A Simple Monte Carlo Model for the Cycle-to-Cycle Reset Transition Variation of ReRAM Memristive Devices

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***Abstract*—In this paper, we present a direct method to obtain a set of curves that reproduce the observed variability of a ReRAM device. We have assumed a model in the flux-charge space, instead of the conventional current-voltage paradigm, because this allows us to use a very simple model that accurately reproduces the observed behavior. Thereby, we have observed that the extracted parameters of this model are correlated and with the help of this correlation, we can generate new parameter sets that have the same correlations, thus obtaining an accurate estimation of possible new resistive switching curves.**

***Index Terms*—ReRAM; memristor; Monte Carlo, Simulation, Variability.**

I. Introduction

Resistive switching RAM (ReRAM) memristive devices belong to the most promising elements for non-volatile memories [1]–[3]. The resistive switching (RS) mechanism shows interesting features such as switching speed, endurance, low power operation, and compatibility with CMOS technology [1]–[3]. However, the variability of the characteristics from one cycle to the next represent an problem in many cases treated in several current investigations. This variability is different from the usual variability between devices, which is related to randomness processes during fabrication. Variability in the characteristics of the same memristor from one cycle to the next is more related to the stochastic process that governs the creation and destruction of the conductive filaments. This random process was even used to implement random number generators [4]. In this work, our investigations are focused on the modeling of memristive devices to characterize some of their main parameters, and study how to reproduce their variability. For this purpose, we have taken devices fabricated and measured at the IMB-CNM (CSIC) in Barcelona [5]. The devices were based on $Ni/HfO2/Si-n+$ structures fabricated on (100) n-type CZ silicon wafers. The resistive switching mechanisms of these devices were characterized and studied previously [6]–[8], and a previous model for the reset transition was presented in [9], [10]. We have chosen a different approach following the lines highlighted by L. Chua and others in the past [9]–[14]. In this respect, instead of using the $V-I$ domain, we consider a domain characterized by the first momentum of the current (also called charge, Q) and the first momentum of the voltage (also called flux, ϕ) magnitudes. The flux is defined as the time integral of the voltage, while the charge is obtained as the time integral of the current [9]–[11], [13]. The paper is organized as follows: after the introduction, in Sec. II the experimental work, then in Sec. III the model and the technique we have applied to model the cycle-to-cycle variations are presented, along with the results. Finally, Sec. IV provides a brief conclusion.

II. EXPERIMENTAL WORK

Devices under study have been fabricated and measured at the IMB-CNM (CSIC) in Barcelona, Spain. The devices are based on a $Ni/HfO_2/Si-n^+$ structure with an oxide layer 20nm thick, fabricated on (100) n-type CZ silicon wafers with resistivity between 0.007 Ω/cm and 0.013 Ω/cm following a field isolated MIS process . The 20 nm-thick HfO_2 layer was deposited by atomic layer deposition using TDMAH and H_2O as precursors. The 200 nm-thick Ni electrode was deposited by magnetron sputtering. The resulting device structures are square devices of 5 x 5 μm^2 [15]. Measurements were performed using a HP-4155B semiconductor parameter analyser at temperatures from 40°C to 175°C. The voltage was applied to the top Ni electrode, while the Si substrate was grounded. In order to evaluate the cycle-to-cycle variability, numerous cycles and measurements need to be assessed. For this purpose, a software tool has been developed and implemented in Matlab to control the instrumentation via GPIB (General Purpose Instrumentation Bus) and to smartly detect the set and reset currents [15]. Experimental measurements have been performed at an average ramp speed of the input voltage, $1V/s$, and the source current compliance was set to $0.1mA$, during the set process.

