COMPARISON OF DIFFERENT WINDOW FUNCTIONS WITH THRESHOLD LOGIC

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ABSTRACT

Memristor is a novel two-port circuit element with a memory, as device that can be used in many applications, such as memory, logic, and neuromorphic systems. As a passive circuit element, the memristor would be a useful tool to analyse circuit behavior via simulation. SPICE model is an appropriate way to describe the real device operation. In this paper, a SPICE model of memristor is incorporated with threshold logic circuit for nonlinear dopant drift. Various window functions have been proposed in nonlinear ion drift memristor devices. The circuit analysis of the proposed memristor models are studied by investigating and characterizing the physical electronic and behavioral properties of memristor device. The simulation output should have a current voltage hysteresis curve, which looks like a bow tie. The loop, maps the switching behavior of the device and makes comparison of these memristor implemented circuit design between different types of memristor window models. The research verifies the proposed threshold memristor model and the possibilities of implementing memristor model in practical analog circuit.

Keywords: Memristor, Memristor SPICE Model, Nonlinear, Window Functions.

INTRODUCTION

Memristor is the contraction of memory resistor which is a passive device that provides a functional relation between charge and flux. It is defined as a two-terminal circuit element in which the flux between the two terminals is a function of the amount of electric charge that has passed through the device [1]. A memristor is said to be charge-controlled if the relation between flux and charge is expressed as a function of electric charge and it is said to be flux-controlled if the relation between flux and charge is expressed as a function of the flux linkage [2].

In 1971, Leon Chua proposed that there should be a fourth fundamental passive circuit element to setup a mathematical relationship between electric charge and magnetic flux which is called as memristor which is short for memory resistor [2].

The current is defined as the time derivative of the charge. According to Faraday's law, the voltage is defined as the time derivative of the flux. A resistor is defined by the relationship between voltage and current dv=Rdi, the capacitor is defined by the relationship between charge and voltage dq=Cdv, the inductor is defined by the relationship between flux and current dφ=Ldi. The fourth fundamental circuit element completes the symmetry of the relation between charge and magnetic flux dφ=Mdq. Table 1 shows the relationship between the fundamental circuit element.

The memristor has a memristance and provides a functional relation between charge and flux. In 2008, Stanley Williams and his team at Hewlett Packard successfully fabricated the first memristor in physical device form [3]. Memristance is a property of the

Basic two Terminal Devices	Equation	Relationship between Fundamental Circuit Element
Resistor, R	dv=Rdi	v and I
Capacitor, C	dq=Cdv	v and q
Inductor, L	df=Ldi	i and f
Memristor, M	df=Mdq	q and f

Table 1. The Four Fundamental Element (Resistor, Capacitor, Inductor, and Memristor)

memristor. When the charge flows in one direction through a circuit, the resistances of the memristor increase. The resistance decreases, when the charge flows in the opposite direction of the circuit. If the applied voltage is turned off, thus stopping the flow of charge, the memristor remembers the last resistance that it had [11].

In HP memristor model, to realize a memristor, they used a very thin film of Titanium dioxide (TiO_2). The thin film is sandwiched between two platinum (Pt) contacts and one side of TiO_2 is doped with oxygen vacancies. The oxygen vacancies are positively charged ion making it conductive. Thus, it behaves as semiconductor. There is a TiO_2 junction where one side is undoped. The undoped region has insulating properties. The device established by HP is shown in Figure 1 [3].

When a positive voltage is applied, the positively charged oxygen vacancies in the TiO_2-x layer are repelled moving them towards to the undoped TiO_2 layer. The boundary between the two materials move causing an increasing in the percentage of the conducting TiO_2-x layer and thus increasing the conductivity of the whole device.

When a negative voltage is applied, the positively charged oxygen vacancies are attracted, pulling them out of TiO_2 layer. This increases the amount of insulating TiO_2, thus increasing the resistivity of the whole device. When the voltage is turned off, the oxygen vacancies do not move. The boundary between the two Titanium dioxide layers is frozen. This is how the memristor remembers the voltage last applied [1].

1. Methodology

The aim of this project is to provide a simulation program that adequately simulates and can be used as a circuit element in design work. To model the electrical characteristics of the memristors [9], SPICE would be an appropriate way to describe the real device operation [4]. Moreover, using the model as a sub-circuit can highly guarantee a reasonable high flexibility and scalability features [5].

