Compact modeling of hysteresis effects in ReRAM devices

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Evolution of the memory market

Memory Production Relative to the Rest of Semiconductors

Important increase of memory market in the last years

Source: Gartner 2Q2014 update, Finance Strategy Wafer Supply Model

Global NAND flash market growth forecast (Unit: $100 million)

Source: Gartner
Motivation

- Increasing need of information storage systems

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

Neuromorphic application

Synaptic weight is based on a change of resistance.

S. Jo et al, Nano Lett 2010
• … 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.

Formation and rupture of a filamentary path

This phenomenon is the working principle of RRAMs: two stable states
Cycling experiments in MIM structures

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

C. Yoshida et al, APL (2007)


J. Choi et al, APL (2009)

NiO(40 nm) /SiO₂(50-300 nm)

Cu-doped SiO₂ (12 nm)
... exhibiting a wide variety of hysteretic I-V curves
Some electrode materials favour the switching process
Newcomers: 2D materials

- h-boron nitride
- MoS$_2$
- Graphene

Variability and reliability: big problems for industry!

LANZALAB, Soochow University
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

![Graph showing the transition between high resistance state (HRS) and low resistance state (LRS) with reset and set events.]

Cu$_2$O

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 $\rightarrow$ logic state "0"
Memory effect: how information is stored

READ OPERATION: high current $\rightarrow$ logic state “1”
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
“… 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)
SET and RESET voltages:
“No appreciable dependence of memory switching on thickness”
S. Seo et al, Samsung Electronics (2011)

“...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

S. Seo et al, Samsung Electronics

“...resistive switches and memories that use SiO\textsubscript{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\textsubscript{x} nanogap system
“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

Distances
Density
0.0 0.2 0.4 0.6 0.8 1.0 1.2
0.0 0.5 1.0 1.5

BW | Intensity Plot
--- | ---
10 µm | 
20 µm | 
50 µm | 
100 µm |
Spatial statistics using angular wavelet analysis

Muñoz Gorriz et al, Mic Eng 2017
Multifilamentary conduction

Filaments are neither spatial nor temporal correlated

X. Saura et al, Mic Rel 2013
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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

Poole-Frenkel and thermionic conduction

“The value of the extracted dielectric constant $\varepsilon_r = 79$ 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)

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

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

SCLC has a precise dependence with oxide thickness !!!
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.”


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

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)
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

\[ R_{\text{SET}} = \rho_{\text{CF}} \frac{t_{\text{OX}}}{S} \]

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

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:

\[ I_{\text{OFF}} = \frac{2e}{\alpha h} \frac{\exp[-\alpha(\Phi_0 - eV - \theta T)]}{\text{sinc}(\pi kT \alpha)} \left[1 - \exp(-\alpha eV)\right] \]

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

\[ G = \frac{I}{V} \]

Quantum conductance unit

\[ G_0 = \frac{2e^2}{h} \]

Resistance of a monomode ballistic conductor

\[ R_0 = G_0^{-1} = 12.9 \text{ K}\Omega \]
"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”

Conductance quantization in RS devices

Data extracted from pulsed measurements on Ti/Ta$_2$O$_5$/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.”

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


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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.

- $T$: transmission probability
- $V$: applied voltage

R. Landauer, 1927-1999
The Landauer approach

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

\[ I = G_0 TV \quad \Rightarrow \quad G = \frac{dI}{dV} = G_0 T \]

T: transmission probability
V: applied voltage

Ballistic Conductor

\[ G = G_0 \]

R. Landauer, 1927-1999
Finite-bias Landauer approach

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

- **T**: Transmission probability
- **V**: Applied voltage
- **β**: Fraction of the potential that drops at the source side \(0 < \beta < 1\)
- **f**: Fermi function
Quantum point contact model for dielectric breakdown

Constriction (parabolic-shaped)

Potential barrier (not material)

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

Miranda & Suñé, IEDM’00, IRPS’01

Y. Li, NRL 2015
Application to Au/HfO$_2$/TiN RS structures

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

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


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

Nonlinear conductance quantization effects

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


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

TiN/HfO$_2$/Hf/TiN

conductance (A/V)

Voltage $V_{ox}$ (V)
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$_2$.”

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

\[ N = \frac{N^+ + N^-}{2} \]

\[ N^+ = 1 \& N^- = 1 \Rightarrow N = 1 \]

\[ N^+ = 2 \& N^- = 1 \Rightarrow N = \frac{3}{2} \]
The quantum point-contact memristor

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

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

\[ \Phi_{\text{Max}} = 2 \text{ eV} \]
\[ \Phi_{\text{Min}} = -2 \text{ eV} \]
\[ \Phi_0 = 0 \text{ eV} \]

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

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

This is the starting point of our own memristive approach

\[ I = G_P (V - I R_S) + I_0 \{\exp[\alpha (V - I R_S)] - 1\} \]
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2008 HP’s breakthrough

A practical implementation of a memristor?

