Semiempirical Memdiode Model for Resistive Switching Devices in Dynamic Regimes

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***Abstract*— A semiempirical memdiode model of resistive switching devices is proposed. This model is a modification of the quasi-static memdiode model (QMM). It is based on the incorporation of time dependencies in the QMM parameters, as well as on the empirically observed asymmetries between the reset and set transition. The model considerably improves the prediction of the response of resistive switching devices to arbitrary input stimuli.**

***Keywords*— memristor, resistive-switching device, memdiode, semiempirical model,**

I. INTRODUCTION

Memristors were first defined by Chua [1] as devices in which there is a linear relationship between charge and magnetic flux. The most typical structure of a resistive switching memristor consists of a metal-insulator-metal (MIM) structure in which the resistivity of the insulator depends on its recent history. Their ability to store information makes them especially interesting for many analog and digital applications such as neuromorphic and bioinspired circuits, medical diagnostics, non-volatile memories, signal processing and control systems. To achieve this, it is necessary to have a model which can be included in circuit simulators. A significant number of memristor models have been proposed in the literature [2-4].

The QMM model [5] is one of the most reputed in this category. In this work we include some modifications to this model to consider experimental observations on the dynamics of set and reset transitions that allow the QMM model to be extended for arbitrary and non-stationary stimuli.

II. EXPERIMENTAL SETUP

The memristors used in this work were TiN/Ti/HfO_2/W MIM capacitors. The 10 nm thick HfO_2 layer was grown by atomic layer deposition at 225°C using TDMAH and H_2O as precursors, and the top and bottom metal electrodes were deposited by magnetron sputtering. Electrical contact to the bottom electrode is made through the Al-metallized back of the silicon wafer. The resulting structures are square cells of 5×5 μm^2.

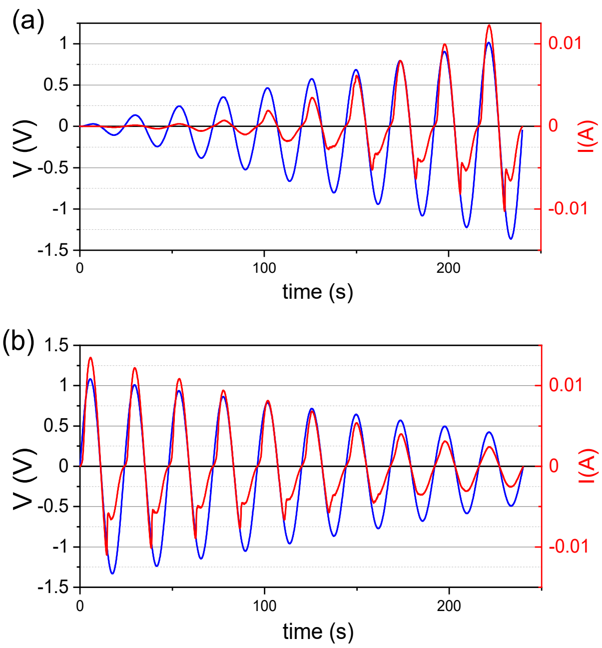

Fig.1. Memristor response to monotonically increasing (a) and decreasing (b) sinusoidal voltage waveforms.