III. MODEL DESCRIPTION

We follow the work in [9], [11], [12], [16], assuming the $\phi-Q$ space. The experimental relationship between the charge, and the flux, during the reset process is shown in Fig. 1, both variables are normalized to their values at the reset point. These data correspond to different reset cycles of just one

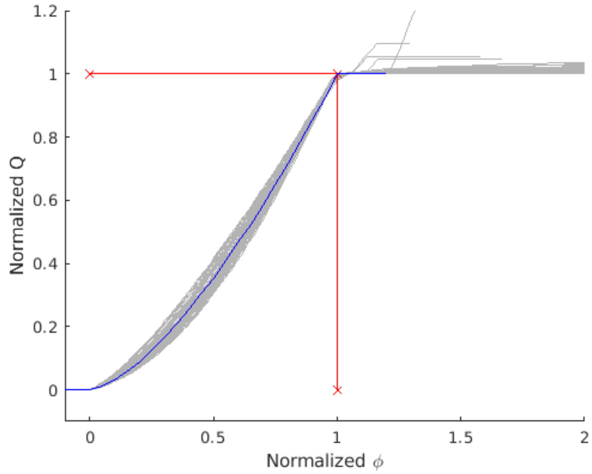

Fig. 1: Normalized Q vs. normalized ϕ for each reset transition. The normalization is performed by scaling each curve in order to fit the reset values to one. The darkest line corresponds to the model proposed in Eq. 1. In the case of $V-I$ curves with several CFs, there can be seen Q values above one; in these cases the normalizing value was connected with the first reset even.

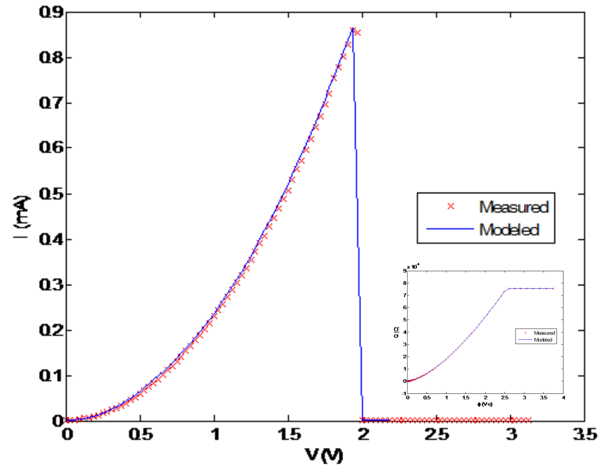

Fig. 2: I vs. V for a single transition (The inset shows Q vs. ϕ.) The original data are shown as red marks while the blue line corresponds the fitted model.

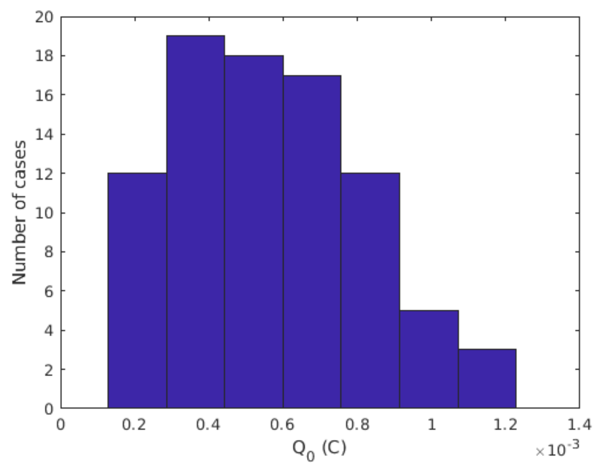

Fig. 3: Histogram of Q_0 values, the data plotted have been previously normalized to the mean values shown in Fig. 1.

device whose characteristics are described in [5]. Each reset cycle was performed using a voltage ramp of given average slope. It can be noticed that there are some cycles where more than one set/reset happens during the same voltage ramp. In these cases, the curves have been normalized to the first reset point.

The following non-linear equation is proposed in [9], [10] to fit the curves when only one conducting filament (CF) is involved:

$$Q = Q_0 \cdot f(1, (\frac{\phi}{\phi_0})^n) \tag{1}$$

Notice that $f(x,y)$ is a function that provides the minimum between x and y in a way should it be smooth or continuous. For a complete discussion of smoothing functions in device modeling, see [8]. In our case, we have chosen the following function

$$f(x,y) = 0.5(x + y - \sqrt{(x-y^2) - 4\delta^2}). \tag{2}$$

The constant δ is a smoothing value which has been fixed to $\delta = 10^{-5}$. Considering an input voltage signal as following

$$V(t) = S \cdot t \tag{3}$$

where S is the slope of the signal and t is the time. Then the flux ϕ and the charge Q are calculated for fitting purposes as mentioned above according to

$$\phi(t) = \int^t V(\tau) d\tau \tag{4}$$

and

$$Q(t) = \int^t I(\tau) d\tau \tag{5}$$

Or, conversely, the current can be calculated as

$$\begin{aligned} I(t) &= \frac{dQ}{dt} = \frac{d\left(Q_0 \cdot f\left(1, \frac{\phi}{\phi_0}\right)^n\right)}{dt} \\ &= \frac{d\left(Q_0 \cdot f\left(1, \frac{\int v(t)dt}{\phi_0}\right)^n\right)}{dt}. \end{aligned} \tag{6}$$

