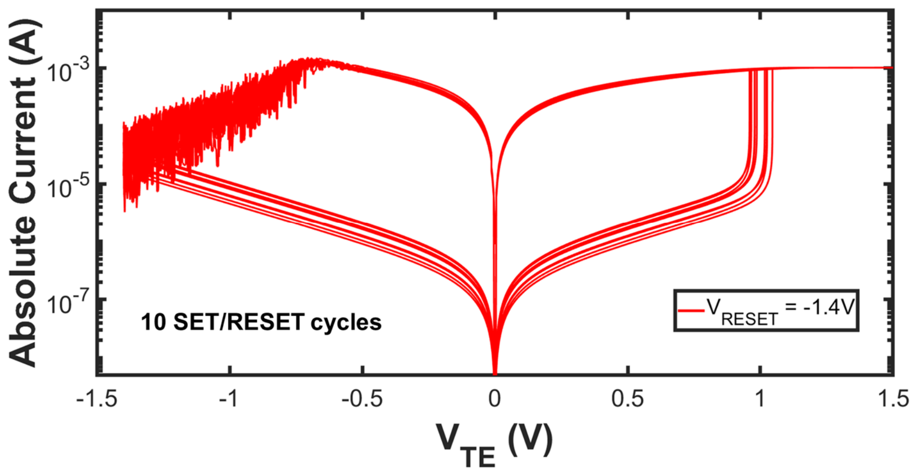


Fig. 11 - Results of the SET/RESET variability simulation considering 10 SET/RESET consecutive cycle using V_{RESET} = -1.4V.

5.2 Fast RESET pulses transient simulation

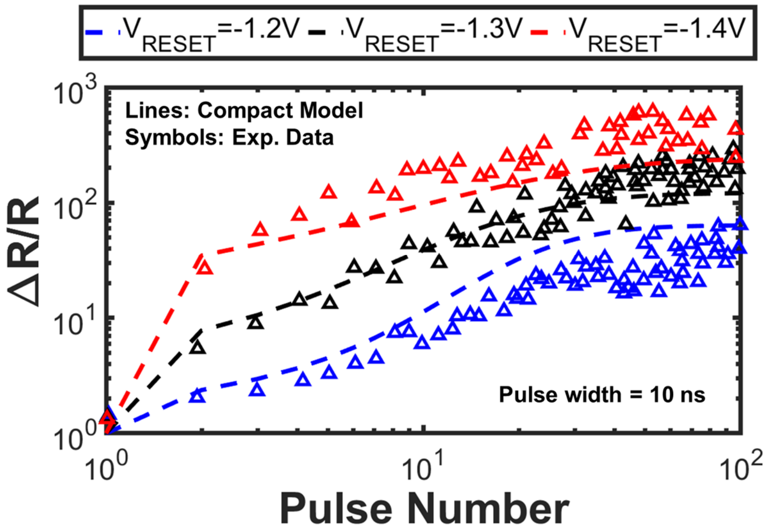


Fig. 12 - Simulated (lines) and experimental (symbols) pulsed reset curves using a train of 10 ns pulses with different amplitudes. Data from [6].

5.3 RTN model transient simulation

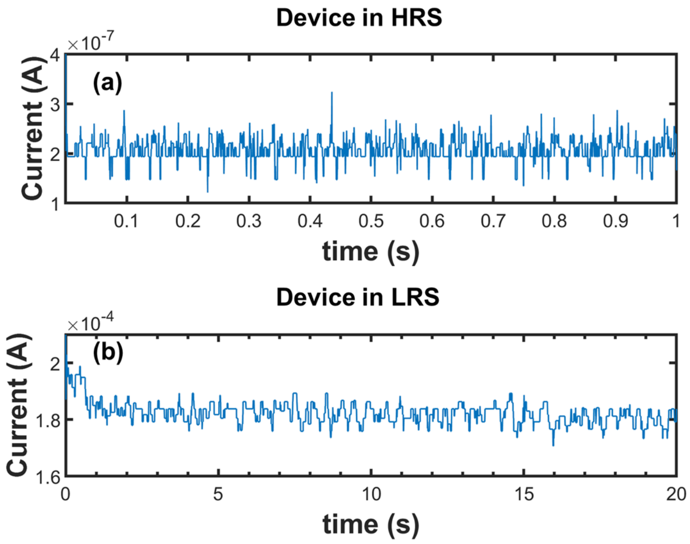


Fig. 13 – Example RTN traces considering the device in HRS (a) and LRS (b) when a constant 100mV read voltage is applied.

6 References

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