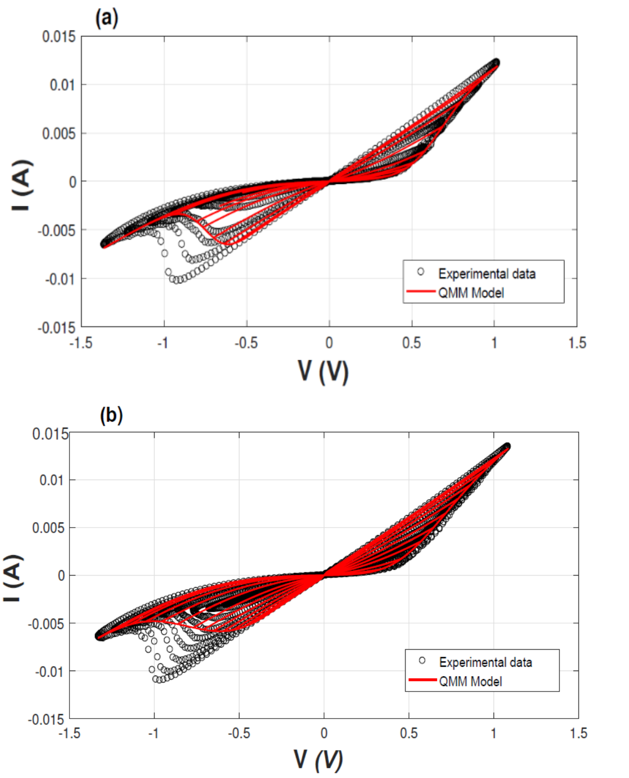

Fig. 2. Experimental data and QMM model fitting of increasing (a) and decreasing (b) sinusoidal voltage waveforms.

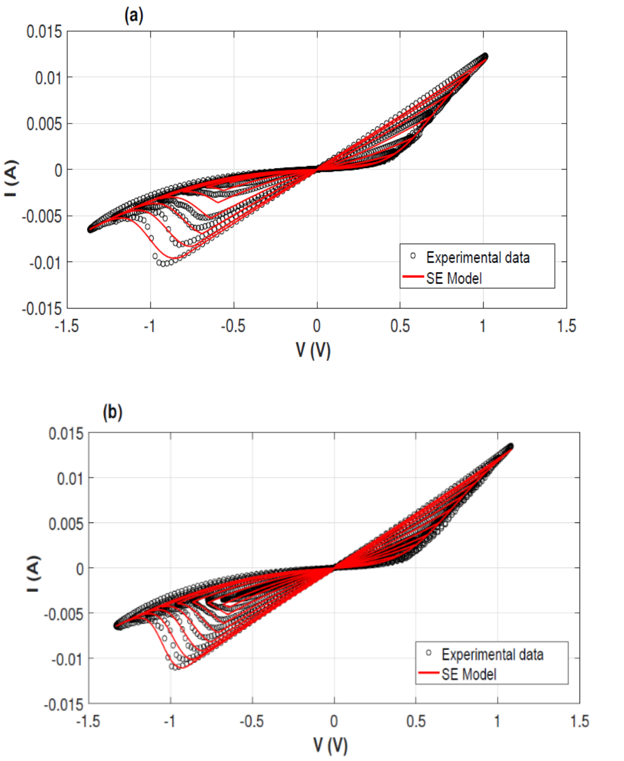

Fig. 3. Experimental data and SE model fitting of increasing (a) and decreasing (b) sinusoidal voltage waveforms.

Electrical characterization was carried out by using a Keithley 4200SCS mainframe. To perform a detailed study of the resistive switching properties, we have designed two experiments in which monotonically increasing or decreasing sinusoidal voltage waveforms were applied and the currents through the memristor were recorded. Figures 1 and 2 show the results obtained in these experiments.

III. Experimental Results and Discussion

The experimental results were subsequently fitted to the QMM model [5]. In the QMM model the device consists of a diode in series with a resistor. The fundamental equations of this model are:

$$I = sgn(V)[(\alpha R)^{-1} W\{\alpha R I_0(\lambda) e^{\alpha(|V| + R I_0(\lambda))}\} - I_0(\lambda)] \qquad (1)$$

where W is the Lambert function, V is the applied voltage, R is the value of the series resistance, α depends on the diode nature, and λ is the memristor internal state variable ($\lambda \in [0,1]$). Finally, the current I_0 represents how the diode current depends on the state of the memristor:

$$I = I_0 \left(e^{\alpha V_D} - 1\right) \qquad (2)$$

$$I_0(\lambda) = I_{0max}\lambda + I_{0min}(1 - \lambda) \qquad (3)$$

In Fig. 2 we plot the best fitting of the experimental data obtained for this model. We have used the Levenberg-Marquardt method [6] to minimize the mean square value of the sum of differences between the experimental and calculated data. The model predicts the experimental results reasonably well for positive voltage values. However, it fails in the negative voltage range, mainly in the regions where the transition from the low resistance state to the high resistance state occurs, i.e., in the reset transition (see Figs. 2(a) and (b)).

