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MODELING AND SIMULATION OF TITANIA NANOSTRUCTURES MEMRISTIVE DEVICE

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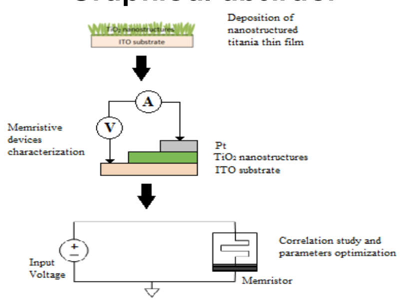
Graphical abstract



Abstract

Study on the SPICE model for nanostructured titania based memristor was carried out. Nanostructured titania thin film was deposited and a memristive device based on the nanostructured film was fabricated and characterized. Various reported SPICE models were applied to simulate the memristive behavior. The parameters for each model were optimized. The optimization process was performed in LTSPICE circuit simulation tool. It showed that Pino's SPICE model fits well with the deposited titania nanostructure memristive behavior.

Keywords: Memristive device; SPICE model; titania nanostructures

1.0 INTRODUCTION

In the past few decades, a new passive device has been proposed to hold the relationship between charge and flux [1]. As the name implies, memristor or memory resistor has the ability to remember its current resistance state even without the applied voltage. Despite of its unique properties, memristor has only been successfully realized in 2008 by HP labs due to the advancement in nanotechnology [2]. Memristor can be used in various applications including non-volatile memory, programmable logic, analog circuit and neuromorphic system [3-6].

In order to allow the implementation of memristor in design and circuit simulation, a model that is capable in incorporating the non-linearities and hysteretic properties of memristor is highly desirable. Other than that the developed model should be able to be tuned thus it can be used for different memristor technologies. Recently, a lot of studies have been carried out to develop a model for memristor. These include linear dopant drift [2], non-linear dopant drift [7-9], ThrEshold Adaptive Memristor model (TEAM) [10], Simmon tunnel barrier [11] and others.

Several efforts have also been made to develop a memristor model by correlating the model to physical characterization data [11-12]. In [11], the SPICE model of a TiO_2 memristive device was developed by taking into account the effect of tunnel barrier width in the metal insulator metal (MIM) structure. Unlike H. Abdalla's et al. [11] model, Pino's et al. [12] offers more compact and simpler model for ion conductor chalcogenide based memristor. Although correlation study has been performed, there is still no prove that both models could be fitted well to other memristor technologies.

In this study, the existing models were correlated to titania nanostructure characterization data in [13]. The parameters optimization process was carried out using LTSPICE. The circuit schematic to conduct the simulation process is shown in Figure 1.

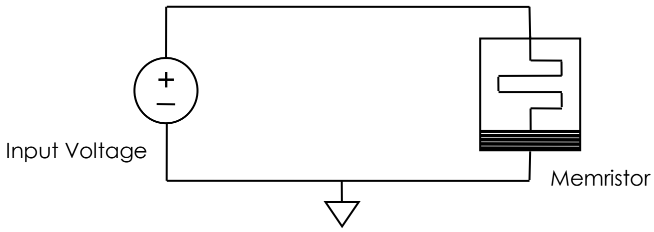


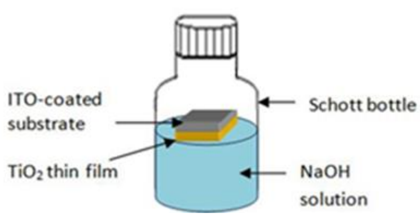
Figure 1 Circuit schematic for parameters optimization in LTSPICE

2.0 EXPERIMENTAL

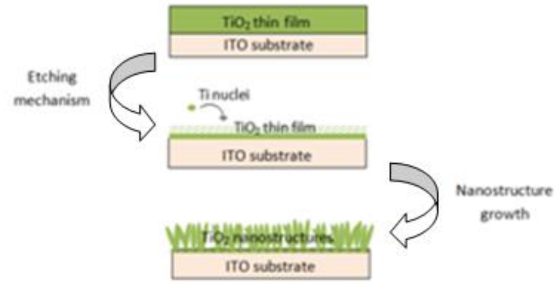
The device structure consisted of Pt/TiO_2 nano-structures/TiO_2/ITO glass was used to study the application of titania nanostructures as the active layer for memristive device [13]. The TiO_2 thin film was initially sputtered onto ITO-coated glass substrate followed by the growth of TiO_2 nanostructures. The sputtering process was performed under 50 sccm argon gas, 5 mtorr working pressure, 300 W RF power at 200°C substrate temperature using TiO_2 (99.999% purity) as the target material.