The missing memristor found

Dmitri B. Strukov¹, Gregory S. Snider¹, Duncan R. Stewart¹ & R. Stanley Williams¹

LETTERS

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…

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

Many researchers have raised serious doubts!
and more recently …

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: $i$, $v$, $q$, $\Phi$
- 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 history of the device and retains its value even if the power is turned off
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

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

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

State Equation

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

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

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

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

\text{window function (ad hoc)}

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)

\[ f_B(\lambda) = 1 - (\lambda - H(-1))^{2p} \]

Prodromakis (2011)

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

- Required for imposing boundary conditions on \( \lambda \)
Memdiode equations

Transport Equation

Original

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

New

\[ I = \text{sgn}(V) \left[ (\alpha R)^{-1} W \left\{ \alpha RI_0(\lambda) \exp \left[ \alpha \left( |V| + RI_0(\lambda) \right) \right] \right\} - I_0(\lambda) \right] \]
\[ I_0(\lambda) = I_{0\text{max}} \lambda + I_{0\text{min}} (1 - \lambda) \]

State Equation

Original

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

New

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

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

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

\[ V \gg IR \]
\[ V \approx 0 : \quad I = I_0 [\exp(\alpha V) - 1] \]
\[ V \approx IR \]
\[ I = \frac{I_0 \alpha}{1 + I_0 \alpha R} V \]

- 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

Exponential
HRS
Linear
HRS
Linear
LRS
Origin of the nonlinear transport equation

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

Two anti-parallel diodes

\[ I = \text{sgn}(V) \left[ (\alpha R)^{-1} W \{ \alpha R I_0(\lambda) \exp[\alpha(|V| + RI_0(\lambda))] \} - I_0(\lambda) \right] \]

\[ I_0(\lambda) = I_{0\text{max}} \lambda + I_{0\text{min}} (1 - \lambda) \]

\( W \) 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

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

- Normalized number of activated channels at voltage \( V \)

\[ \lambda(V) = \int_{-\infty}^{+\infty} H(V - \xi) f(\xi) d\xi \]

Heaviside function

[Diagram showing the Heaviside function and convolution]
Origin of the state equation

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

- Number of conducting channels grows up as a logistic curve
Origin of the state equation

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

\[ \frac{d\lambda}{dV} = \eta \lambda (1 - \lambda) \]

\[ \frac{d\lambda}{dt} = \frac{d\lambda}{dV} \frac{dV}{dt} = \eta \lambda (1 - \lambda) \frac{dV}{dt} \]

First-order State Equation

\[ \frac{d\lambda}{dt} = \eta \lambda (1 - \lambda) \dot{V} \]
Ridge functions

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

Admissible inputs: \(-\infty \leq V \leq \infty\)
Bounded output: \(0 < \lambda < 1\)

Describe the creation and rupture of conducting channels

\textbf{Logistic hysteron}
Controlling the shape of the hysteron

Control of SET/RESET VOLTAGES

\[ V_1^- = V_2^- \quad \text{and} \quad V_1^+ < V_2^+ \]

Control of TRANSITION RATES

\[ \Gamma^\pm (V) = \left\{ 1 + \exp \left[ -\eta^\pm (V - V^\pm) \right] \right\}^{-1} \]
Experimental hysterons (current@low voltage)

![Graph showing current hysterons](image)

**TiN-Ti/HfO₂/W devices**
*Results from Universidad de Valladolid*

**TiN/HfO₂/Ti devices**
*Results from LETI, Grenoble*
Experimental and model results
Minor hysteretic loops (neuromorphic applications)

State space: domain of feasible states

\[ \Omega(\Gamma^-, \Gamma^+) \]

State of the system

\[ (V, \lambda) \]

\[ V(t) \quad \lambda(t) \]

Ridge functions

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

Simplest case:

\[ \frac{d\lambda}{dV} = 0 \quad if \quad (V, \lambda) \in \Omega \]

Channels can neither be created nor destroyed inside \( \Omega \)

\[ \tau_{ions} \gg \tau_{signal} \]
Krasnosel’skii-Pokrovskii (KP) hysteresis operator

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

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

Krasnosel’skii-Pokrovskii (KP) hysteresis operator

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

The previous output is the next initial state

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

- 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)
Time-independent model
Model and simulation results for LCMO

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

Superposition of hysterons: *super-hysteron*

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

\[ \sum \gamma_i = 1 \]

\( \Gamma \): sigmoidal hysterons
\( \gamma \): weight coefficients

EU project PANACHE 2014-2017

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

(a) Bottom (BE)  
ReRAM  
Gate  
Top (TE)

(b) Metal 2  
TiN 200 nm  
Ti 10 nm  
HfO2 10 nm  
TiN 200 nm  
Metal 1  

\[ A_{ReRAM} \ (0.3\mu m \times 0.3\mu m) \]

W = 5\mu m  
L_G = 0.35\mu m

(d) spot measurement  
@ ramp voltage  
@0.1V

(e) RVS  
\[ \Delta V = 50mV \]

