Semiempirical Modeling of Reset Transitions in Unipolar Resistive-Switching Based Memristors

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Abstract. *We have measured the transition process from the high to low resistivity states, i.e., the reset process of resistive switching based memristors based on Ni/HfO_2/Si-n+ structures, and have also developed an analytical model for their electrical characteristics. When the characteristic curves are plotted in the current-voltage (I-V) domain a high variability is observed. In spite of that, when the same curves are plotted in the charge-flux domain (Q-ϕ), they can be described by a simple model containing only three parameters: the charge (Q_{rst}) and the flux (ϕ_{rst}) at the reset point, and an exponent, n, relating the charge and the flux before the reset transition. The three parameters can be easily extracted from the Q-ϕ plots. There is a strong correlation between these three parameters, the origin of which is still under study.*

Keywords

RRAM, memristor modeling, reset voltage (Vrst) determination, variability

1. Introduction

Resistive switching memories (RRAMs) are one of the most promising alternatives among emerging non-volatile memory technologies [1-3]. Resistive switching (RS) phenomena have been reported as early as the 1960s. These devices show very interesting features such as low program/erase currents, fast speed, endurance, viability for 3D memory stacks and CMOS technology compatibility [1–3].

RRAMs belong to a wider group of electron devices known as memristors [4]. These recently fabricated devices [5], whose theoretical features were predicted a long time ago [6], have shown many different possibilities ranging from non-volatile memory cells to neuromorphic circuit applications [1]. There are many technologies available to fabricate memristors [1], [2]. It has been shown that the physical background behind the device characteristics can be linked to different operation principles. Memristors based on electrochemical metallization phenomena show different features in comparison to devices controlled by thermochemical or valence change mechanisms. Therefore, many characterization, simulation and modeling studies are needed to understand the operation of these devices and to build the circuit simulation infrastructure needed to design memristor-based applications. Different modeling [5], [7–10] and simulation [11–16] studies have been published so far devoted to different flavors of memristive devices although there is still a long way to go in this field.

In this paper we have focused on the modeling of memristive devices to characterize some of their main parameters. To do so, we have used devices fabricated and measured at the IMB-CNM (CSIC) in Barcelona [17]. The devices were based on Ni/HfO_2/Si-n^+ structures fabricated on (100) n-type CZ silicon wafers. The resistive switching mechanisms of these devices were characterized and studied previously [11], [17].

The manuscript is organized in the following manner: In Sec. 2 we characterized the experimental measurements to use them for modeling purposes; in Sec. 3 we introduce our model and, finally, we draw the main conclusions in Sec. 4.

2. Memristor Experimental Analysis for Modeling Purposes

Several hundreds of resistive switching (RS) cycles were performed and measured on the devices described above after a forming process [17]. Some of the reset (process that leads the device from a low resistance state to a high resistance state) I-V curves have been plotted in Fig. 1 for a single device. It must be noted that, as reported previously [17], there is a great dispersion in the shapes of the curves and in the reset current and voltages (see the definition of these magnitudes in [18]). Although it is commonly accepted and used the device characterization in terms of I-V curves, we have chosen a different approach following the lines highlighted by L. Chua and others in the past [4], [9]. In this respect, instead of using an I-V domain we will work in a domain characterized by the charge (Q) and 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 [4]. Thus, Fig. 2 plots again the data of Fig. 1, but in the Q-ϕ domain.

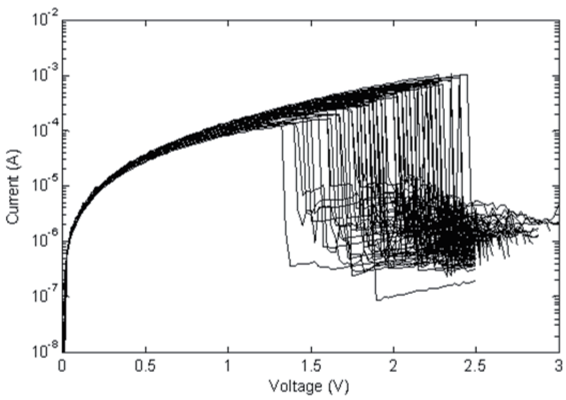

Fig. 1. I-V characteristics of reset transitions corresponding to 100 RS consecutive cycles on a single device.