This simple and explicit model fits experimental data in a fairly well using only three parameters (Q_0, ϕ_0 , n) in the $\phi - Q$ domain [9]. As an example, one fitting result is provided in Fig. 2, that show measured compared to modeled values, where a reset transition is modeled in the $\phi - Q$ space and in the $V-I$ one. As can be seen, the correspondence between the modeled and the measured values is fairly good. The histograms of obtained model parameters values are shown in Figures 3, 4, and 5. In Fig. 6 the extracted model parameters for each RS cycle are provided. As can be seen

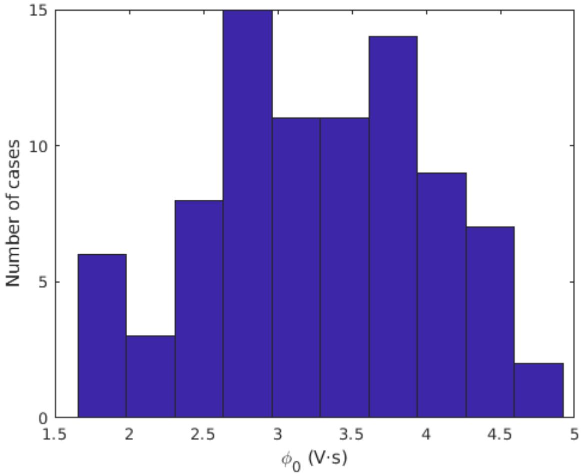

Fig. 4: Histogram of ϕ_0 values, the data plotted have been previously normalized to the mean values shown in Fig. 1.

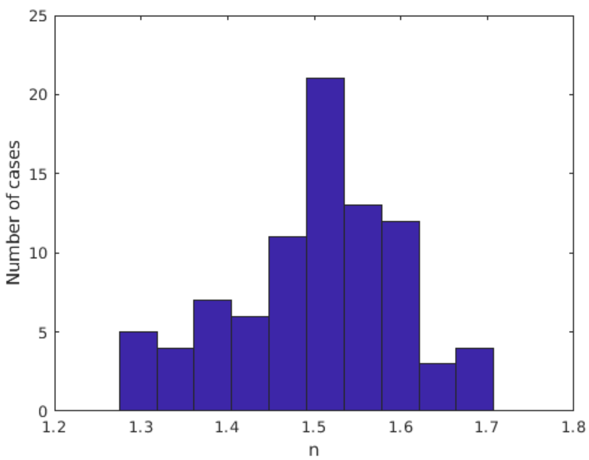

Fig. 5: Histogram of n values.

from this figure, it can be concluded that they are strongly correlated through some underlying process which, according to our assumptions, are caused by their dependence on the number of conductive filaments and their radii that control RS processes [17], [18]. The nature of these correlations has been addressed in [10] and seems to be linked to the initial radius of the CF and the height of the quantum point contact (QPC) barrier. This simple model can be complemented with other effects such as contact effects, as already done in other devices (see [19], for instance). It can be also employed to analyze the statistical behavior of resistive switching unipolar memristive devices. The mean values of the fitting parameters are provided in Table I.