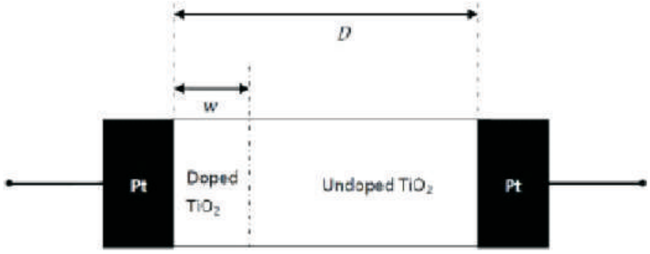


Figure 1. Memristor Model adapted from [3]

The PSPICE is used to create a memristor model and design new symbol of the memristor circuit for the simulation because PSPICE is much easier to handle compared to others. The authors use SPICE model that been adapt from [6] and made some adjustment so it can be used for several window functions that have been proposed for nonlinear ion drift model.

The SPICE model is created based on the mathematical model of the HP Labs memristor. After the memristor has been modeled, then we will start to design and implement the memristor with an analog circuit. We will investigate and make a comparison between the memristor circuit with analog circuit to see the difference and study the behavior of the circuits.

1.1 Model of the Memristor from HP Labs

In the model of a memristor presented here, there is a thin semiconductor film that has two regions, one with a high concentration of dopant that behaves like a low resistance called R_{ON} and the other with a low dopant concentration with higher resistance called R_{OFF} [3]. The film is sandwiched between two metal contacts as in Figure 1.

The total resistance of the memristor, R_{MEM}, is a sum of the resistances of the doped and undoped regions, is the width of the doped region, referenced to the total length D of the TiO_2 layer, and R_{OFF} and R_{ON} are the limit values of the memristor resistance for w=0 and w=D, respectively. The ratio of the two resistances is usually given as,

$$R_{MEM}(x) = \left(R_{ON}(x) + R_{OFF}(1-x)\right) \quad (1)$$

where,

$$x = w/D \in (0, 1) \quad (2)$$

The Ohm's law relation is applicable between the memristor voltages and current,

$$v(t) = R_{MEM}(w)i(t) \quad (3)$$

The application of an external bias v(t) across the device will move the boundary between the two regions by causing the charged dopants to drift. For the simplest case of ohmic electronic conduction and linear ionic drift in a uniform field with average ion mobility μ_v, we obtain

$$v(t) = (R_{ON}\frac{w(t)}{D} + R_{OFF}(1-\frac{w(t)}{D}))i(t) \quad (4)$$

$$\frac{dw(t)}{dt} = \mu_v \frac{R_{ON}}{D} i(t) \quad (5)$$

which yields the following formula for w(t),

$$w(t) = \mu_v \frac{R_{ON}}{D} q(t) \quad (6)$$

By inserting equation (6) into equation (4), the memristance of this system can be obtained, which for $R_{ON}=R_{OFF}$ simplifies to,

$$M(q) = R_{OFF}(1-\frac{\mu_v R_{ON}}{D^2} q(t)) \quad (7)$$

where μv is the average drift velocity (cm^2/Sv), D is the thickness of Titanium-dioxide film, R_{OFF} and R_{ON} are on-state and off-state resistances, respectively, and q(t) is the total charge passing through the memristor device.

1.2 Nonlinear ion Drift Model

Even a small voltage across the nanodevices will produce a large electric field [7] causing the ion boundary position to move in a decidedly non-linear way [10]. Nonlinear dopant drift adds nonlinear window function f(x) to the state equation within zero and unity. The window function decreases as the state variables drift speed approaches the boundaries until it reaches zero when reaching either boundaries [8]. The speeds of the movement of the boundary between the doped and undoped regions are depending on several factors according to state equation [1].

$$\frac{dx}{dt} = ki(t)f(x), \quad k = \frac{\mu_v R_{ON}}{D^2} \quad (8)$$

where u_v is the dopant mobility. The speed of the boundary between the doped and undoped regions decreases gradually to zero [1]. The nonlinear ion drift memristor model is simulated with these window functions to see the difference and the issue that has been faced by them.

1.3 Window Function

Window function is a function of the state variable. Window function forces the bounds of the device and to add nonlinear behavior close to these bounds. There are several window functions that have been proposed till date. These window functions are implemented in the SPICE model to see the difference and the issue that been faced by them. The implemented window functions are, Strukov, Joglekar and Wolf, Biolek, and Prodromakis.

