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A simple, robust, and accurate compact model for a wide variety of complementary resistive switching devices

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A R T I C L E I N F O

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A B S T R A C T

Complementary Resistive Switching (CRS) using memristive devices has been intensively investigated in the last decade. The objective of CRS is to generate low and high resistance windows in the *I-V* characteristic of the selector device with the aim of reducing the sneak-path conduction problem in crossbar arrays. Though a wide variety of compact models for CRS have been proposed, the one presented here stands out for its simplicity, robustness, and accuracy. The flexibility of the memdiode model is demonstrated through a series of fitting exercises using experimental data found in the literature. The model script for the *LTSpice XVII* simulator is also provided.

1. Introduction

Complementary Resistive Switching (CRS) takes place when two memristive devices are anti-serially connected forming a single functional structure. This simple device arrangement has been proposed as a way of reducing the sneak-path conduction problem in crossbar arrays used for information storage and neuromorphic computing [1]. As illustrated in Figs. 1 and 2, the combined action of the two resistive switches, with their respective low (LRS) and high (HRS) resistance states, leads to the alternate appearance of ON and OFF conducting windows in the *I-V* characteristic. Remarkably, these windows can exhibit a wide variety of behaviors both in shape (abrupt/progressive) and magnitude (small/large) that are not only a consequence of the selected materials (metals and dielectric) but also the result of the particular features of the generated filamentary structures (oxygen vacancy- or metal ion-based pathways, lateral size, internal series resistance, etc.). In this work, a simple, robust, and accurate compact model capable of reproducing different CRS behaviors reported in the literature is presented and tested. The CRS conduction characteristics are modeled connecting two opposite-biased quasi-static memdiodes [2–4] and the system is simulated in *LTSpice XVII* from Linear Technologies. A quasi-static approach is followed here because neither programming steps nor frequency effects are within the scope of this paper. Although this may sound obvious, a key issue for the accurate modeling of the CRS *I-V* characteristic is the detailed modeling of the individual memristors that constitute the CRS structure. In this regard, the model of each memristor needs to include the crucial features required for the realistic simulation of the curves, such as the snapback (SB) and snapforward (SF) effects (see Fig. 2). These effects correspond to the vanishing and formation of a gap along the atomic filamentary structure, respectively, and are essential for correctly addressing the device behavior.

After the completion of the filament formation process (SET) in a memristive structure, the voltage at the constriction suddenly drops (SB effect) following the circuit load line dictated by the series resistance R_i (green solid line in Fig. 2). This resistance can be internal, external, or both. Beyond this point, the filament laterally expands or, alternatively, accumulates defects at a constant voltage called the transition voltage Vt (vertical line in Fig. 2). When in LRS, the curve reaches the RESET point at negative bias and drops (SF effect) following again the load line of the device. The red solid line in Fig. 2 corresponds to the same curve but taking into account the additional potential drop across the series resistance. Depending on the magnitude of the SB and SF effects occurring in each memristive device, the CRS *I-V* curve can exhibit abrupt or gradual transitions as those illustrated in Fig. 1. In order to demonstrate the flexibility of our model to cope with these situations (Section II), a number of experimental curves found in the literature were analyzed and simulated (Section III). Interestingly, the proposed model can also be used to deconstruct the CRS experimental curve into its separate constituents when the corresponding information is not available.

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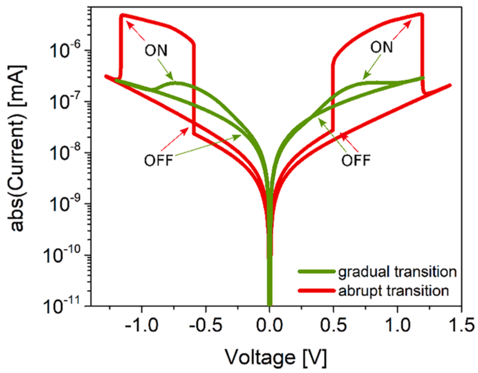

Fig. 1. Simulated I-V characteristics with gradual (green line) and abrupt (red line) transitions between the ON and OFF states. The curves were simulated with the model reported in this work.

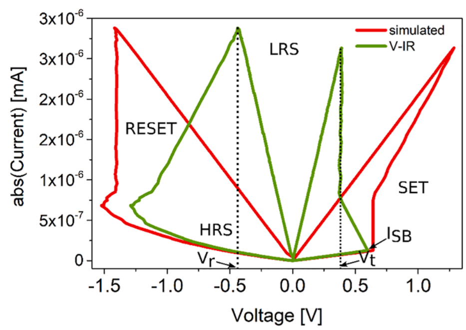

Fig. 2. Simulated I-V characteristics for a single memristor with (green line) and without (red line) SB and SF corrections (V-IR$_i$). Notice that the V_r=-V_t in the corrected curve. I_{SB} denotes the triggering current for the SET process.