The nano-structures were grown on the TiO_2 thin film through the immersion method in NaOH aqueous solution for 30 mins. The samples were then subjected to annealing process to enhance the crystallinity of the TiO_2 nanostructures. Fig. 2 (a) and (b) show the schematic diagram during nanostructures synthesis Process and the growth mechanism of TiO_2 nanostructures on TiO_2 thin film respectively

The current-voltage (I-V) characterization was carried out by 2-points probe measurement method using a Keithley 4200 semiconductor characteristic system. The bias voltage is swept from 0 V to 5 V followed by 5 V to 5 V and back to 0 V while simultaneously measuring the current. Fig. 3 shows the I-V characteristic of the TiO2 nanostructure memristive device.



(a)



(b)

Figure 2 Schematic diagrams of (a) nanostructure synthesis process (b) the growth mechanism of TiO_2 nanostructures on TiO_2 thin film [13]

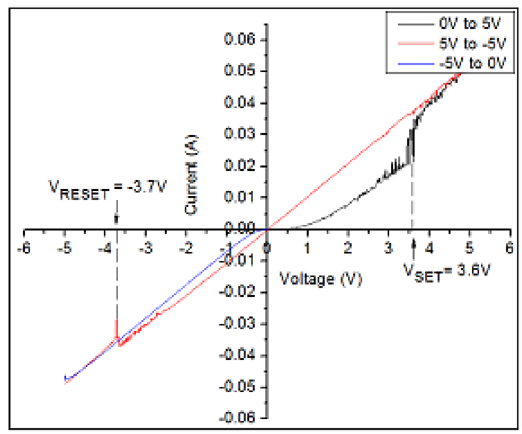


Figure 3 Current-voltage characteristic of TiO_2 nanostructure memristive device [13]

3.0 MEMRISTOR SPICE MODELS

In general, a physical model of memristor proposed by Strukov *et al.* consisted of doped and undoped TiO_2 layers sandwiched between top and bottom electrodes [2] as shown in Figure 4. When an external voltage is applied to the device, the charged dopants drift causing the width, *w* of the doped area changes. This will then changes the total resistance of memristor R_{MEM}. Assuming linear ionic drift with average ion mobility μ_v, the total resistance is given by

$$R_{MEM} = R_{ON}\frac{w(t)}{D} + R_{OFF}\left(1 - \frac{w(t)}{D}\right) \qquad (1)$$

where R_{ON} and R_{OFF} is the minimum and maximum resistance respectively, *D* is the device thickness and *w(t)* is the thickness of the TiO_2 doped layer.

The memristor SPICE model was later improved by multiplying the derivative of state variable by window function (equation (2)) [14]. The window function not only has the ability to take into account the non-linearity effect in nano-scale devices but also could provide the state variable working region [15].

$$\frac{dx}{dt} = ki(t)f(x), \qquad k = \frac{\mu_v R_{ON}}{D^2} \qquad (2)$$

Several studies have been carried out to implement the window function in memristor SPICE model. The first window function was proposed by Strukov *et al.* [2]. This window function (equation (3)) could reach its maximum value when x = 0.5 and minimum value when x = 0 or 1. Though a symmetrical behavior could be achieved using Strukov's window function, it has been suffering from a terminal state problem.

$$f(x) = x(1-x)^2 \tag{3}$$

$$\text{where} \quad x = {}^{w}\!/_{D} \tag{4}$$

Another window function was proposed by Joglekar *et al*. [7] and is given as follows

$$f(x) = 1-(2x-1)^{2p} \tag{5}$$

where *p* is the control parameter to control the nonlinearity of the function. Although this window function will ensure zero drift near the boundary [16], the state variable could not be changed easily.