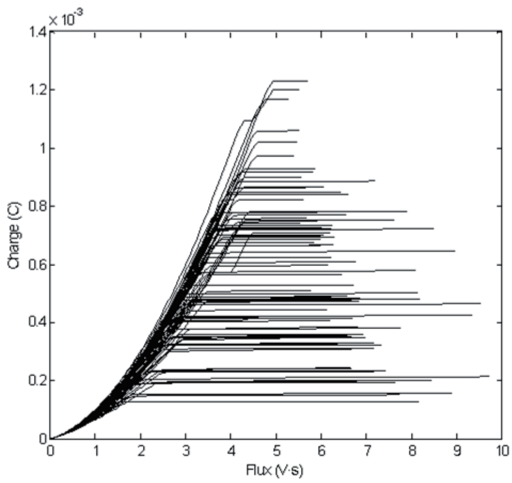

Fig. 2. Q-ϕ characteristics for the same reset cycles shown in Fig 1.

It is worth noticing that, as expected, after the reset voltage is achieved, the charge remains practically constant since the device current is reduced in several orders of magnitude and there is no contribution to the time integral of the charge. As reported in [11–16], the characteristic conductive filaments responsible for the RS operation in conductive bridge cells are broken when the reset process takes place. We take profit from this fact to extract the reset voltage (V_{rst}) and the reset current (I_{rst}). In fact, we first extract the reset flux (ϕ_{rst}) and the corresponding reset charge (Q_{rst}); afterwards we recover the corresponding reset voltage and current values. To extract Q_{rst} and ϕ_{rst} values, we fit two lines in the Q-ϕ plot (Fig. 3): one to the region where the charge remains constant and the other to the upper part of the monotonously increasing curve prior to the plateau. The desired reset point is given by the intersect point of the crossing lines, as depicted in Fig. 3a and 3b. The first figure shows the application of the method to a curve with a single current step, while Fig. 3b shows the application of this algorithm to a curve corresponding to a cycle with several current steps (an in-depth study on the physics behind these multisteps reset curves can be found in [16]). From these values (ϕ_{rst} and Q_{rst}, respectively), it is straightforward to calculate V_{rst} and I_{rst}, since the flux and charge are monotonically increasing functions.

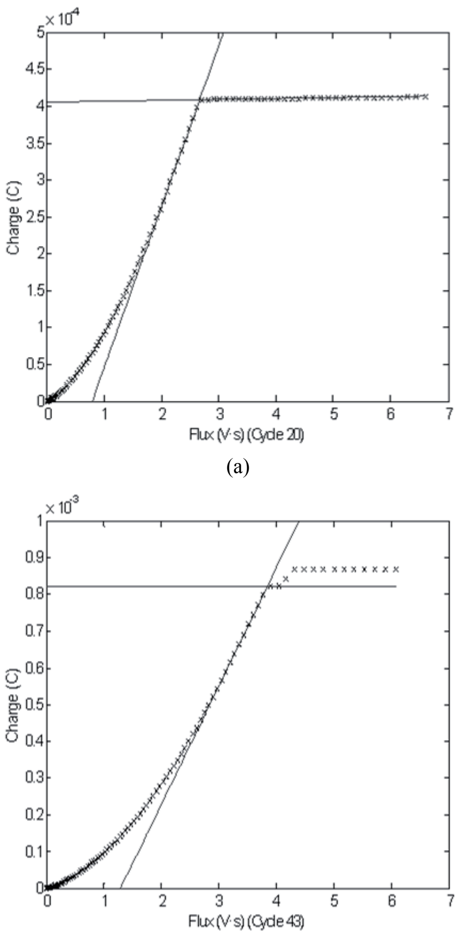

Fig. 3. Q versus ϕ for two different reset curves: (a) shows a single plain transition, while (b) shows a multiple transition. The fitting lines are shown as continuous, while the crosses are the transformed measured data. The reset point is assumed to be located at the intersection point between the lines.

	ϕ_{rst} (Vs)	Q_{rst} (mC)	V_{rst} (V)	I_{rst} (mA)
Average	3.28	0.56	1.98	0.167
Standard dev.	0.76	0.25	0.26	0.088

Tab. 1. Mean values and standard deviations of the obtained reset values for the flux, charge, voltage and current.

