A Quick User Guide on

Peking University
Analog Resistive Random Access Memory (RRAM) SPICE Model

Version: 3.1

Patent Pending.

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1. Model Files

This documentation pertains to the model files in the PKU Analog RRAM SPICE Model v3.1 package. A brief summary and description of the model files included in the package are shown in Table 1.

Table 1. Summary of Model Files

File Name	Description
RRAM_v_3_1.va	Analog RRAM SPICE Model File

Additional Files

File Name	Description
User Guide	
Analog_RRAM_Model_v3.1_Quick_User_Guide.pdf	This User Guide in PDF format.
References/Publications	[1]-[6]
Sample Decks	
AC_analog_SET.sp	Example HSPICE decks: AC SET pulse
AC_analog _RESET.sp	Example HSPICE decks: AC RESET pulse

The package should include all the sample decks, plus this User Guide document. A summary of the model scope is in *2. The scope of the Model*; details regarding model usage and instantiation can be found in *3. Model Usage*; and *4. Sample results* describe the sample results using our model and discussion concerned.

2. The scope of the Model

Table 2 below summarizes the scope of the model.

Table 2. Summary of the Scope of the RRAM Model

Device Types	
Metal-Oxide Bipolar RRAM with Intermediate Modulation Layer (IML)	
Physics Aspects	
Filament Growth	Microscopic changes of oxygen vacancies and oxygen ions
Electronic Conduction	Combined: Ohmic & Fowler-Nordheim tunnelling mechanism
Analog switching characterize	Electrical and thermal properties of IML layer
Temperature and Heat Conduction	Joule heating

Different from the previously published RRAM_v_2_1, RRAM_v_3_1 is designed for fast and accurate simulation of analog metal-oxide based RRAM devices with intermediate modulation layer [1]. The underlying influences of electrical and thermal properties of IML on the analog switching behavior is dominant in improving the linearity [2] [3]. The model captures the pulse conductance update of analog RRAM devices with microscopic physical descriptions including the changes of oxygen vacancies (Vo) and oxygen ions (O^{2-}) .

Fig. 1 shows the proposed physical model of filamentary RRAM including the resistive switching (RS) model and conduction model. The RS behavior involves the processes of oxygen vacancy (Vo) generation and recombination, oxygen ions (O^{2-}) absorption and release from IML. The conductive filament (CF) consists of one RS region and one Vo rich (VR) region. The electrical properties of the filament are determined by the dimension of the filament [4] [5]. For SET process, the increased percentage of Vo (ΔC_V^+) in RS regions is attributed to the Vo generation, where C_V is the Vo percentage denoting the number of Vo divided by the total number of lattice oxygen. For RESET process, the release of O^{2-} from IML and the recombination of Vo and O^{2-} lead to the decrease of C_V (ΔC_V^-). The changes of C_V are directly associated with the conductance of CF, especially associated with the conductance of RS region. Parameter extraction method can be referred to [6].

In VR region, the conductivity is assumed as metallic-like conduction.

In RS region, the effective conductivity is deduced by adopting the Maxwell-Garnett model [7] based on effective medium theory (EMT), which depends on three parameters, namely, the conductivity of intrinsic HfO_2, the conductivity of VR region, and Vo percentage (C_V). Here the CF region is regarded as the intrinsic RS material with the changeable Vo. The main conduction mechanism of the intrinsic RS material without traps involved is assumed as Fowler-Nordheim tunnelling [8] and the conductivity is a function of electric field.

In IML region, The conductivity of IML is calculated by considering the O^{2-} percentage of IML according to EMT.