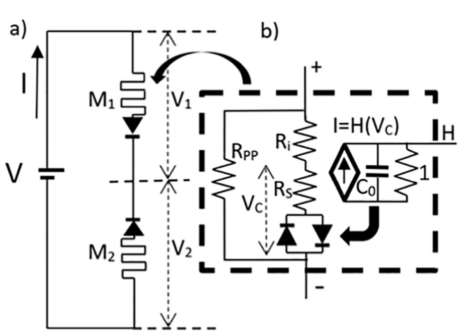

Fig. 3. Schematic circuit for (a) the CRS structure consisting in two memristors anti-serially connected; (b) the internal implementation of the QMM for a single device (see Fig. 10 in the appendix). The model contains a two-port circuit for the I-V characteristic and a memory circuit for tracking the hysteresis effect. The memory circuit controls the diode parameters.

2. The memdiode model for CRS devices

The Quasi-static Memdiode Model (QMM) is considered here for simulating each device in the CRS structure [2–4]. As illustrated in Fig. 3 (a), two anti-serially connected devices of this kind define the CRS structure. The *I-V* characteristic for each memdiode reads:

$$I(V) = I_0(\lambda)sinh\{\alpha(\lambda)[V - (R_S(\lambda) + R_i)I]\}$$

where $I_0(\lambda) = I_{omin} + (I_{omax} - I_{omin})\lambda$ is the current amplitude factor. I_{omin} and I_{omax} are calibration parameters. V is the voltage across the terminals, R_S a variable series resistance, and α a fitting parameter. Both α and R_S, if required, can be described by relationships similar to that

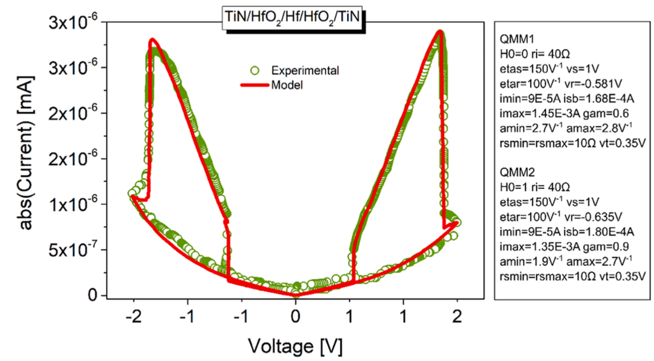

Fig. 4. Experimental and model results for two Ti/HfO_2/Hf-based structures anti-serially connected [5].

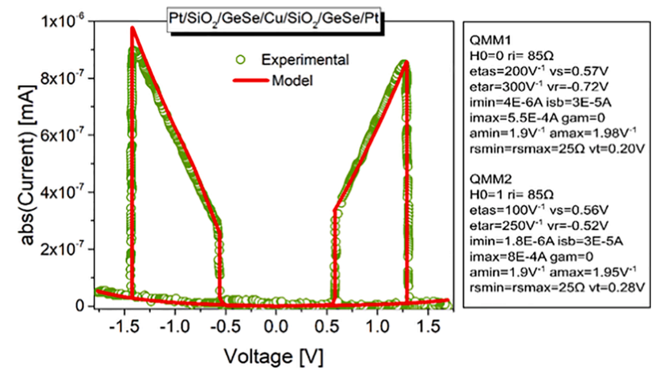

Fig. 5. Experimental and model results for a SiO_2/GeSe-based CRS structure [1]. Notice that the I-V characteristic is not symmetric.

used for I_0. (1) resembles the *I-V* relationship for two opposite-biased diodes with shared series resistance (see Fig. 3(b)). Eq.(1) replaces the Lambert function and the Hermite-Padé approximation considered in [4]. The second equation relates the memory state λ to the voltage drop across the constriction $V_C = V - (R_S(\lambda) + R_i)I$ through the recursive hysteresis operator [2]:

$$\lambda(V_C) = min\left\{\Gamma^-(V_C), max\left[\lambda(\overleftarrow{V_C}), \Gamma^+(V_C)\right]\right\}$$

where Γ^+ and Γ^- are the so-called ridge functions, which physically represent the ion/vacancy movement. $\lambda\left(\overleftarrow{V_C}\right)$ is the memory value a timestep before (hysteretic behavior). The model contains other parameters for the fine-tuning of the simulated curves. In particular, the *gam* parameter, not considered before [4], is used to fit the reset region of the devices. Eqns. (1) and (2) are implemented in *LTSpice* using an equivalent circuital approach with behavioral components and sources (see the script in the Appendix). A very important feature of the model is that the SET event can be triggered not only by a set voltage V_S but also by a threshold current I_{SB} (see Fig 2). This leads to a variety of behaviors suitable for capturing the details of the experimental curves. In this regard, it is worth mentioning the possibility of generating gradual or abrupt ON transitions in the CRS curves as well as departures from the abrupt OFF transitions. The key issue behind the observation of abrupt ON transitions is a noticeable SB effect in the individual devices.

