A behavioral model of unipolar resistive RAMs and its application to HSPICE integration

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Abstract: We propose a behavioral model of unipolar resistive RAMs (ReRAMs). The model integrates three behavioral characteristics of unipolar ReRAMs; *i.e.*, i) ON/OFF resistive switching characteristics for transient voltage pulses, ii) I-V characteristics exhibiting ON/OFF resistive switching with current compliance, and iii) current-compliance dependence of both ON resistance and OFF threshold currents. The model is described by three nonlinear differential equations with several static functions, which enables us to employ the model in any numerical or circuit simulator. As an example, we integrate the model on HSPICE, and show the simulated results using experimental parameters extracted from fabricated ReRAMs of TiO_2 thin films.
Keywords: Resistive RAM (ReRAM), behavioral model, SPICE
Classification: Integrated circuits

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1 Introduction

Resistive RAMs (ReRAMs), where the resistance is changed by voltage and current biases, have extensively been studied to develop high-speed and large-capacity nonvolatile memories as well as functional nonvolatile memories [1]. ReRAMs are so far intended for use as alternatives to contemporary flash memories, but the applications are not limited to Boolean alternatives indeed. For example, an artificial neural computing system has been proposed where bipolar memristive characteristics of nanojunctions were fully utilized [2]. Furthermore, nonlinear oscillators have been designed by using passive or active bipolar memristors for possible applications in neuromorphic systems [3], whereas memristor cellular automata have also been proposed, aiming at parallel image-processing applications [4]. More recently, a memristive synapse, which precisely mimics spike-timing dependent plasticity of neuronal synapses, has been proposed for developing brain-like (neuromorphic) computers [5].

Although physical mechanisms of resistive switching in ReRAMs have not fully been understood, to explore novel computing architectures for ReRAMs (*e.g.*, brain-like computers), mathematical or circuit-level ReRAM models based on behavioral characteristics of ReRAMs have to be developed in advance. Behavioral mathematical models of "bipolar" ReRAMs (memristors) have already been proposed in the literature, and have widely been accepted by many researchers (*e.g.*, [2, 3, 4, 5]). For "unipolar" ReRAMs, a behavioral circuit model has been proposed for a popular circuit simulator (HSPICE) [6]. The unipolar model showed good agreement with experimental results of transient ON/OFF switching characteristics. Although practical unipolar ReRAMs exhibit innegligible dependence of the compliance currents on the resistance and the threshold values (*e.g.*, [7]), the ON resistance and OFF threshold current in the unipolar model were fixed, and were independent of the compliance current. Furthermore, the unipolar model consisted of many nonlinear circuit elements; *i.e.*, an RS flip flop for ON/OFF storage, six transfer gates for ON/OFF switching, two operational amplifiers (comparators), etc., which may prevent us from very-large-scale circuit-level simulations. It was also very hard to transfer the model in numerical simulators (MATLAB, etc.) due to the lack of explicit definition of the model dynamics.

In this paper, we propose a behavioral mathematical model of "unipolar" ReRAMs which has compliance-current dependence of the ON resistance and OFF threshold current. The model is described by three simple dynamics which can easily be integrated in any numerical or circuit simulator. As an example, we integrate the model on HSPICE, and show the simulated results using experimental parameters extracted from fabricated ReRAMs of TiO_2

thin films.

2 Behavioral model of unipolar ReRAMs

To mimic the ON/OFF storage behavior of unipolar ReRAMs, we first assume the following double-well potential function[1]:

$$H(u) \equiv \frac{1}{2}u^2 - \beta^{-1}\ln\cosh[\beta(u-v)] \qquad (1)$$

where u represents the ON/OFF state ($u = 1$: ON and $u = -1$: OFF), v the ON/OFF transition control input, and β the gain ($\gg 1$). Both u and v are dimensionless. When $-1 < v < 1$, Eq. (1) forms a double well (H has two potential valleys at $u = \pm 1$), and the potential valley at $u = 1$ (or $u = -1$) disappears when $v \geq 1$ (or $v \leq -1$). Therefore when $v \geq 1$, "OFF" state is stable, whereas "ON" state is stable when $v \leq -1$. The resistance of a ReRAM is then expressed in terms of u as

$$R_{\text{ReRAM}} = \frac{1}{2}[(R_{\text{on}} - R_{\text{off}})u + R_{\text{on}} + R_{\text{off}}] \qquad (2)$$

where R_{on} and R_{off} represent the ON and OFF resistance, respectively.

