

RRAM Device Model Calibration

6.1 Introduction

A device model is a crucial component in development and understanding of electronic device. A compact mathematical model of RRAM is a set of equations that shows similar I - V or switching characteristics as that of the fabricated device for similar stimuli [Ielmini and Milo, 2017]. The models provide a way to simulate the fabricated device characteristics, and thus can be used to predict the device behavior under different stimuli. A simple and accurate device model is of paramount importance for design and verification of circuits utilizing the device. The models can be physics based where the physical parameters (like dielectric constant of material, thickness of dielectric layer, etc.) govern the switching characteristic and values of the fitting parameters can be tuned to achieve desired characteristics [Li *et al.*, 2013; Jiang *et al.*, 2014]. Moreover, to enable simulation based study of the fabricated device a mathematical model is calibrated with the experimental results to extract the values of fitting parameters. Extraction of fitting parameter was done by utilizing Keysight Technologies' IC-CAP (Integrated Circuit Characterization and Analysis Program). IC-CAP is a customizable semiconductor device modeling tool which accepts experimental data and input model files in Verilog-A, an industry standard modeling language for analog circuits. Moreover, IC-CAP allows to vary the model parameters so that simulated data fits well with the experimental data for efficient extraction of correct model parameters.

There are various RRAM models available, and each model has its own advantages and disadvantages [Hajri *et al.*, 2019]. The table shown in Fig. 6.1.1 shows various widely accepted RRAM models which includes the Linear Ion Drift Model [Strukov *et al.*, 2008], Non-Linear Ion Drift Model [Strukov and Williams, 2009], Simmons Tunnel Barrier Model [Pickett *et al.*, 2009], Threshold Adaptive Memristor (TEAM) Model [Kvatinsky *et al.*, 2012], Voltage Threshold Adaptive Memristor (VTEAM) Model [Kvatinsky *et al.*, 2015], and the Stanford Model [Jiang and Wong, 2014; Jiang *et al.*, 2014] along with their parameter metric for comparative analysis. It can be observed that Stanford model performs better, and it can be utilized to simulate the device characteristics with higher accuracy. In our study we have utilized Stanford RRAM model (version 1) for simulating the characteristic behaviors of fabricated devices.

6.2 Model Calibration with Eco-Friendly RRAM Devices

One can observe from the $\log(I)$ - $\log(V)$ plots that multiple conduction mechanisms like trap assisted tunnelling, Poole-Frenkel tunnelling, etc. may coexist during RRAM device switching (Fig. 4.3.3 and 5.3.5). All these mechanisms share an exponential relation with gap (g) and electric field strength [Cheong *et al.*, 2021]. This exponential dependence is simplified and a current

Metric \ Model	Linear	Nonlinear	Simmons	TEAM	VTEAM	Stanford
Bipolar switching	✓	✓	✓	✓	✓	✓
Low complexity	✓	✗	✗	✓	✓	✗
Actual memristive behaviour	✗	✗	✓	✓	✓	✓
Non linearity	✗	✓	✓	✓	✓	✓
Voltage Controlled	✗	✓	✗	✗	✓	✓
High frequency support	✗	✗	✓	✓	✓	✓
Pulse voltage programming	✗	✗	✗	✗	✓	✓
Pulse time programming	✗	✗	✗	✗	✗	✓
Temperature dependence	✗	✗	✗	✗	✗	✓
Threshold	✗	✗	✗	✓	✓	✓
Retention	✗	✗	✗	✗	✗	✓

Figure 6.1.1: Comparative analysis of few widely accepted RRAM models.

equation (I_{cell}) is obtained. The evolution of gap (g) is due to formation/dissolution of filament as per Arrhenius law combined with the probability of ion to overcome the activation energy barrier and the local field enhancement factor (γ) accounts for the polarizability with change in filament growth/rupture [Jiang *et al.*, 2016a].

Earlier the reported RRAM model was used mainly for simulating inorganic oxide switching layer devices [Ge *et al.*, 2017], [Ielmini and Milo, 2017]. By incorporation of two aspects, i.e. inclusion of compliance current module, and utilization of effective oxide thickness (t_{eo}), the model is extended to be used for devices with bilayer of switching materials. Fig. 6.2.1 shows the curve fitting of I-V characteristics of the fabricated Ag/Gelatin/HfO_x/ITO device with the extended version of the mathematical model. Firstly, the model equation is updated to take care of the bilayer or even multilayer dielectric material during simulation by this simple strategy to find the t_{eo} .