A common technique used in semiconductor characterization is principal component analysis (PCA) [20], [21]. Using this technique, the correlations between the variations of the parameters are easily detected and modelled. Because of that,

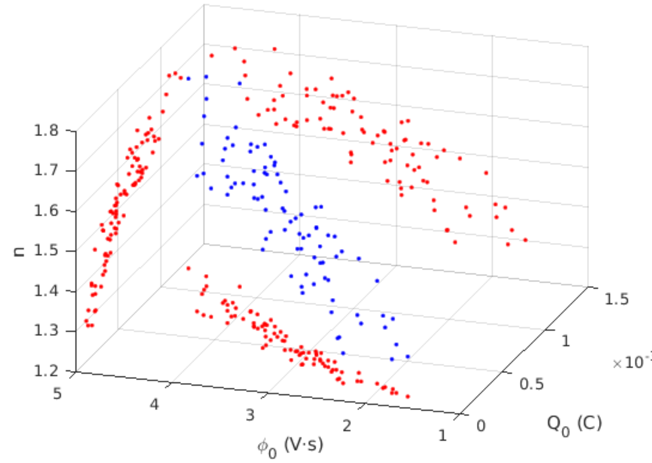

Fig. 6: Extracted parameters Q_0, ϕ_0, and n represented in 3D plot. Blue dots are the points in the 3D space, while the red points correspond to projections into the corresponding axis.

this technique allows to perform a data dimension reduction. This technique is, basically, a spatial rotation so that the new axes will be the axes where the variations are more important. Thus, representing the values of the parameters, a vector $P = (Q_0,\ \phi_0,\ n)$ the rotation matrix by L, we can write that the components K of the rotated P (called scores in the notation of PCA) will be given by:

$$K = L \cdot P \tag{7}$$

In agreement with our assumption, we have found that we can reduce the set from three dimensions to only two, consistent with the fact that we are somehow modeling the number and geometry of the conductive filaments. Then, if we wish to generate a new random set of data parameters, all we have to do is generate random values for the values of the scores, bound by the experimental values, and anti-transform. That is, a new point $P^{'}$ in the parameter space will be given by:

$$P^{'} = L^{-1} \cdot \begin{pmatrix} \alpha(m_1, s_1) \\ \alpha(m_2, s_2) \\ 0 \end{pmatrix}$$

Where $\alpha(m, s)$ is a function returning a random number with a normal distribution of mean m and standard deviation s. An example of a generated set of parameters is shown in Fig. 7. It is apparent that the generated set of parameters is inside the expected region and, thus, the $V - I$ curves will also behave as expected.

IV. CONCLUSION

In this work we have assumed a representation of the ReRAM memristive devices in the flux-charge space, instead of the conventional voltage-current paradigm, because this

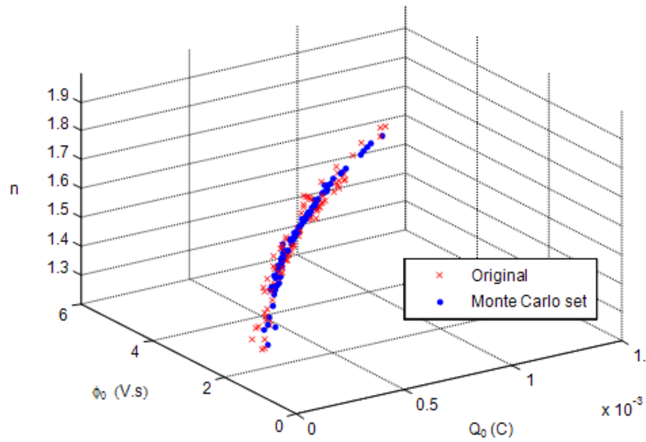

Fig. 7: Original (crosses) and Monte Carlo generated (blue dots) parameters. As is apparent, the generated points are inside the expected region.

TABLE I: Extracted mean values and Standard deviations for the parameters of the model described in Eq. 1.

	ϕ_0 $(V.s)$	Q_0 (μC)	n
Average	3.28	562	1.5
Standard deviation	0.76	255	0.0999

allows us to use a very simple model that, however, accurately reproduces the observed behavior. This model is based only on three parameters (Q_0, ϕ_0, n) that are strongly correlated. Here we are assuming in our ongoing research that these parameters depend on the number and geometry of the conducting filaments. Observing that they are correlated, we propose a direct method to obtain a set of curves that reproduce the observed random behavior of an ReRAM memristive device. That is, we propose using principal component analysis to generate new sets of parameters that follow the same observed correlations, thus obtaining an accurate estimation of possible new RS curves. Using this technique, we are able to obtain new sets of parameters that provide distributions of parameters very similar to the parameters extracted directly from measurements.

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