Here let us introduce the dynamics of u. Since the stable condition is given by $du/dt = -\nabla H$, we obtain

$$\tau_1 \frac{du}{dt} = -u + \tanh[\beta(u-v)] \qquad (3)$$

where τ_1 represents the ON/OFF switching time constant. The control input (v) is defined by the following differential equation:

$$\tau_2 \frac{dv}{dt} = -v + u \cdot \alpha(u) \qquad (4)$$

where $\alpha(u)$ is the static ON→OFF or OFF→ON function, and τ_2 the fidelity time constant to α (one may assume $\tau_2 \approx \tau_1$). The function α is defined as

$$\alpha(u) = \frac{1}{2}[(n_{\text{off}} - n_{\text{on}})u + n_{\text{off}} + n_{\text{on}}] \qquad (5)$$

where n_{off} and n_{on} represent normalized ON→OFF and OFF→ON conditions, respectively. The normalized conditions are given by

$$n_{\text{off}} = \left|\frac{I_{\text{ReRAM}}}{I_{\text{th}}^{\text{off}}}\right|, \qquad n_{\text{on}} = \left|\frac{V_{\text{ReRAM}}}{V_{\text{th}}^{\text{on}}}\right| \qquad (6)$$

where I_{ReRAM} represents the current across a ReRAM, V_{ReRAM} the voltage across the ReRAM, $I_{\text{th}}^{\text{off}}$ the ON→OFF threshold current of the ReRAM, and $V_{\text{th}}^{\text{on}}$ the OFF→ON threshold voltage of the ReRAM (> 0).

Now, let us see how the dynamical model works. When $u = -1$ (OFF state), v approaches $-n_{\text{off}}$ because $\alpha(u) = n_{\text{off}}$, and n_{off} exceeds 1 if V_{ReRAM}

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[1]In principle, one may assume any double-well function here, $e.g.$, $H(u) = -u^2/2 + u^4/4 + \xi$, if the stable points can be controlled by input ξ. In this example, $\xi \equiv u \cdot v$ yields qualitatively the same characteristics as Eq. (1), however, the stable point is shifted by the amount of ξ, which results in a nonlinear form of Eqs. (2) and (5). We therefore employ the form of Eq. (1) where the stable point is $u = 1$ or -1 regardless of values of v.

exceeds the threshold ($V_{\text{th}}^{\text{on}}$), which results in the disappearance of the potential barrier because $v \leq -1$. Therefore, OFF→ON transition happens ($u = -1 \rightarrow 1$). On the other hand, v approaches n_{on} when $u = 1$ (ON state), and n_{on} exceeds 1 if I_{ReRAM} exceeds the threshold ($I_{\text{th}}^{\text{off}}$), which results in the ON→OFF transition ($u = 1 \rightarrow -1$).

The values of ON resistance (R_{ON}) and OFF threshold current ($I_{\text{th}}^{\text{off}}$) depend on the value of the compliance current at the OFF→ON transition (*e.g.*, [7]). To mimic this phenomenon, the compliance current has to be memorized in the model as an internal state. To this end, we introduce

$$\tau_3 \frac{dI_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}}}{dt} = \gamma(u) \cdot (-I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}} + I_{\text{ReRAM}}), \quad \gamma(u) = \frac{1-u}{2} \quad (7)$$

where $I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}}$ is the compliance current (to be memorized) and τ_3 the time constant. Because $\gamma(u)$ is 0 (or 1) when $u = 1$ (or $u = -1$), $I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}}$ approaches I_{ReRAM} when $u = -1$ (OFF state), whereas $dI_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}}/dt$ becomes 0 when $u = 1$ (ON state). Consequently, Eq. (7) integrates I_{ReRAM} during the OFF state, and at the timing of OFF→ON transition, I_{ReRAM}, which is equal to the compliance current at the ON state, is preserved as $I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}}$. Note that one has to ensure $\tau_3 \ll \tau_1$ because $I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}}$ has to be preserved before the completion of OFF→ON switching transition.

Now the ON resistance and OFF threshold currents are described in terms of functions of $I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}}$ as $R_{\text{ON}}(I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}})$ and $I_{\text{th}}^{\text{off}}(I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}})$, respectively. The overall model[2] is represented by a set of closed equations, *i.e.*, Eqs. (2) to (7) with the compliance functions $R_{\text{ON}}(I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}})$ and $I_{\text{th}}^{\text{off}}(I_{\text{comp}}^{\text{OFF}\rightarrow\text{ON}})$.