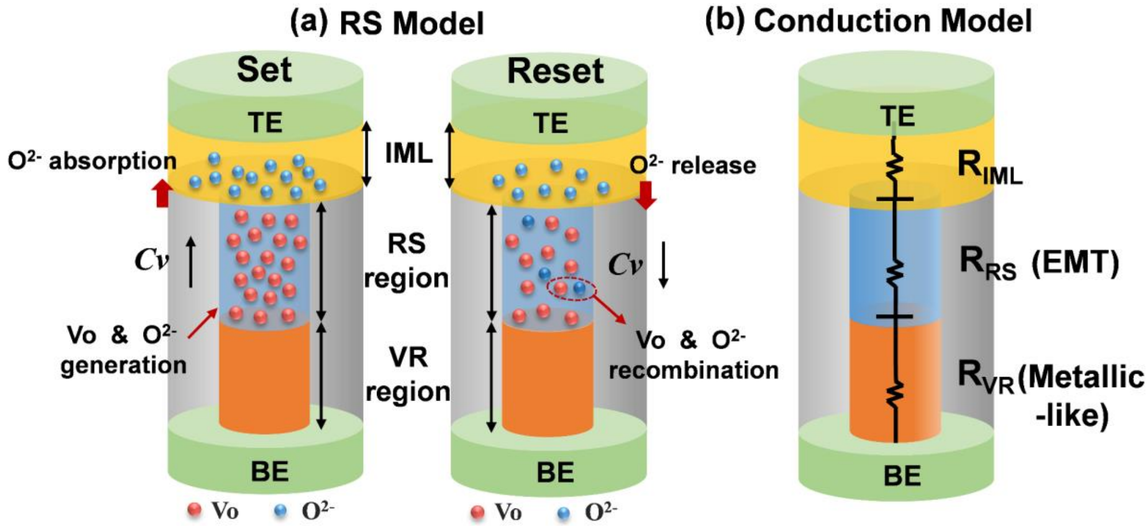

Fig. 1 Physical model of analog RRAM(a) RS model. The CF formation and rupture are determined by the changes of C_V. (b) Conduction model using effective medium theory (EMT) in RS region and metallic-like conduction in VR region.

3. Model Usage

The model is developed in Verilog-AMS, and it can be instantiated in HSPICE or other SPICE tools (with the appropriate Verilog-AMS support). **Here we recommend that user adopt Linux system as a simulation environment**. **We use *Hspice-2016_linux* as our simulation tool.** This section illustrates how to instantiate the model in HSPICE.

3.1 Convergence and Settings

For improved accuracy and convergence, include the following commands at the beginning of the SPICE deck:

```
************************************************
.option converge = 0
.option RUNLVL = 6
.option METHOD=GEAR
************************************************
```

3.2 Model Instantiation

To instantiate the devices in the model, the library (model file) must be included at the beginning of the SPICE deck. If the model file and your test file are located in the same folder, you can use the syntax below. Otherwise, you should specify the absolute address where your model file is saved.

```
.hdl RRAM_v_3_1.va
```

To instantiate an RRAM device, use the appropriate syntax below. The usage of this model is similar to that of the Si CMOS transistor model.

```
* Analog RRAM Model
X_RRAM TE BE RRAM_v_3_1 <Parameter_Name = Parameter_Value>
```

The port definitions, *TE and BE,* for the top electrode and the bottom electrode of RRAM, respectively. The ports *TE* and *BE* are not interchangeable in this model due to the nature of the asymmetry of the RRAM programming mechanism and the details of the model implementation.

The device parameters indicated in the < ... > are optional and can be set differently for each device instance. If the device parameters are omitted, default or global values set in the parameter definition file are used. The syntax for setting a parameter is: *parameter_name* = *value or parameter*

Table 3 below lists the definitions and default values of the device parameters.