According the QMM model, the formation and destruction of conducting filaments follows the following equation:

$$\Gamma^{\pm}(V) = [1 + e^{-\eta^{\pm}(V - V^{\pm})}]^{-1} \qquad (4)$$

where $\eta^{\pm} = 1.702/\sigma^{\pm}$, $(\sigma^{\pm})^2$ is the variance of the creation and destruction of conducting filaments which is assumed to be Gaussian. These parameters describe the formation (η^{+}) and destruction (η^{-}) rates of the conductive filaments. On the other hand, the voltages $V^{\pm}$ determine the mean absolute values of the voltages necessary for the filament formation (V^{+}) and destruction (V^{-}). In the QMM model all parameters are fixed. However, Fig. 2 shows that the higher the positive voltage during the previous cycle, the higher the values η^{-} and V^{-} must be. This fact has been considered in the semi-empirical model presented in this work. In Fig. 3 we see how the fitting improves significantly when the η^{-} y V^{-} are calculated ad-hoc for each experimental loop. The higher the positive voltage applied during the set process, the larger the number of filaments formed. The subsequent destruction of these filaments requires higher negative voltage values. Once this voltage is reached, the rate of destruction is higher because it is an autocatalyzed process, as described in [7].

In our semiempirical model we have varied the parameters η^{-} and V^{-} in each *I-V* loop, whereas the rest of the parameters have remained constant with the following values: η^{+}=11.22 V^{-1}, V^{+}= 0.84 V, α = 5 V^{-1}, R = 74.63 Ω,

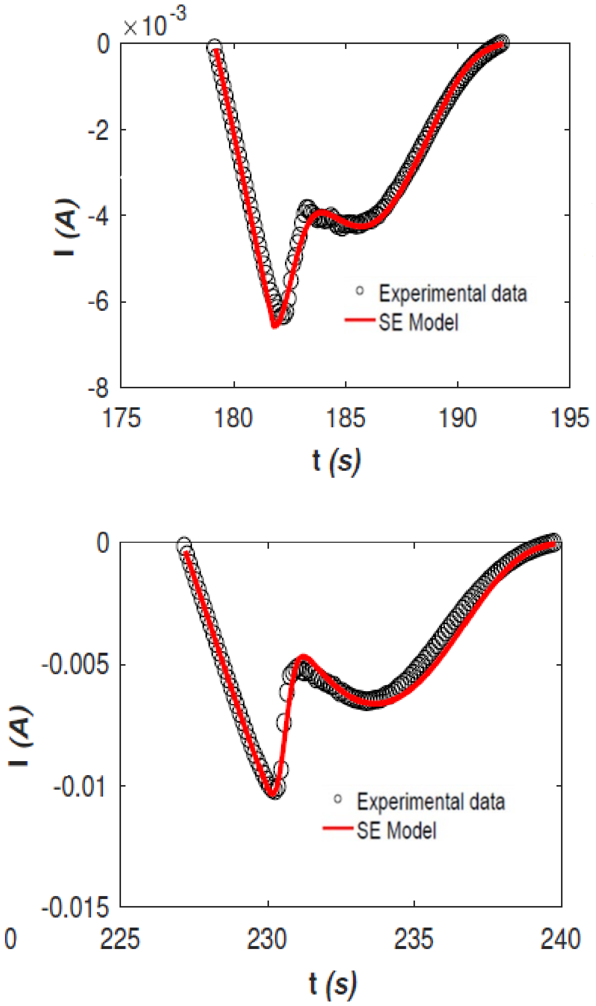

Fig.4. Detailed view of the SE model fitting in the current-time domain of two IV loops for negative voltages