The median of first 25 cycles of experimental data is used for matching with the extended mathematical model. Further, to improve the model and implement the compliance current in the simulation, an additional conditional loop was introduced. This makes it more suitable for RRAM simulation, where compliance current is a crucial parameter for operation and stability of the devices. It makes sure that I_{cell} is always less than compliance current, which was 500 μA in our experiments. The following equations are used to simulate device behaviour.

$$I_{cell} = I_0 \times \exp\left(-\frac{g}{g_0}\right) \times \sinh\left(\frac{V_{cell}}{V_0}\right) \quad (6.1)$$

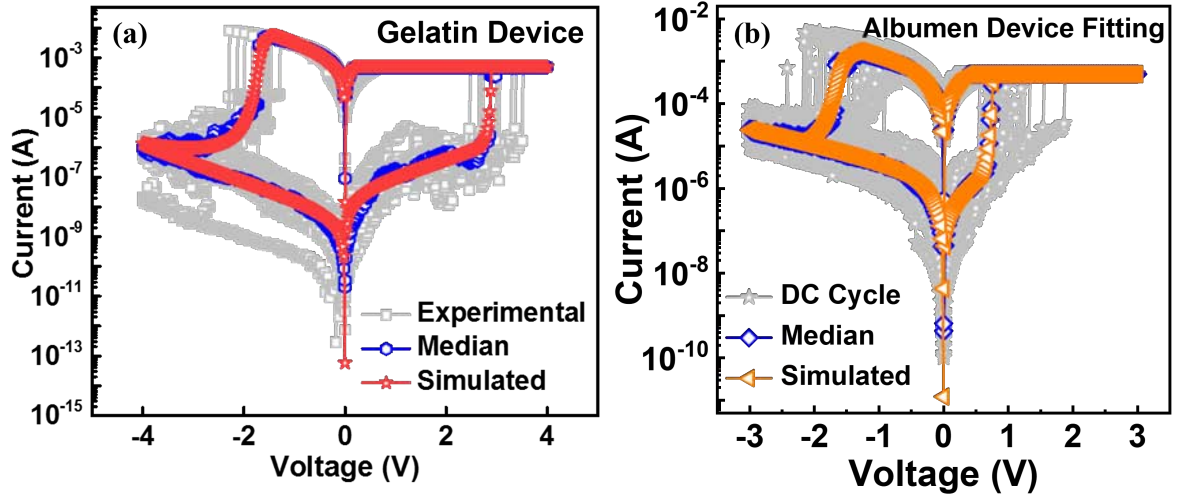


Figure 6.2.1: Fitting of simulated characteristic with median of experimental result obtained from fabricated Ag/Gelatin/HfO_x/ITO device.

$$\frac{dg}{dt} = -v_0 \times \exp\left(-\frac{E_a}{kT}\right) \times \sinh\left(\gamma \times \frac{a_0}{t_{eo}} \times \frac{qV_{cell}}{kT}\right) \quad (6.2)$$