Table 3. Model Parameter Descriptions and Default Values			
Parameters	Descriptions	Default Value	Suggested Range[1]
a	Lattice oxygen distance	0.5 nm	[0.3,1]
f	O^{2-} vibration frequency	10^{13} Hz	[10^{12}, 10^{14}]
E_a	Activation energy of O^{2-}	1.0 eV	[0.8,1.5]
E_r	Recombination barrier between V_O and O^{2-}	1.25 eV	[0.8,1.5]
E_o	Kinetic barrier of O^{2-} from IML to RS region	1.0 eV	[0.8,1.5]
E_{AC}	Activation energy of conductance in VR region	-0.001 eV	[-0.01,0]
Ψ_1	Energy barrier between RS layer and BE	1.55 V	[0.5,2]
Ψ_2	Energy barrier between IML and RS layer	0.85 V	[0.5,2]
α_1	Field enhancement factor for SET	0.95	[0.5,1.5]
α_2	Field enhancement factor for RESET	1.2	[0.5,1.5]
Z & e	Charge number & unit charge	2 & e	2 & e
R_{th}	Effective thermal resistance	1.8×10^6 K/W	[1×10^6,5×10^6]
L_{IML}	Intermediate modulation layer thickness	60 nm	[0,100]
L_{VR}	VR region height	5.5nm	[0,10]
L_{RS}	RS region height	2.5 nm	[0,10]
W_{IML}	Intermediate modulation layer width	30 nm	[0,100]
w_0	Conductance filament redius	2.5nm	[0,5]
A	(The coefficient associated with the relationship	1.5×10^{-6}	1.5×10^{-6}
B	between conductance and electric field)	1×10^9	1×10^9
C_{V0}	The proportion of Vo in lattice oxygen	0.9	[0,1]
C_{O0}	The proportion of O^{2-} in lattice oxygen	0	[0,1]
σ_{v0}	Initial conductivity of VR region	3×10^4 Ω^{-1} m^{-1}	~10^4
σ_{IML}	Initial conductivity of IML region	1.25×10^5 Ω^{-1} m^{-1}	[10^3,10^6]

[1] The range listed represents reasonable values based on experimental observations and physical insights. The units should be the same as the default values.

4. Sample Results

RRAM_v_3_1 is validated by the experimental data [9]. When inserting an IML between the top electrode and RS layer, the analog behavior with continuous conductance accumulation is obtained under the identical pulse training, as shown in Fig. 2 and Fig. 3. By adjusting the resistivity of IML, the analytic model shows an excellent agreement with the measurements about the linearity improvement of conductance modulation whether SET or RESET.

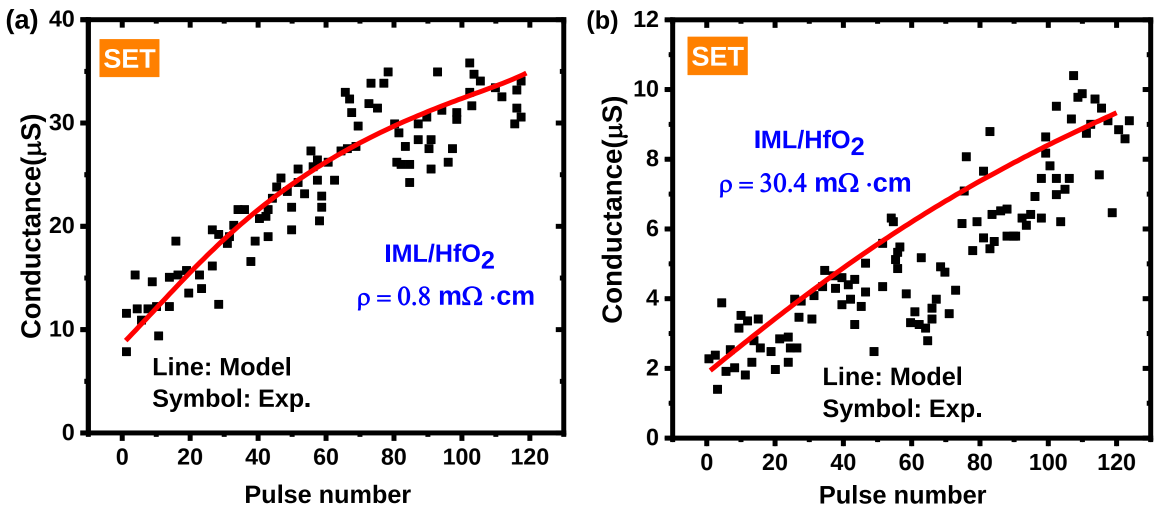

Fig. 2 Analog behavior of IML/HfO2 RRAM with identical pulse in SET process. (a) the resistivity of IML is 0.8 mΩ·cm (b) the resistivity of IML is 30.4 mΩ·cm.