Several window functions were proposed in the literature. Strukov proposed the following window function [3],

$$f(x) = x - x^2 \quad (9)$$

However, this window function lacks flexibility. Another window function was proposed by Joglekar [4], which has a control parameter p which is a positive integer.

$$f(x) = 1-(2x-1)^{2p} \quad (10)$$

This control parameter controls the linearity of the model, where it becomes more linear as p increases. This window function ensures zero drift at the boundaries. However, a significant liability of this model lies in the fact that if w hits any of the boundaries (w = 0 or w = D), the state of the device cannot be further adjusted. This will be from now on termed as the terminal state problem. Until Biolek proposed another window function that allows the memristor to come back from the terminal state problem.

$$f(x) = 1-(x-stp(-i))^{2p} \quad (11)$$

The reversed bias should be now move back the state variable after it reaches either boundary. This feature is described by a current dependent step function, stp(i), which is a part of a new window function f(x) that behaves differently in each voltage bias direction.

$$stp(i) = \begin{cases} 1 & pro \quad i \geq 0 \\ 0 & pro \quad i < 0 \end{cases} \quad (12)$$

The latest window function is proposed by Prodromakis,

$$f(x) = 1-[(x-0.5)^2 + 0.75]^p \quad (13)$$

It allows the window function to scale upwards which implies that $f_{max}(x)$ can take any value within $0 < f_{max}(x) < 1$. In addition, p can take any positive real number allowing a greater extent of flexibility. The boundary issues are also resolved with the window function returning a zero-value at the active bi-layer edges.

1.4 SPICE Model of Memristor

In the given circuit in Figure 2, V_{MEM} is the input voltage and I_{MEM} is modeled to be the current through the memristor. The flux is calculated by integrating the voltage V_{MEM} and the charge is calculated by integrating the current I_{MEM}. EM

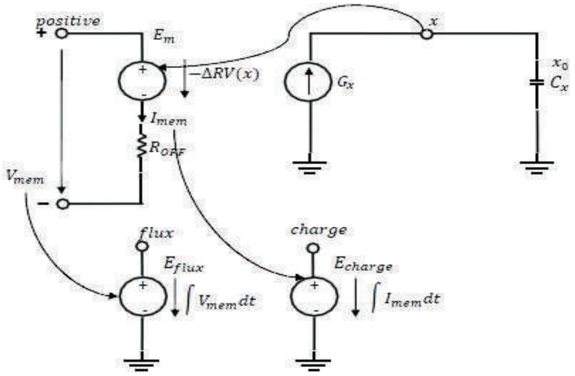


Figure 2. Memristor Spice Model

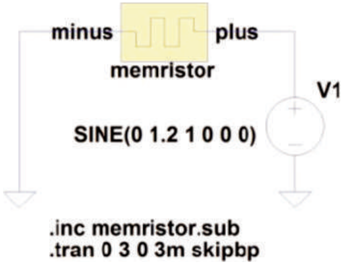
is the voltage source whose terminal voltage is controlled according to the formula xΔR. G_X is a current source whose current is controlled according to the equation $I_{MEM}f(V(x))$ where V(x) is the voltage across the capacitor C_x and it models the normalized width of the doped layer [6].

The relation between memristor current and voltage is modeled as on the basis of R_{MEM} (x) = R_{OFF} -xΔR, where ΔR= R_{OFF}-R_{ON}. R_{OFF} is the resistor in series voltage source whose terminal voltage is controlled by the formula xΔR. The voltage V(x) across the capacitor C_X models the normalized width x of the doped layer. The initial state of x is modeled by the initial voltage of the capacitor. The flux is calculated by the time-integral of voltage, and the charge is calculated by the time-integral of current.

2. Results and Discussions

All models were simulated in PSPICE using SPICE model that was given in [6], they now add new nonlinear window functions that was proposed by Prodromakis and Strukov to compare all suggested window functions. Figure 3 shows a single memristor for measuring the behavior of memristor model in PSPICE with a sine wave input voltage of 1.2 V with 1Hz frequency. The values for the memristor parameters u_v, D, R_{ON}, R_{OFF} and $R_{INITIAL}$ are 10-10 cm 2s-1V-1, 10 nm, 100 ohm, 16 kohm, and 11 kohm. All models use the same window function para meter p=10.

Figure 4 shows the simulation result of memristor SPICE model for Strukov window function. The figure shows the I-V characteristic of the devices. The current of the memristor, I_{MEM} is varying up to approximately 100 μA for maximum of 1.2 V voltage applied. The R_{MEM} for this model show that the values are in range of 11 kohm to 12 kohm, which means the effect of the voltage applied to the memristor gives only slight changes on the value of the memristor.