3 Experimental and simulation results

Figure 1 (a) shows our target ReRAM device. The TiO_2 thin films were grown on Pt/Ti/Si(100) substrate by pulsed laser deposition method (ArF excimer, $\lambda = 193\,\text{nm}$). The film thickness was controlled to be 40 nm. Prior to the deposition of TiO_2 thin films, Pt (the bottom electrode) was de-
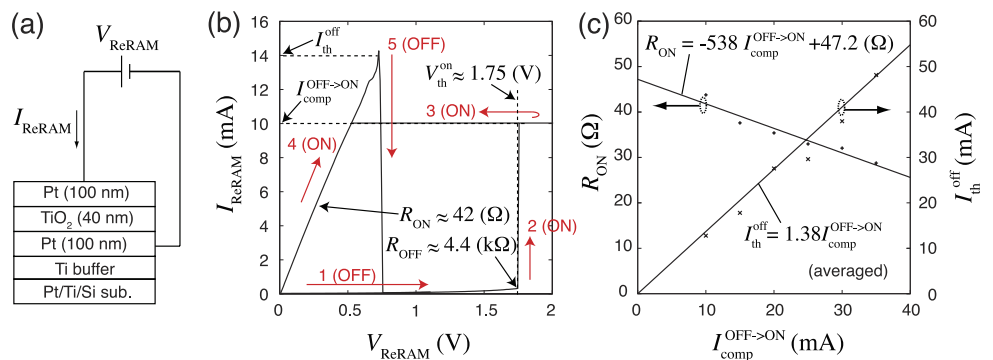

Fig. 1. Target ReRAM device and characteristics.

[2]The initial "forming" operation was omitted from the model for simplicity, but one may easily add an additional potential that represents the forming status, by using the same double-well strategy (formed or non-formed).

posited onto the substrate with Ti buffer layer. The thickness of Pt bottom electrode was 100 nm. The top electrode was then deposited onto the TiO_2 thin films by using a metal mask with an area of $50 \times 50\,\mu m^2$. Current-voltage characteristics [I_{ReRAM} vs V_{ReRAM} defined in Fig. 1 (a)] were evaluated by a semiconductor parameter analyzer (Keithley 4200-SCS) at room temperature in ambient atmosphere.

Figure 1 (b) shows the I-V characteristics. Initially, the ReRAM device was set at "off state" after the forming process. During the first forward and backward sweep of V_{ReRAM} [red arrows indexed by 1, 2 (forward) and 3 (backward) in Fig. 1 (b)], the parameter analyzer's compliance current was set at 10 mA, to avoid the breakdown in the on-state device. In the first forward sweep (arrows indexed by 1 and 2), when V_{ReRAM} exceeded on-threshold voltage $V_{\mathrm{th}}^{\mathrm{on}}$ ($\approx 1.75\,V$), the device was turned on. Then in the subsequent backward sweep (an arrow indexed by 3), the device was kept in the on state. Before the second forward sweep (arrows indexed by 4 and 5), the parameter analyzer's current compliance was disabled. In the second forward sweep, when I_{ReRAM} exceeded off-threshold current $I_{\mathrm{th}}^{\mathrm{off}}$ ($\approx 14\,mA$), the device was turned off again. These correspond to typical operations of unipolar ReRAMs [1]. Figure 1 (c) shows the $I_{\mathrm{comp}}^{\mathrm{OFF \to ON}}$ dependence of ON resistance [$R_{\mathrm{ON}}(I_{\mathrm{comp}}^{\mathrm{OFF \to ON}})$] and the dependence of the OFF threshold current [$I_{\mathrm{th}}^{\mathrm{off}}(I_{\mathrm{comp}}^{\mathrm{OFF \to ON}})$], which represented the ReRAM's innegligible dependence of the compliance currents on the resistance and the threshold values. From Figs. 1 (b) and (c), we extracted the following parameter values and functions:

$$R_{\mathrm{OFF}} = 4.4\ (k\Omega), \quad R_{\mathrm{ON}}(I_{\mathrm{comp}}^{\mathrm{OFF \to ON}}) = -538 \cdot \left| I_{\mathrm{comp}}^{\mathrm{OFF \to ON}} \right| + 47.2\ (\Omega),$$

$$V_{\mathrm{th}}^{\mathrm{on}} = 1.75\ (V), \quad I_{\mathrm{th}}^{\mathrm{off}}(I_{\mathrm{comp}}^{\mathrm{OFF \to ON}}) = 1.38 \cdot I_{\mathrm{comp}}^{\mathrm{OFF \to ON}},$$

where R_{OFF} was approximately obtained by calculating differential resistance $V_{\mathrm{th}}^{\mathrm{on}}/I_{\mathrm{ReRAM}}$ with subcritical I_{ReRAM} ($\approx 0.4\,mA$) in the off state.