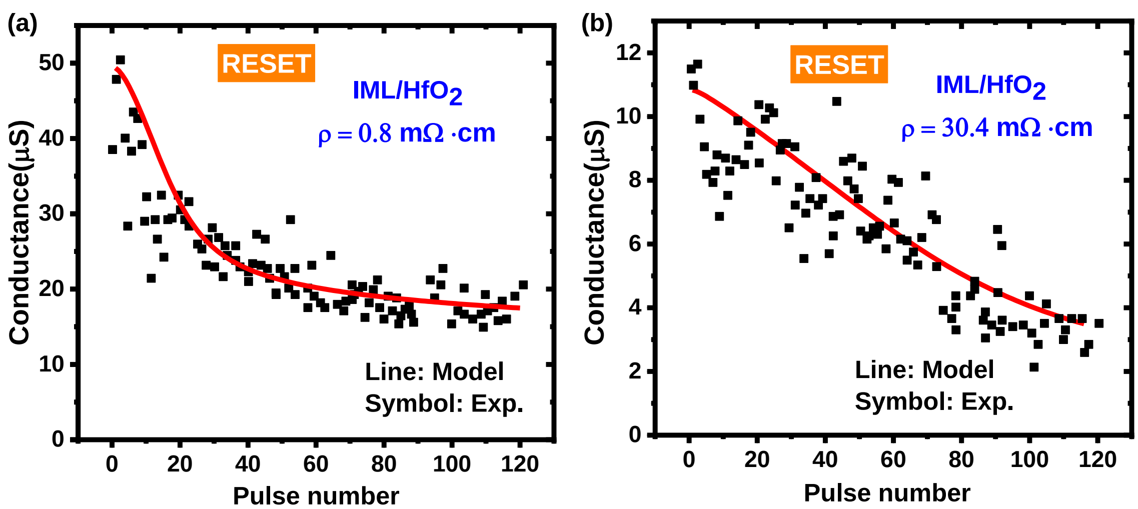

Fig. 3 Analog behavior of IML/HfO2 RRAM with identical pulse in RESET process. (a) the resistivity of IML is 0.8 mΩ·cm (b) the resistivity of IML is 30.4 mΩ·cm.

Below is a short introduction of the key parameters that influence the resistive switching characteristics of RRAM. For further analysis purpose, users can print values of key variables in the model by calling system functions. As for the usage of system functions, please refer to the Verilog-AMS language documents.

Parameters which are critical to analog RRAM behavior during SET process include $\boldsymbol{E_a}$, $\boldsymbol{\alpha_1}$, and $\boldsymbol{C_{V0}}$.

1. $\boldsymbol{E_a}$ and $\boldsymbol{\alpha_1}$ control the rate of V_O generation during the SET process. In the model, decreasing $\boldsymbol{E_a}$ or increasing $\boldsymbol{\alpha_1}$ leads to worse nonlinearity.
2. $\boldsymbol{C_{V0}}$ determines the initial RRAM states and affects the linearity and resistance of RRAM with pulse numbers.

Parameters which are critical to analog RRAM behavior during RESET process include $\boldsymbol{E_r}$, $\boldsymbol{E_o}$, $\boldsymbol{\alpha_2}$, and $\boldsymbol{C_{V0}}$.

1. $\boldsymbol{E_o}$ and $\boldsymbol{\alpha_2}$ control the rate of O^{2-} released from IML, which is the first step of the RESET process. In the model, decreasing $\boldsymbol{E_o}$ or increasing $\boldsymbol{\alpha_2}$ can accelerate RESET process.
2. $\boldsymbol{E_r}$ is critical to the rate of the recombination between V_O and O^{2-}, which is the second stage during the RESET process. In the model, increasing $\boldsymbol{E_r}$ leads to the slower RESET process with the identical pulse.
3. $\boldsymbol{C_{V0}}$ determines the initial RRAM states and affects the linearity and resistance of RRAM with pulse numbers.

For more parameter descriptions, users can look up our model file.

5. References

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Please report any bugs to us. Suggestions and comments are also welcome.