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.inc memristor.sub
.tran 0 3 0 3m skipbp
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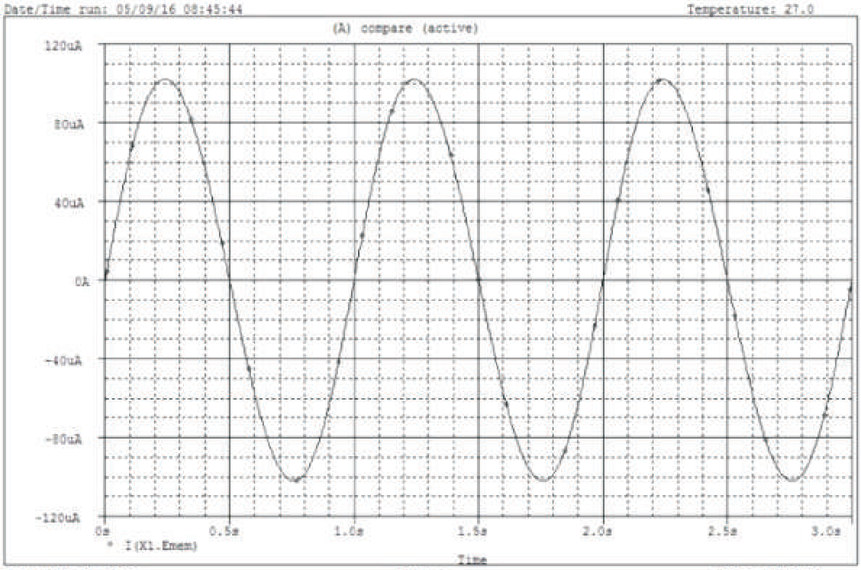
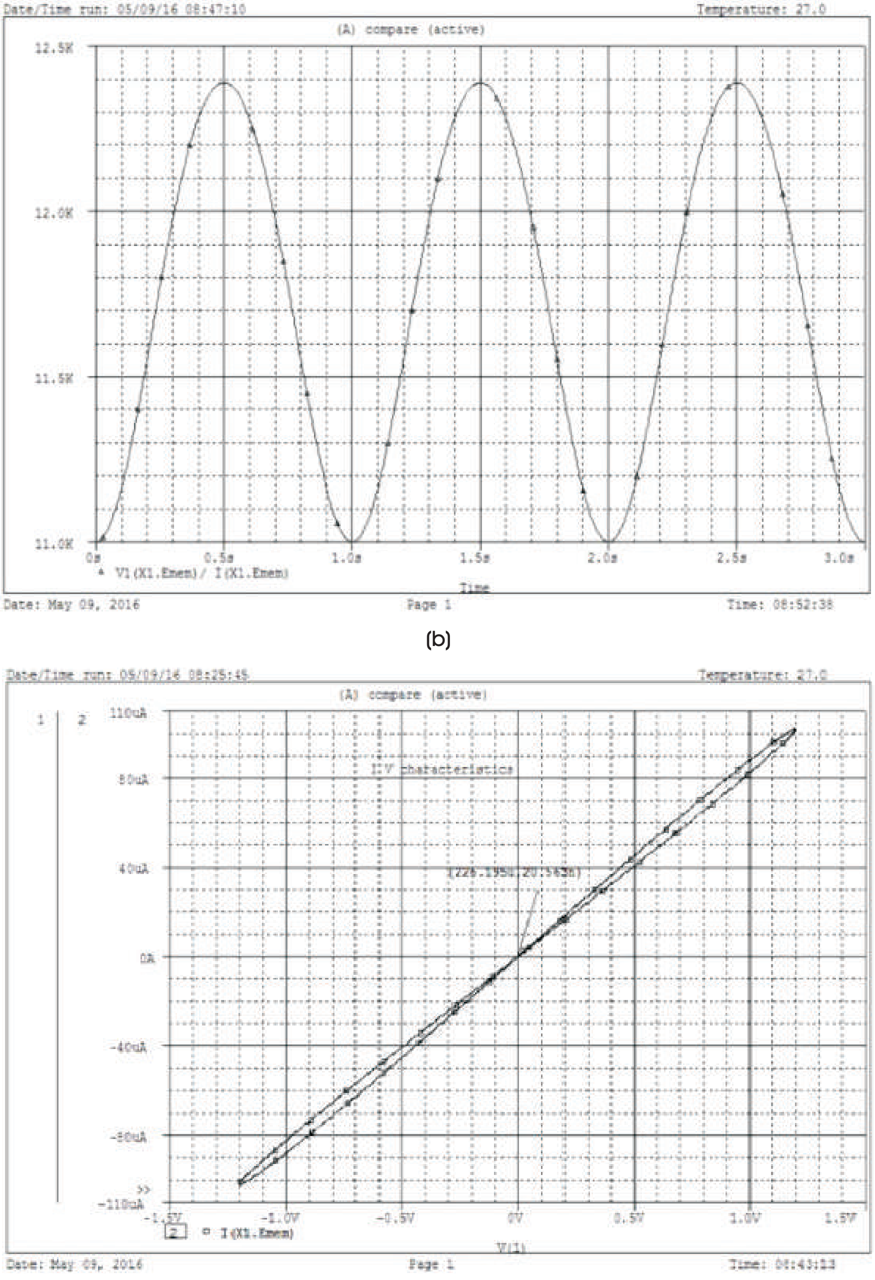
Figure 3. Memristor Circuit