$$\gamma = \gamma_0 - \beta \times g^3 \quad (6.3)$$

$$t_{eo} = k_{low-k} / k_{HfO_2} \times t_{low-k} \quad (6.4)$$

$$T = T_0 + V_{cell} \times I_{cell} \times R_{th} \quad (6.5)$$

where V_{cell} is the voltage applied across the electrodes, I_{cell} is the total current flowing through the RRAM cell, g is the distance between tip of filament and the opposite electrode i.e, average tunneling gap distance, E_a is the activation energy, a_0 is the atomic spacing, q is the elementary charge, k is the Boltzmann constant, γ is the local field enhancement factor, k_{low-k} and t_{low-k} are dielectric constant and thickness of low-k material (which is gelatin in this case), T_0 is the room temperature, R_{th} is the equivalent thermal resistance, and I_0 , g_0 , V_0 , v_0 , β , γ_0 , are fitting parameters. The extracted values of these parameters are $I_0 = 3.802\text{E-}03$, $g_0 = 160\text{E-}12$, $V_0 = 496.6\text{E-}03$, $v_0 = 3.423$, $\beta = 44.06\text{E-}03$ and $\gamma_0 = 18.37$ for set cycle with a RMS error of 2.4%. Similarly the obtained values of the fitting parameters for reset cycle are $I_0 = 9.967\text{E-}03$, $g_0 = 111.9\text{E-}12$, $V_0 = 700\text{E-}03$, $v_0 = 33.33\text{E-}03$, $\beta = 2.77$ and $\gamma_0 = 16.00$ with a RMS error of 4.7%. A very good curve fitting with a relative RMS error of less than 5% is obtained by using both the processes separately rather than simulating and fitting complete cycle as one process which results in higher relative error [Hajri *et al.*, 2019]. This indicates that the given model with these values of fitting parameters can be used to simulate the device behaviour to a great extent of accuracy in device and circuit simulations.

6.3 Induction of Cyclic Variability

Cyclic variability refers to the variation of resistance level of the device after each switching cycle.

The experimental curve of Fig. 6.2.1 (a) and (b), shows that there is a variation in the experimental I-V characteristics of the device for different cycles. This cycle-to-cycle variation or tem-

poral variation is an intrinsic characteristics of the RRAM devices, and thus it is important to include these variations in the device model. Among different model parameters, gap between tip of the filament and the opposite electrode (h) is widely discussed as the source of variation during RRAM operation [Pan *et al.*, 2014]. To incorporate this in the model, a random Gaussian variation (χ) using Monte-Carlo of the initial gap of the filament (δ_0) is introduced as shown in Eq. 6.6.