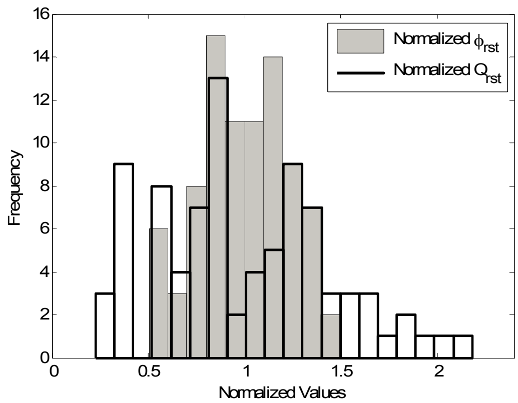

Fig. 4. Histogram of Q_{rst} and ϕ_{rst} values, the data plotted have been previously normalized to the mean values shown in Tab. 1.

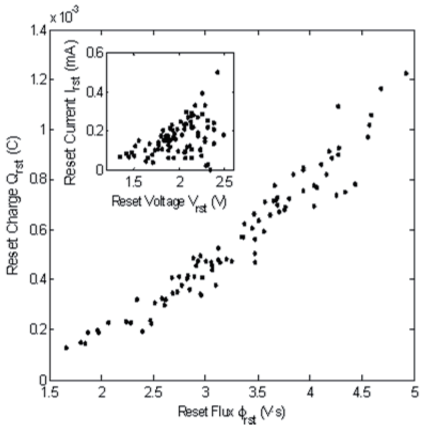

Fig. 5. Q_{rst} vs ϕ_{rst} for each reset transition. The inset shows I_{rst} versus V_{rst}. The correlation is clearly much better in the first case.

The mean values and standard deviations for all these calculated parameters are provided in Tab. 1. Figure 4 shows the statistical distribution of ϕ_{rst} and Q_{rst}. It has to be noted that only 100 cycles is not enough to distinguish whether the distribution is Gaussian or not; nevertheless, since this is not the key issue of this paper, we have not deepen on the statistical properties of the devices.

Figure 5 plots Q_{rst} versus ϕ_{rst} and I_{rst} versus V_{rst} (in the inset). It is worth calling the reader attention to the fact that the correlation between them is much higher in the flux-charge variables than in the current-voltage pairs. This result is coherent with the fact that the Q-ϕ domain is the natural space for memristor modeling [4].

3. Semiempirical Model

Once the ϕ_{rst}, Q_{rst}, V_{rst} and I_{rst} are calculated, we can normalize the measurements, scaling the curves in the Q-ϕ domain in order to obtain $Q_{rst} = 1$ and $\phi_{rst} = 1$. Figure 6 shows the results of the normalized charge versus the normalized flux. It is apparent that the behavior of the whole set of curves is very similar. In this respect, taking into consideration the work of Chua [4] and Shin [9] outlining a work plan for modeling in the Q-ϕ domain, we propose a non-linear relation between the charge and the flux in the following way (we assume a voltage-controlled memductor whose constitutive relationship is the following equation [9]):

$$Q = Q_{\mathrm{rst}} \cdot \min\left(1, \left(\frac{\phi}{\phi_{\mathrm{rst}}}\right)^{n}\right). \tag{1}$$

Notice that we have not taken into account any residual charge after the reset transition. This simple and explicit model fits the experimental data in a reasonable manner with only three parameters (Q_{rst}, ϕ_{rst}, n). Some examples of this are shown in Fig. 7 and 8, where three random curves are depicted. The model fits experimental values fairly well, mostly in the Q-ϕ domain. The mean values of the fitting parameters are provided in Tab. 2. The values of ϕ_{rst} and Q_{rst} are obviously the same than those given in Tab. 1, but are repeated here for completeness.

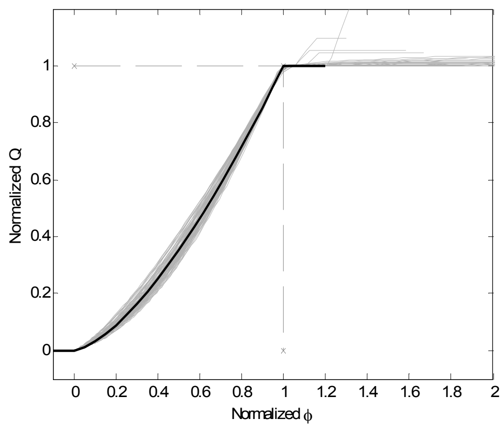

Fig. 6. Normalized Q vs normalized ϕ for each reset transition. The normalization is performed by scaling each curve in order to fit the reset values to one. The darkest line corresponds to the model proposed in (1). In the case of I-V curves with several current steps, there can be seen Q values above one; in these cases the normalizing value was connected with the first reset event.