(a)



(b)

(c)

Figure 4. Strukov Memristor Model

Joglekar window function seems to be promising [12]. Figure 5 shows the simulation result of memristor SPICE model for Joglekar window function. The current of the memristor, I_{MEM} is varying up to approximately 300 μA for maximum of 1.2 V voltage applied. Joglekar window function gives higher current compared to others. It shows that the current in the memristor are much easier to move. The R_{MEM} are within range of nearly 0 ohm to 11 kohm which gives full range of values for the memristor. This shows that the value of memristor is varying when the voltage is applied through time. The hysteresis loop I-V characteristic shows the switching behavior as much more sensitive on the voltage level than Strukov window function.

Biolek window functions are supposed to solve the terminal state problem as in literature [4]. It should solve the boundary problem of the terminal state. Figure 6 shows the

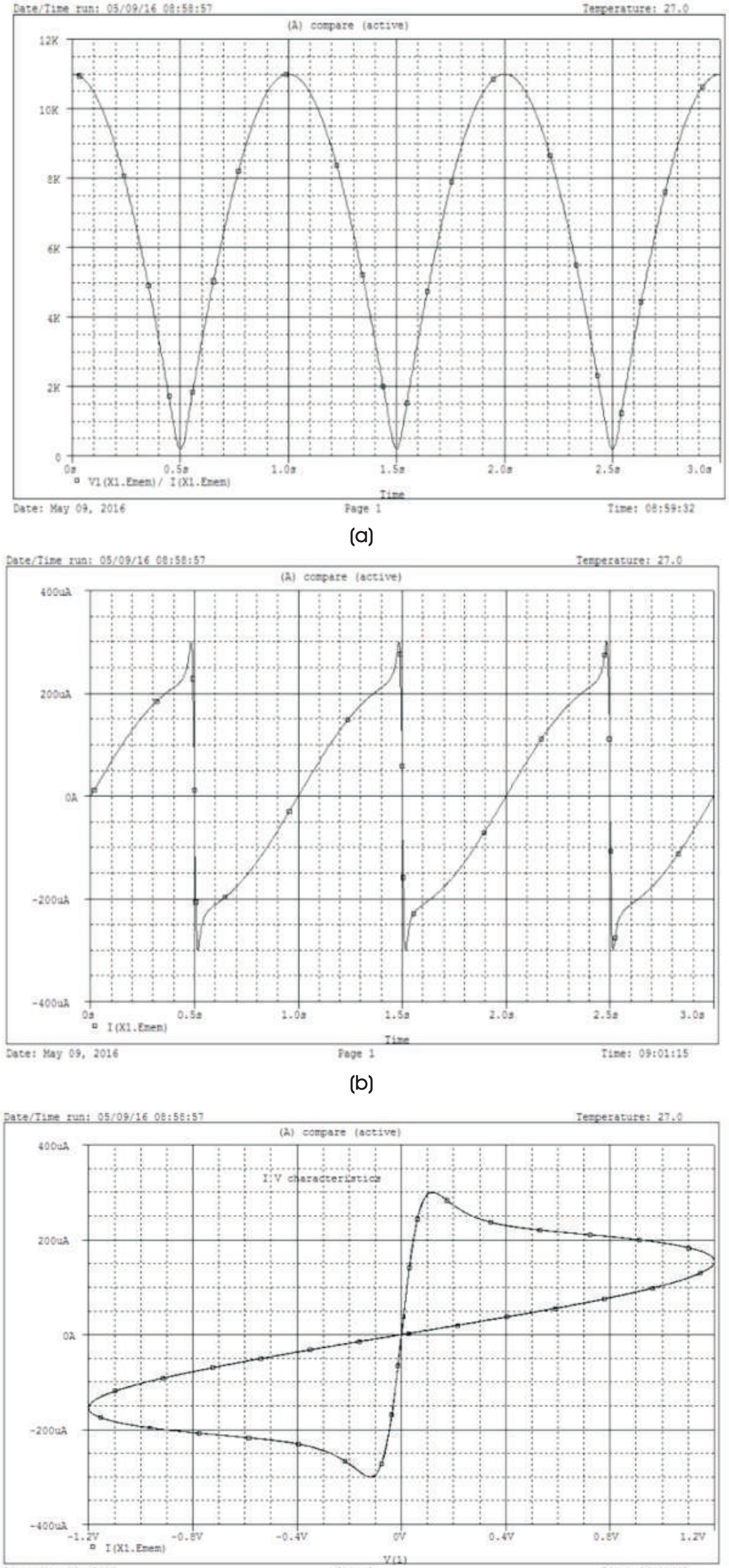


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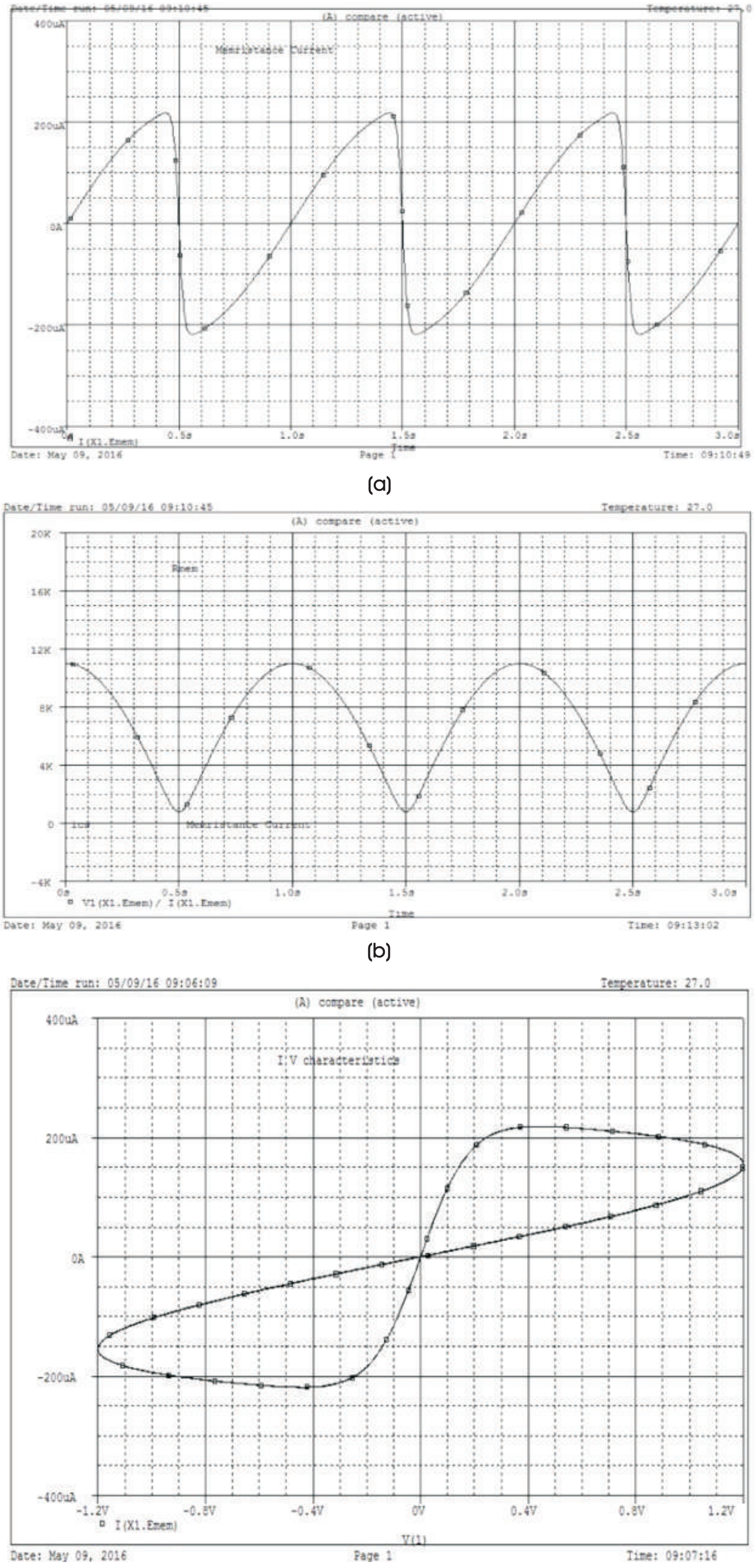
Figure 5. Joglekar Memristor Model