3. Experimental curves and simulations

In order to assess the versatility of the QMM for CRS devices, we present simulations for a number of experimental *I-V* characteristics reported by other authors. The model parameters are indicated in the table next to each curve. Figure 4 shows experimental and simulation

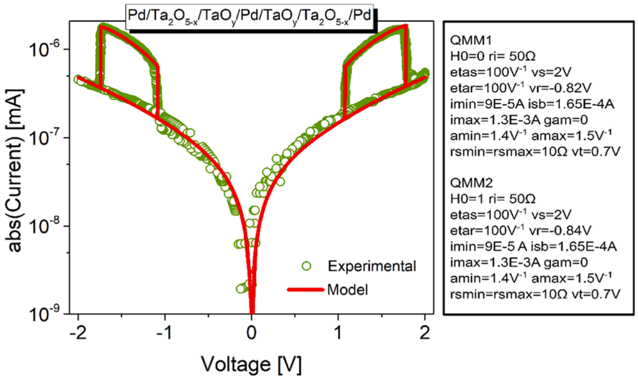

Fig. 6. Experimental and model results for a symmetric Tantalum oxide-based CRS structure [6].

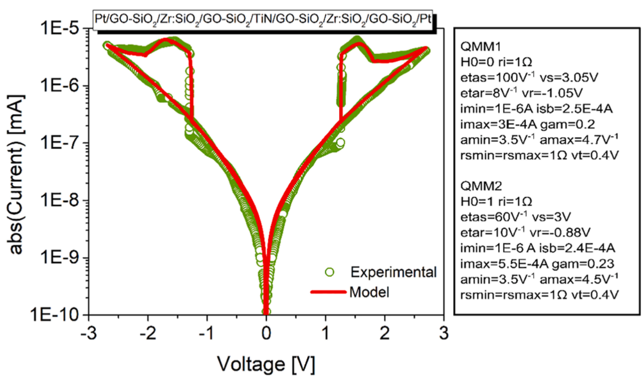

Fig. 7. Experimental and model results for two-sided graphene oxide doped silicon oxide-based memristors forming a CRS structure [7].

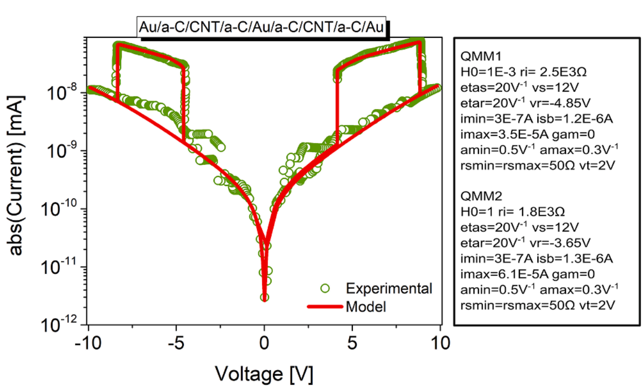

Fig. 8. Experimental and model results for a-C(amorphous-Carbon)/ CNT-based memristors forming a CRS structure [8].

results for combined TiN/HfO_2/Hf devices [5]. In this plot, the SET and RESET transitions are abrupt and have associated SB and SF effects, respectively. Notice the small departures of the experimental curve at the end of the OFF transitions and how the model is able to capture the detail. Figure 5 illustrates completely abrupt CRS transitions for two Pt/SiO_2/GeSe/Cu devices [1]. Figure 6 shows a similar behavior for two bilayer Pd/Ta_2O_{5-x}/TaOy/Pd combined devices but in log-linear axis [6]. Figure 7 shows experimental and simulation results for graphene/Zr-based structures [7]. As reported by these authors, the two-sided graphene oxide (GO) structures exhibit an intrinsic current restriction ability and uniform switching (the model can also be applied in this case). Notice the details of the OFF transitions achieved by means of the effective voltage reduction parameter in the reset equation of the model

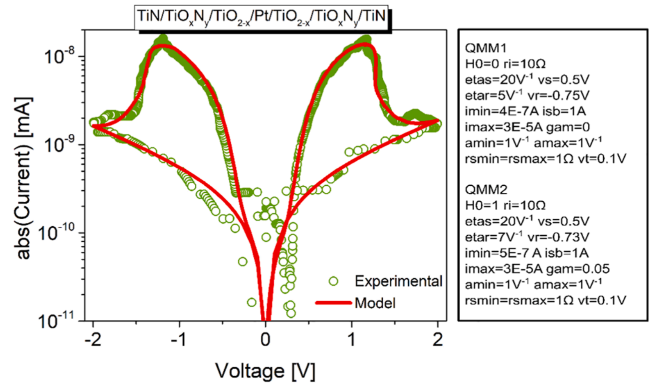

Fig. 9. Experimental and model results for TiN/TiO_xN_y/TiO_{2-x}/Pt memristors forming a CRS structure [9].