An alternative window function that improves the previous window function were proposed by Biolek [8] and Prodromakis [9] and described in equation (6), (7) and (8).

$$f(x) = 1-(x-stp(i))^{2p} \tag{6}$$

$$stp(i) = \begin{cases} 1 \; if \; i > 0 \\ 0 \; if \; i < 0 \end{cases} \tag{7}$$

$$f(x) = 1-\left|(x-0.5)^2+0.75\right|^p \tag{8}$$

A new SPICE model has been developed by Pino *et al.* which correlates well with the device characterization data [12]. In this model, the rate of change in resistance of memristor device is defined by the following equations [12]

$$if \; V(t) > T_h \quad \therefore \frac{dR}{dt} = \begin{cases} -K_{h1}e^{K_{h2}(V(t)-T_h)}, & R(t) > R_{ON} \\ 0, & R(t) \le R_{ON} \end{cases} \tag{9}$$

$$if \; V(t) < T_l \quad \therefore \frac{dR}{dt} = \begin{cases} K_{l1}e^{K_{l2}(V(t)-T_l)}, & R(t) < R_{OFF} \\ 0, & R(t) \ge R_{OFF} \end{cases} \tag{10}$$

where,

T_h = Threshold voltage required to enter non-linear region from the off region

K_{h1}, K_{h2} = fitting parameters need to capture the non-linear effects

T_l = Threshold voltage required to enter non-linear region from the on region

K_{l1}, K_{l2} = fitting parameters need to capture the non-linear effects

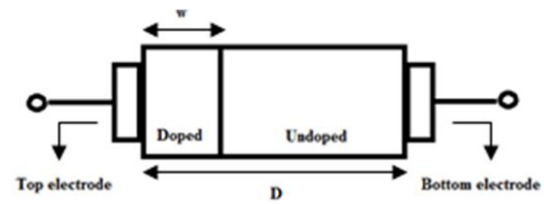
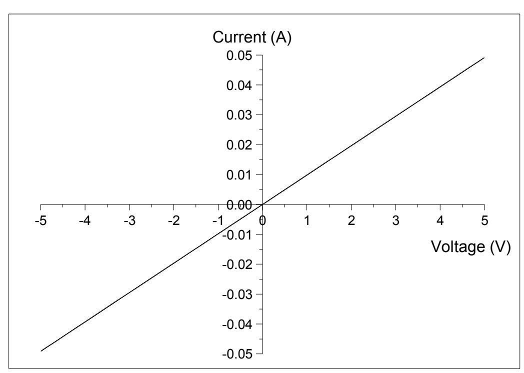


Figure 4 Physical model of memristor [2]

4.0 RESULTS AND DISCUSSION

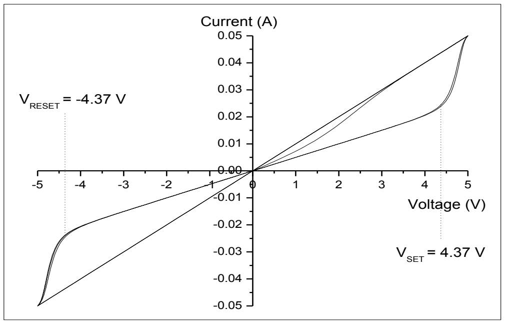
In this study, the nanostructure TiO_2 characterization data is correlated to the memristor SPICE model developed by Strukov, Joglekar, Biolek and Pino. Figure 5(a) – (f) shows the I-V characteristics for TiO_2 nanostructure after optimization process in LTSPICE. From the results obtained, it can be seen that Pino's model accurately described the pinched hysteresis loop of the characterized data (Figure 3). The V_{SET} and V_{RESET} were measured to be 3.67 and -3.71 V respectively.

As shown in Figure 5(a) the Strukov's linear model cannot accurately model the characterized nanostructure memristive device. This is due to the non-linearity occurs in nanoscale device do not model properly. By multiplying the derivative of state variable by window function a symmetrical hysteresis loop could be obtained as shown in Figure 5(b). As mentioned previously in Section 3, the addition of window function to the state equation could overcome the non-linearity problem. As can be seen in Figure (c), (d) and (e), using Joglekar [7], Biolek [8] and Prodromakis [9] window functions resulted in better memristive behavior respectively. However, the loop achieved at the negative cycle for all models is not similar as the characterized data.

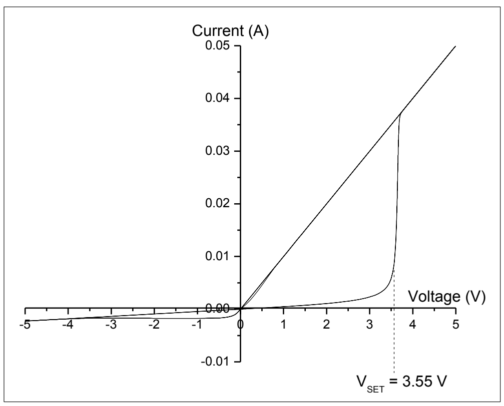


(a) Simulation results using Strukov memristor model. Optimized parameters: R_{ON} = 100 Ω, R_{OFF} = 165 Ω, X_0 = 0.55, D = 60 nm and μ_v = 10^{-14} $m^2s^{-1}V^{-1}$ V = 5sin(2πt) V.