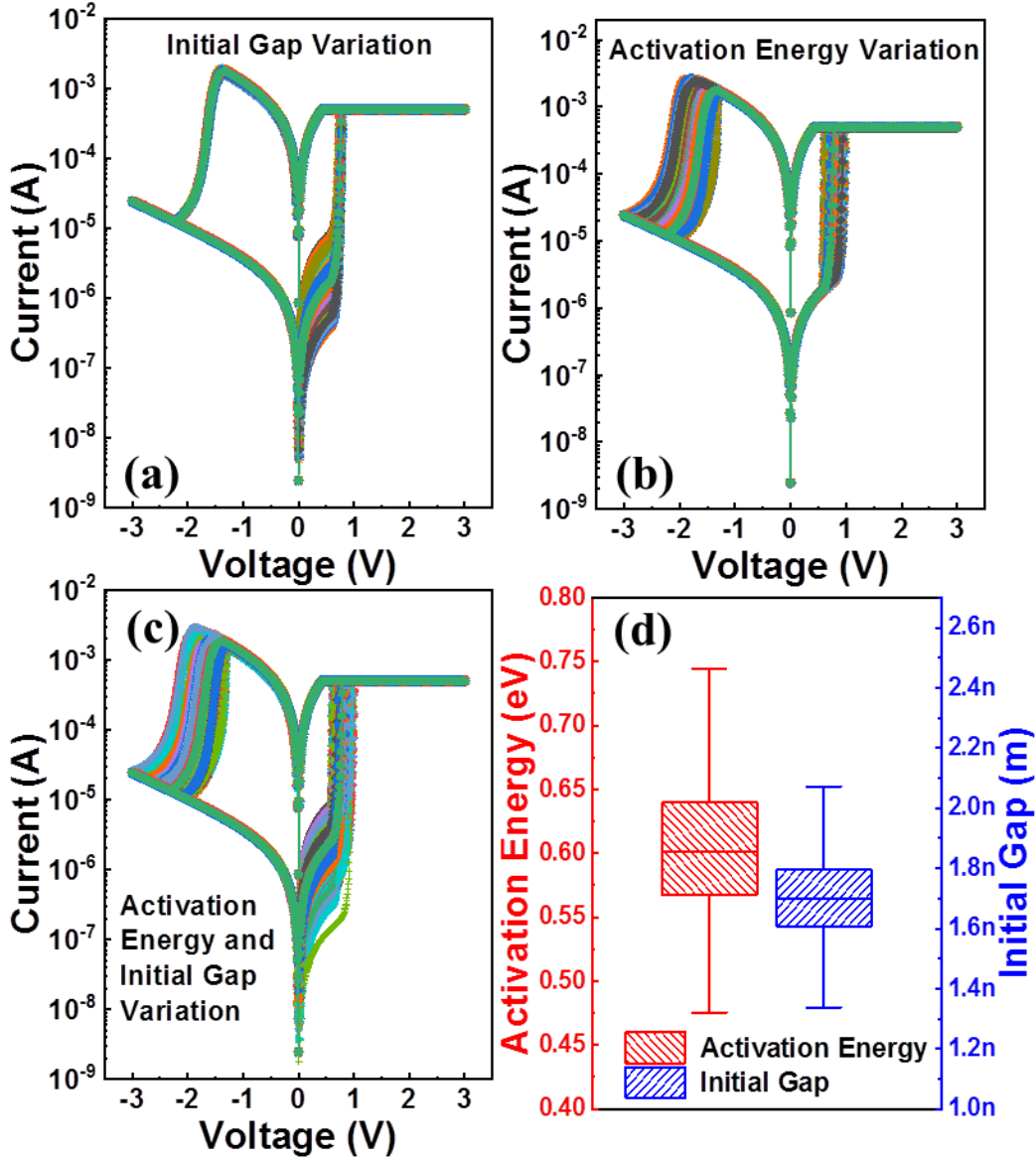


Figure 6.3.1: Simulated I - V characteristics with (a) initial gap variation, (b) activation energy variation, (c) both δ_0 and E_a variation of the device for 1000 cycles. (d) Statistical distribution of activation energy and initial gap.

Fig. 6.3.1 (a) shows the 1000 switching cycles of the model with initial gap variation. It can be observed that by introducing variation in δ_0 , only the starting point or the initial current of the curve varies, and thus it can be concluded that only variation of initial gap is not sufficient. The other important parameter is the activation energy (E_a), which plays a crucial role in cyclic vari-

ation [Ambrogio *et al.*, 2014a]. Fig. 6.3.1 (b) shows the switching characteristic with E_a variation as obtained by using Eq. 6.8. It can be observed that E_a variation takes care of variation of V_{SET} and V_{RESET} , but it has no effect at the current levels at the starting or initial phase. Although it can be observed that the practical device has variations in both initial current levels and switching voltages, thus to make the model more accurate both the parameters (δ_0 and E_a) variation was included simultaneously, and they were varied independently. The equations to include variations are as follows:

$$\delta_0 = \chi(\delta_{ini}, 0.5, 6), \text{ where} \quad (6.6)$$

$$\delta_0 = h(@t = 0) \quad (6.7)$$

$$E_a = \chi(E_{a0}, 0.5, 6) \quad (6.8)$$

The default value of δ_{ini} is 1.8 nm for set cycle and 0.2 nm for reset cycle, and E_{a0} is 0.6 eV in the model, and the variations are induced on these default values only. In Eq. 6.6 & Eq. 6.8, 0.5 refers to 50% variation in nominal value, and '6' represents the six sigma deviation. Fig. 6.3.1 (c) shows the I-V characteristic with variation of both the parameters. This plot shows similar switching characteristics as of a fabricated device, although not identical but very close. The exact and complete reasons for the cyclic variation in the RRAM device is still not very clear and an active area of research, and its discussion is out of scope of this paper. Finally, Fig. 6.3.1 (d) shows the statistical variation of activation energy and initial gap that has been used for the above simulations. This method, although limited, provides a simple technique to simulate near practical device behaviour without compromising the underlying physic of device behaviour.

6.4 Conclusion

A widely accepted physics driven device model was utilized to obtain model fitting parameters by calibrating the model with median of experimental results. For Ag/Gelatin/HfO₂/ITO device, the fitting parameters are obtained with root mean square (RMS) error of less than 5%, and for Ag/Albumen/HfO₂/ITO device the fitting parameters were obtained with a RMS error of less than 4.5%. Later, The switching variation was then introduced in the calibrated model by varying initial gap of the filament and activation energy parameters using Monte Carlo Gaussian random variation. The model with the switching variations enables the designers to simulate RRAM devices with near practical results, thus enabling them to use the model in further circuit and system simulations.