(*gam*). Figure 8 shows results for the *I-V* curve of carbon nanotubes (CNT)-based devices [8]. The parameter values used in this simulation are very different from those used before because the switching voltages are higher than those observed in the other materials. Finally, Fig. 9, which corresponds to a combination of TiN/TiO_xN_y/TiO_{2-x}/Pt devices [9], exhibits both gradual and large ON and OFF transitions in the CRS conduction characteristic. They are well captured by the proposed model. It is worth mentioning that, though in all the cases we attempted to use in the simulations parameter values close to their corresponding experimental ones, it was sometimes difficult to identify the right values. The current behavior is affected by a combination of parameters and the only information available is the final CRS curve. In our simulations, and for simplicity, we have considered initial states λ=0 and λ=1 for each memdiode. Experimentally, both memdiodes are initially in the HRS state and reach the complementary behavior in the following cycles. The simulated curves are shown for the stationary loop.

4. Conclusions

Complementary resistive switching is a key element to control the crosstalk effects in memristor-based crossbar arrays. In this paper, we have reported and discussed a compact model (the quasi-static

```
.subckt QMM + - H
.params
+ H0=0                              ; 0 for HRS, 1 for LRS
+ etas=50 vs=1 etar=50 vr=-1        ; Transitions
+ imax=1E-3 amax=2 rsmax=10         ; LRS parameters
+ imin=1E-5 amin=2 rsmin=10         ; HRS parameters
+ vt=0.5 isb=1e-4 gam=0.2           ; isb=1, gam=0 no SB/SF
+ ri=10 CH0=1E-3 RPP=1E10           ; Resistance/capacitance
*Memory equation
BH 0 H I=min(R(V(C,-)),max(S(V(C,-)),V(H))) Rpar=1
CH H 0 {CH0} ic=H0                  ; Initial condition
*I-V
RE + C {ri}                         ; Snapback resistance
RS C B R=RS(V(H))                   ; Constriction resistance
BD B - I=I0(V(H))*sinh(A(V(H))*V(B,-))
RB + - {RPP}                        ; Parallel resistance
*Auxiliary functions
.func I0(x)=imin+(imax-imin)*x
.func A(x)=amin+(amax-amin)*x
.func RS(x)=rsmin+(rsmax-rsmin)*x
.func VSB(x)=if(x>isb,vt,vs)
.func ISF(x)=if(gam==0,1,pow(x,gam))
.func S(x)=1/(1+exp(-etas*(x-VSB(I(BD)))))
.func R(x)=1/(1+exp(-etar*ISF(V(H))*(x-vr)))
.ends QMM
```

Fig. 10. LTSpice script for the QMM used in RS. The label QMM designs the memdiode. To simulate CRS, two devices of this kind are connected in series.

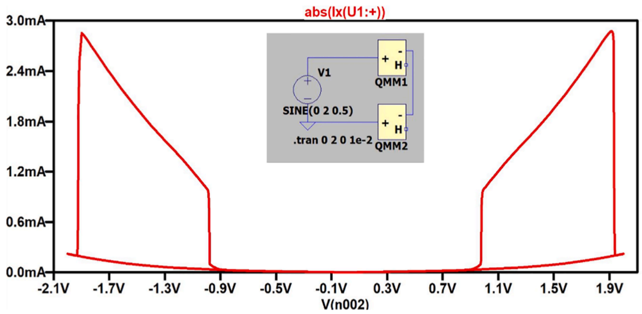

Fig. 11. Model CRS curve obtained with the script shown in Fig. 10. The inset of the figure shows the schematic used for the simulation.

memdiode model) suitable for the simulation of a wide variety of experimental data. The model for each individual device consists in two equations, one for the electron transport and a second equation for the memory state of the device. When both structures are combined, the CRS behavior emerges. To the best of our knowledge, no other published model can cope with the variety of curves reported here.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

The code shown in Fig. 10 for *LTSpice XVII* corresponds to a single memristive structure. When connected in series two of these devices as illustrated in the inset of Fig. 11, the CRS behavior shows up. The script contains four sections: *i)* model parameter definitions, *ii)* memory equation using the recursive operator, *iii) I-V* characteristic with series resistance effects, and *iv)* definition of the auxiliary functions. The model can be simplified further but was written this way for the sake of clarity. The output H corresponds to the memory state of the device and can be eliminated as a pin.

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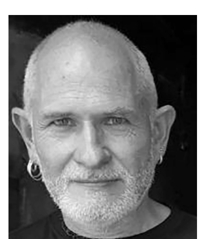

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