(t)  
100 ns  

(f) CVS  
\[ V_{cvs} \]

(e) PULSES  
\[ A_v \]

\[ \Delta t \]
Typical switching behavior
Transistor as selector

(a) Drain Current [mA] vs. $V_{DS}$ [V]
(b) Current [mA] vs. Voltage [V]
(c) Reset Current [mA] vs. Current Compliance [mA]
(d) Voltage [V] vs. Current [A]

- $V_G = 0.75$ V
- $V_G = 1$ V
- $V_G = 1.25$ V
- $V_G = 1.50$ V
- $V_G = 2.00$ V
- $V_G = 2.50$ V
- $V_G = 3.00$ V
- $V_G = 3.5$ V
- $V_G = 4$ V

- $V_{RESET} = 1.2$ V
- $V_{RESET} = 1.0$ V
- $V_{RESET} = 0.8$ V

(93)
Set statistics: accurate determination of acceleration law

\[ \tau = \tau_0 e^{-\gamma V} \]

Experimental results for CVS confirm this model for the switching time

A. Rodriguez et al, EDL (2018)
Pulsed measurements with different ramp rates

(a) Voltage [V]
-1.0 -0.5 0.0 0.5 1.0
Current [mA]
-100 -50 0 50 100
5.10 V/s
5.10^2 V/s
5.10^3 V/s
5.10^4 V/s

V_{SET} = 0.021 \ln(RR) + 0.39
RR=50 V/s @ RESET
RR @ SET
-1.0 -0.5 0.0 0.5 1.0

(b) RR @ RESET
-1.0 -0.5 0.0 0.5 1.0
Current [mA]
-200 -100 0 100 200
5.10 V/s
5.10^2 V/s
5.10^3 V/s
5.10^4 V/s

V_{RESET} = 0.021 \ln(RR) + 0.49
RR = 50 V/s @ SET

(c) Memory State
-1.0 -0.5 0.0 0.5 1.0
Voltage [V]
0.0 0.2 0.4 0.6 0.8 1.0

(d) Memory State
-1.0 -0.5 0.0 0.5 1.0
Voltage [V]
0.0 0.2 0.4 0.6 0.8 1.0
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

\[ \tau = \tau_0 e^{-\gamma V} \]
Effect of ramp rate: experimental and model results

- \( I_{\text{max}} = 1.3 \times 10^{-4} \) A
- \( I_{\text{min}} = 3.5 \times 10^{-5} \) A
- \( \alpha_{\text{max}} = 3.5 \) V\(^{-1}\)
- \( \alpha_{\text{min}} = 1 \) V\(^{-1}\)
- \( \Delta t_{\text{exp}} = 70 \) V\(^{-1}\)
- \( \gamma_{\text{RESET}} = 70 \) V\(^{-1}\)
- \( \gamma_{\text{SET}} = 50 \) V\(^{-1}\)
- \( \tau_{\text{RESET}} = 5 \times 10^{19} \) s
- \( \tau_{\text{SET}} = 1 \times 10^{7} \) s
- \( R_S = 500 \Omega \)
Outline

• Introduction to filamentary-type ReRAM
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• 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

\[ R_{mem}(x) = R_{on}x + R_{off}(1-x) = R_{off} - (R_{off} - R_{on})x \]

\[ \frac{dx}{dt} = k \bar{i}(t) f(x), \quad k = \frac{\mu_v R_{on}}{D^2} \]

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.

VOFF = 0  
VAMPL = 1  
FREQ = 0.1
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)

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)

```verilog
// VerilogA model for memristor
//
// kerentalis@gmail.com
// Dimasfiltr@gmail.com
// skva8tx.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 = Mtr;
units = "m";
abstol = 0.1m;
endnature

discipline Distance
potential.distance;
enddiscipline

// Linear Ion Drift model
if (model==0) begin // Linear Ion Drift model
dw = dt*(I*Ron/D)*I(p,n);

// change the w width only if the
// threshold voltage permits!
if(abs(I(p,n))<threshold_voltage) begin
    w = w_last;
end

// No window
if ((window_type==0) || (window_type==4)) begin
    w = dw + dt*+w_last;
end // No window

// Jorgelar window
if (window_type==1) begin
    if (sign(I(p,n))==1) begin
        sign_multiply=0;
        if(w==0) begin
            sign_multiply=1;
        end
        if (sign(I(p,n))==-1) begin
            sign_multiply=0;
            if(w==0) 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 l=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

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 $\text{SiO}_x$

Simulation of MEMDIODE using LTSpice

Simulation of MEMDIODE using EXCEL

Modeling multi-level conduction

In collaboration with UCL, UK
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*

Outline

- Introduction to filamentary-type ReRAM
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Variability in SiO$_x$-based ReRAM devices

- LRS: fully formed filament
- HRS: partially formed filament

Variability in SiO$_x$-based ReRAM devices:

- LRS: fully formed filament
- HRS: partially formed filament
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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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