I_{max} = 12.9 mA and I_{min} = 1 µA. As an example, Table I shows the parameter values for four selected loops. In this table we also include the initial value of the state variable, λ_0, which is calculated from the value of the current for the highest positive voltage value in each loop. Table I shows how the initial state of each cycle determines the reset process. The higher the valued λ_0 the higher the value of V^- and η^-. That is, the process of dissolution of the filaments begins at higher voltages, since more energy is needed for their dissolution. On the other hand, once the dissolution process begins, it occurs faster for higher λ_0. This occurs because the higher the initial value of λ_0 the larger the number of filaments to be dissolved.

TABLE I. SEMIEMPIRICAL MODEL FITTING PARAMETERS FOR FOUR SELECTED LOOPS

Loop	Voltage swing	Semiempirical model parameters		
		η^- (V^{-1})	V^-(V)	λ_0
a	[-1.33, 1]	33.3	-0.91	0.88
b	[-1.08, 0.8]	24.6	-0.75	0.67
c	[-0.77, 0.65]	20.7	-0.65	0.47
d	[-0.8, 0.56]	17.5	-0.55	0.34

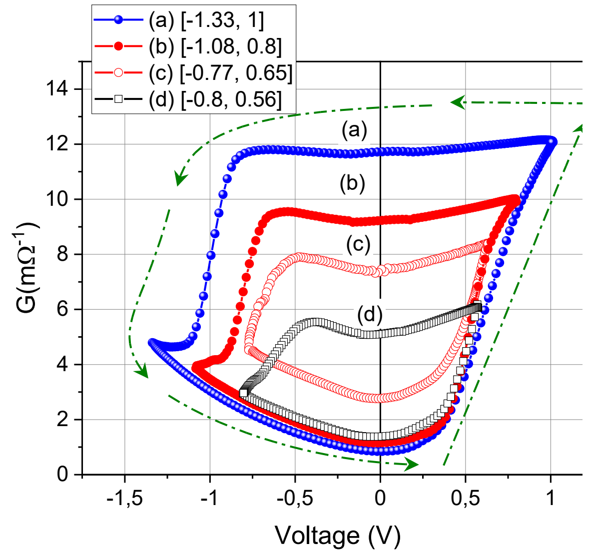

Fig.5. Experimental curves of conductance versus voltage for several loops with different voltage swings.

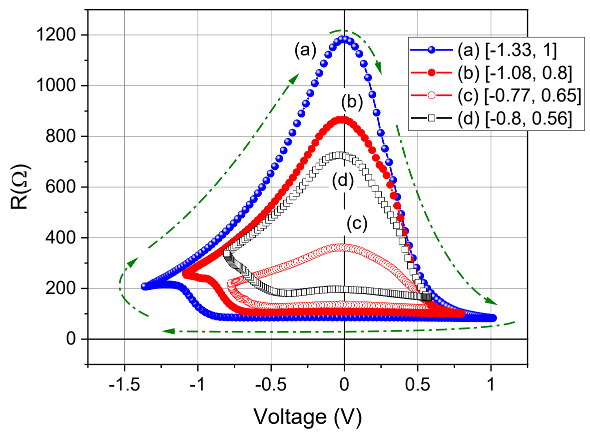

Fig.6. Experimental curves of resistance versus voltage for several loops with different voltage swings.

We have determined that V^- and η^- follow linear dependencies with λ_0 :

$$\eta^- = 7.2 + 28.4\,\lambda_0\,,\quad [V^{-1}] \tag{5}$$

$$V^- = -0.33 - 0.65\,\lambda_0\,,\quad [V] \tag{6}$$

When we use these expressions the mean square error of the fittings decreases by an order of magnitude compared to that obtained with the QMM model. In Fig. 4 we show detailed views showing the good fitting obtained with the semiempirical model in the negative voltages region.