(a)

(b)

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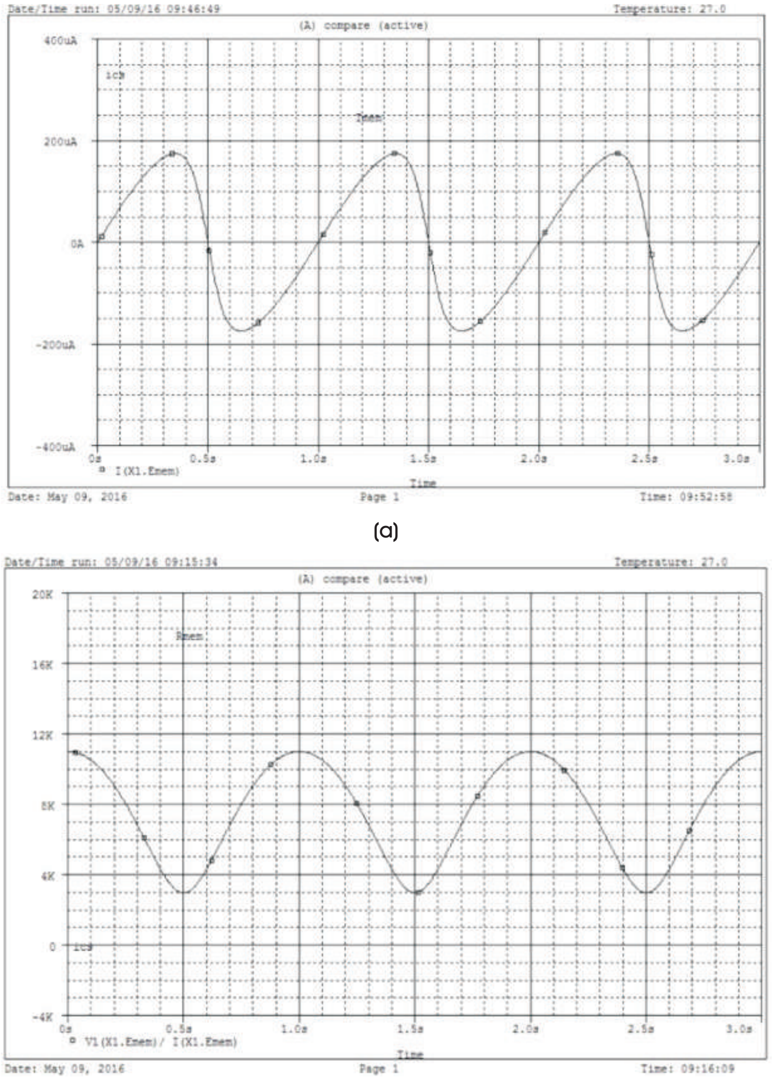
Figure 6. Biolek Memristor Model

simulation result of the memristor SPICE model for Biolek window function. The current of the memristor, I_{MEM} is varying up to approximately 220 μA for maximum of 1.2 V voltage applied. The R_{MEM} are within range of nearly 1 kohm to 11 kohm.

Prodromakis window functions are also said to solve the boundary issue. Figure 7 shows the simulation result of memristor SPICE model for Prodromakis window function. The current of the memristor, I_{MEM} is varying up to approximately nearly 180 μA for a maximum of 1.2 V voltage applied. The R_{MEM} are within range of nearly 3 kohm to 11 kohm. The hysteresis loop is shown to be asymmetrical while the OFF state of the device is highly non-linear compared with other.

In this model as shown in Figure 8, the current-voltage relationship is undefined and can be freely chosen from any current-voltage relationship. The dependence of the internal state derivative on current and the state variable itself can be modeled as independently multiplying two independent functions; one function depends on the state variable and the other function depends on the current.