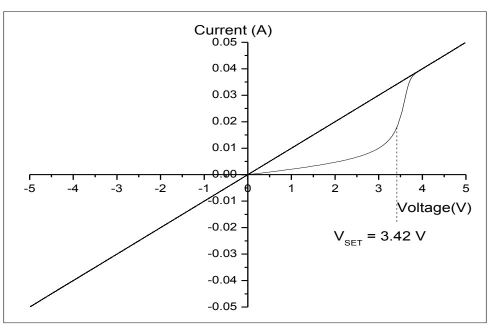
Since, threshold voltages were observed during positive and negative cycles in the reported data, using Pino's *et al.* model is more appropriate. This is because they have accounted for the effect of threshold voltage in their SPICE model (equation (9) and (10)).



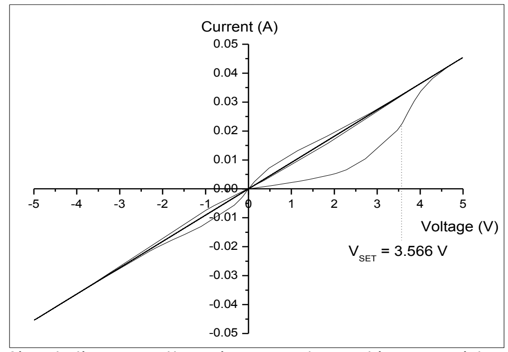
(b) Simulation results using Strukov memristor model. Optimized parameters: R_{ON} = 100 Ω, R_{OFF} = 200 Ω, X_0 = 0.55, D = 60 nm and μ_v = 10^{-14} $m^2s^{-1}V^{-1}$ V = 5sin(2πt) V.



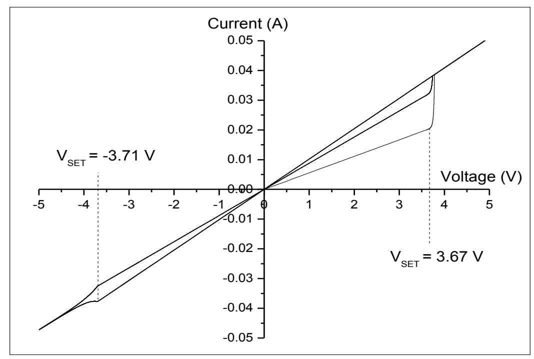
(c) Simulation results using Joglekar memristor model. Optimized parameters: R_{ON} = 100 Ω, R_{OFF} = 1 kΩ, X_0 = 0.55, D = 60 nm, μ_v = 10^{-14} $m^2s^{-1}V^{-1}$, p = 5, and V = 5sin(2π5t) V.



(d) Simulation results using Biolek memristor model. Optimized parameters: R_{ON} = 100 Ω, R_{OFF} = 2.7 kΩ, X_0 = 0.98, D = 60 nm, μ_v = 20^{-14} $m^2s^{-1}V^{-1}$, p = 5, and V = 5sin(2πt) V.



(e) Simulation results using Prodromakis memristor model. Optimized parameters: R_{ON} = 110 Ω, R_{OFF} = 1 kΩ, X_0 = 0.58, D = 60 nm, μ_v = 10^{-14} $m^2s^{-1}V^{-1}$, p = 1, and V = 5sin(2πt) V.



(f) Simulation results using Pino memristor model. Optimized parameters: R_{ON} = 98 Ω, R_{OFF} = 180 Ω, T_h = 3.6, Tl = -3.7, K_{h1} = 2(10^2), K_{h2} = 40, K_{l1} = 3(10^3), K_{l2} = 5, and V = 5sin(2π5t) V.

Figure 5 I-V characteristics for TiO_2 nanostructure after optimization process in LTSPICE

5.0 CONCLUSION

Various SPICE models have been correlated to TiO_2 nanostructure characterization data in order to determine the suitable model. The parameters for each memristor model have been optimized in LTSPICE. It was found that Pino's model fits well with the characterized data.

Acknowledgement

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