In Figs. 5 and 6 a more detailed inspection of the loops selected in Table I is performed. Here we represent the evolution of the conductance (Fig.5) and the resistance (Fig.6) when the voltage travels through a complete loop. In Fig.5, we observe that the higher the positive voltage applied, the higher the conductance values are reached. Then, as the voltage decreases, the conductance decreases until it reaches a minimum value at 0 Volts. Subsequently, when the voltage becomes negative, the conductance increases again. This increase is more pronounced the lower the conductance reached on the positive side, i.e., the lower the value of the state variable, λ_0 . This is because the more conductive the memristor is, the smaller the effect of diode behavior on the total current. When the voltage approaches values close to V^- the conductance decreases sharply, with a faster rate as higher λ_0. We also observe that if the voltages exceed sufficiently V^-, the conductance decays towards values corresponding to the HRS state (loops (a), (b) and (d)). However, if the minimum applied voltage is close to V^-, as occurs in loop (c), the return path follows an intermediate path. That is, it is possible to achieve intermediate states with proper control of the minimum applied negative voltage.

Fig. 6 gives a more detailed view of what happens in the high-resistance state (HRS) for the same loops as in Fig.5. First, we see that the resistance is not constant on the return path from the time the HRS state is reached until the voltage is 0 V. The resistance varies from relatively small values on the order of 200-300 Ω at negative voltages, to higher values at 0 V. This variation indicates that as states closer to full reset are reached, the diode behavior prevails over the purely resistive (ohmic) one. In addition, the values at 0 V are highly dependent on how effective the filament dissolution was during the reset.

Thus, in the loops shown in Fig.6 we see that the resistance at 0 V varies over a wide range from 400 Ω to 1.2 kΩ. In short, the value of the resistance at voltages close to 0 V provides, with great sensitivity, a measure of how complete the memristor reset has been. For example, clear differences can be observed in the value of the resistance at 0 V between cycles (c) and (d), even though in both cases the maximum negative voltage reaches similar values. These differences are since in loop (c) the set voltage was higher (0.65 V) than in loop (d) (0.56 V), and λ_0 is higher in the first case. Consequently, the threshold voltage, V^-, for reset is higher in loop c and since in this case the voltage does not reach sufficiently negative values, the reset process is prematurely interrupted, and the resistance reaches lower values than in loop (d).

When the voltage becomes positive, the resistance decreases until it reaches the low values corresponding to the LRS state. The return path to 0 depends on the maximum applied voltage, i.e., to what extent the full set has been reached. However, these differences can be seen much better in Fig, 5, where clear differences in the conductance values at 0 V as a function of the maximum applied voltage can be seen in the four loops shown.

IV. Conclussions

A semi-empirical model is proposed that consists of an improvement of the QMM model in which experimental data obtained by applying monotonically increasing and decreasing sinusoidal waveforms are considered. This model enhances the accuracy of the QMM model by an order of magnitude. The proposed model improves the QMM mainly at voltages where the LRS to HRS transitions occur. The experimental results show that the values of the threshold voltage (V^-) and the dissolution coefficient (η^-) at these transitions linearly depend on the value of the state variable (λ_0) determined by the previous set voltage. In other words, the voltage applied during the set process not only determines the conductance value in the set state, but also predicts the values of the voltage at which the reset occurs as well as the rate at which the reset takes place. This paper shows how it is possible to obtain intermediate values by means of an adequate control of the maximum and minimum applied voltages. Finally, we note that the conductance value is very sensitive to the state when the state is near the full set (λ close to 1). On the contrary, when the state reaches values close to full reset (λ close to 0), it is the value of the resistance measured at 0 V which provides maximum accuracy to distinguish between very close states.

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