In comparing of I-V characteristic hysteresis loop, as we can see in Figure 9, it shows all hysteresis loops for all proposed window functions. By using the same parameter, we can see the difference in each model. Joglekar window function seems to have a strong memristance compared to others. All models seem to be a good approximation of the measurement of the real



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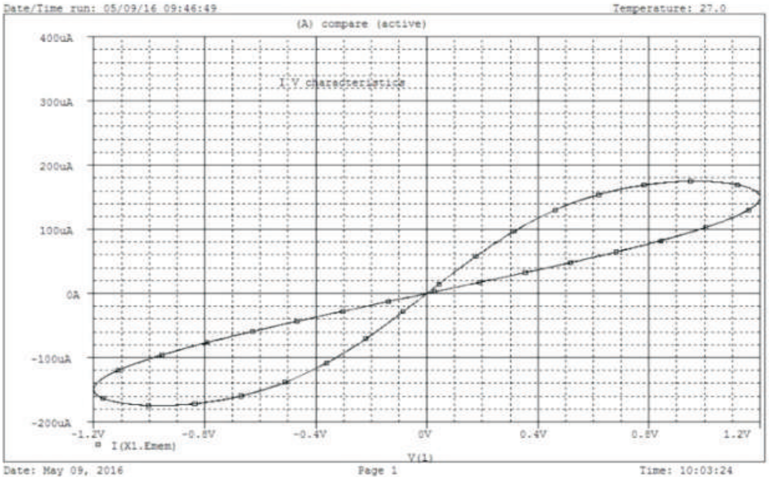

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Figure 7. Prodromakis Memristor Model

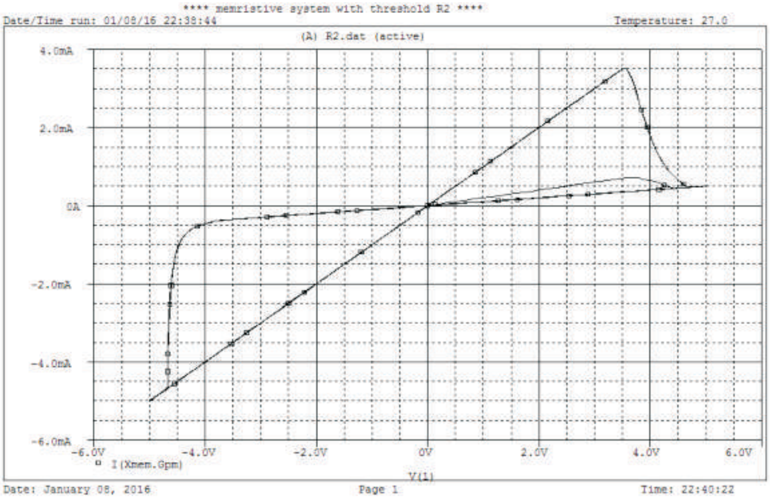

Figure 8. Threshold Memristor Model

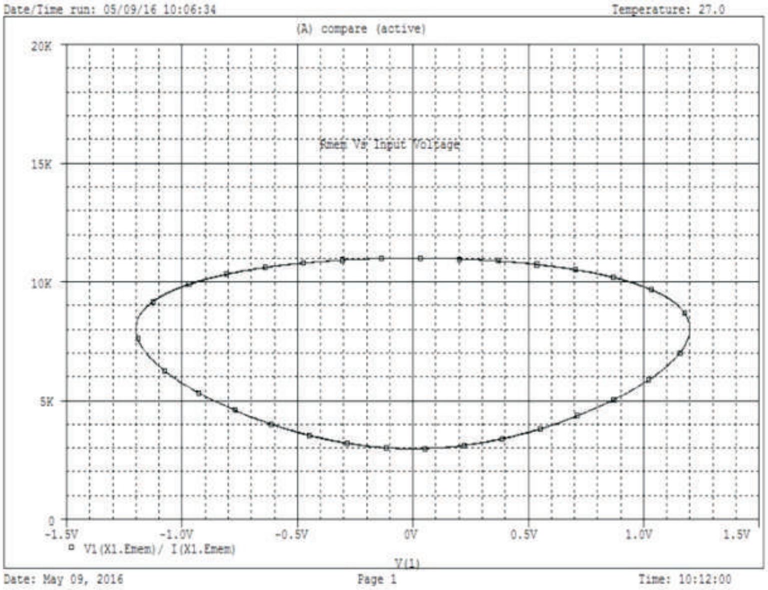

Figure 9. I-V Hysteresis Loop for all Models

memristor produce by HP Labs.

Conclusion

As a conclusion to this research it is said that, it could bring a new light of familiarization in the integration of memristive components in any kinds of electronic devices that are at nanoscale. It is useful to have a computer model of the memristor as a tool for the analysis of the behavior of the circuits in developing application of this memristor as passive circuit element via simulation. SPICE model will definitely help us to conduct interesting simulation experiments and can be of great importance for such a research in future while the memristor are still hard to fabricate to study the behavior of the circuit. Different models with strong behavior and reason give a lot of benefits in development purpose to create the possibilities of the implementation in an integrated circuit. The possibilities for implementation of the memristor with practical analog circuit are wide open.

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