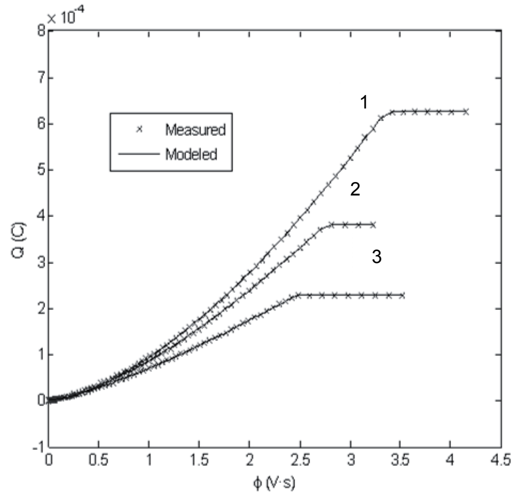

Fig. 7. Experimental (crosses) and modeled (lines) behavior of three different transitions in the Q-ϕ domain. The numbers refer to the corresponding curves in Fig. 8.

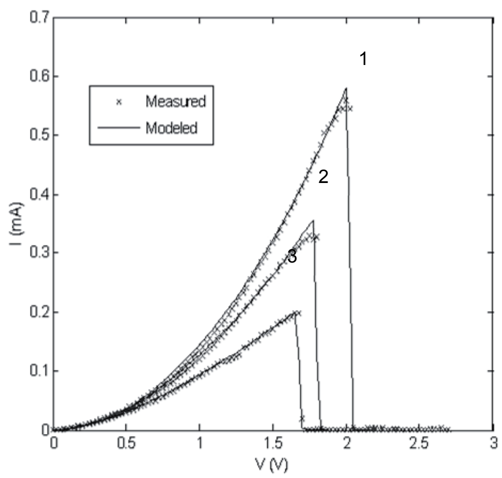

Fig. 8. Experimental (crosses) and modeled (lines) behavior of three different transitions in the current-voltage domain. The numbers refer to the corresponding curves in Fig. 7.

	ϕ_{rst} (Vs)	Q_{rst} (μC)	n
Average	3.28	562	1.50
Standard dev.	0.76	255	0.0999

Tab. 2. Extracted mean values and deviations for the parameters of the model described in (1).

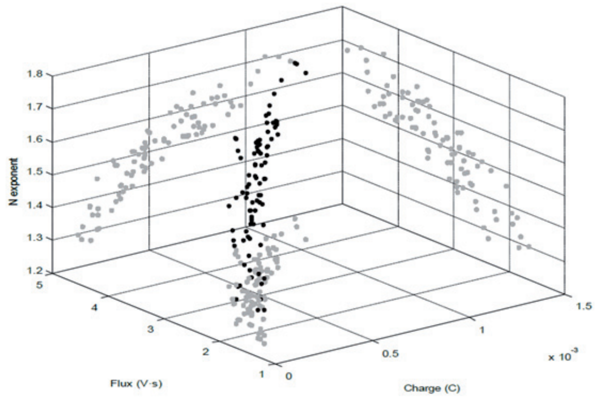

Fig. 9. Extracted parameters ϕ_{rst}, Q_{rst} and n represented in 3D plot. Dark dots are the points in the 3D space, while the clear points correspond to projections into the corresponding axis planes.

In Fig. 9 we have represented the extracted model parameters for each RS cycle considered. From this figure, it can be concluded that there is some correlation between them. In this respect, there might be connections between the values of these parameters and the geometry and number of conductive filaments that control RS processes. We are still deepening on the physics of RS in these devices to shed light on this issue.

4. Conclusions

In this work we have presented measurements of 100 reset cycles of a single unipolar RS-based memristor. We have moved from the usual representation in the I-V space to a representation in the Q-ϕ domain, and we have extracted the reset voltages and reset currents in these new domain. We have seen that, after normalizing all the RS reset cycles with the values of Q_{rst} and ϕ_{rst}, the curves can be modeled with a single explicit analytical expression in the Q-ϕ domain, shown in (1). The fitting is fairly good, as shown in Fig. 7 and 8. This simple model has three fitting parameters, but, as can be seen in Fig. 9, they are strongly correlated through some underlying process, which we assume to be the number of filaments and their radii, but this is still under study.

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 used to simulate the statistical behavior of resistive switching unipolar memristors.

It must be noted also that it does not depend on the shape of the input waveform, since the model is, as recommended in [4], in the Q-ϕ domain. New experiments are in process with different waveforms and frequencies to further check the validity of this approach.

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