Figure 2 shows HSPICE netlists of the proposed ReRAM model. Figure 2 (a) represents the ReRAM subcircuit. The l.h.s. and r.h.s. of Eqs. (3), (4) and (7) were represented by currents of capacitors (HSPICE's 'c' elements) and voltage-controlled currents ('g' elements), respectively, while the rest static functions [Eqs. (2), (5), and (6)] were implemented by 'e' elements as voltages.[3] The extracted device parameters above were described in the ".param" cards. Two terminals across a ReRAM are represented by nodes "n1" and "n2" in the figure. To ensure the timing constraints ($\tau_1 \approx \tau_2 \gg \tau_3$), we assume $\tau_3 = 10^{-3}\tau_1$ and $\tau_1 = \tau_2$ in the subcircuit. Figures 2 (b) and (c)

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[3]In general, one may simulate any ordinary differential equation (ODE) on SPICE. Assume that we solve ODE $\tau_1 dx_1/dt = f(x_1, x_2, \cdots)$ on SPICE. The equivalent circuit can be represented by a 'c' element (capacitor) and a 'g' element (voltage-controlled current source) that accepts voltages $(v_1, v_2, \cdots)$, as shown in the inset of Fig. 2 (a). Since capacitor's current is given by $C \cdot dv_1/dt$, where C and v_1 are the capacitance and the voltage across the capacitor, respectively, one obtains a node equation of $C \cdot dv_1/dt = I_0 \cdot f(v_1, v_2, \cdots)$ where $I_0 \cdot f(\cdot)$ represents 'g' element's current. By comparing the original equation [$\tau_1 dx_1/dt = f(x_1, x_2, \cdots)$] and this node equation, one may obtain the normalized conditions: $x_1 = v_1/\,[1\,V]$ and $\tau_1 = C/I_0$. Therefore, by assuming $I_0 = 1\,[A]$ ($\tau_1 = C/\,[1\,A]$), all the capacitances of the 'c' elements in Fig. 2 (a) can be replaced with the time constants of Eqs. (3), (4) and (7).

(a) ReRAM subcircuit

(b) Test fixture for simulating pulse responses

(c) Test fixture for simulating I-V characteristics
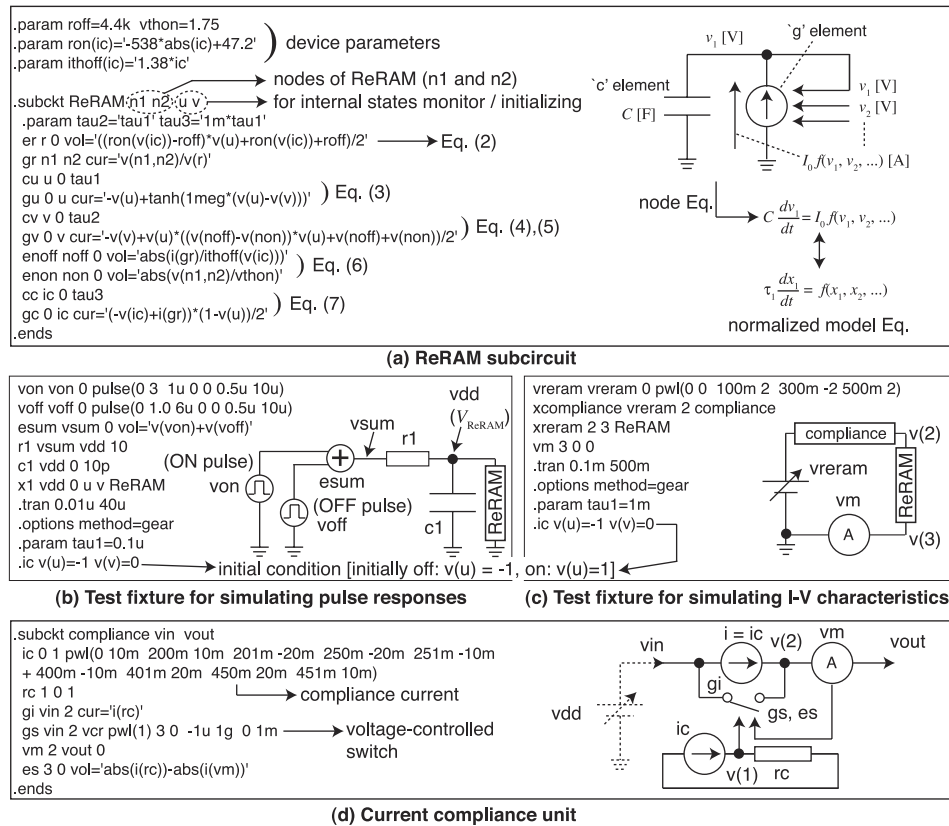
(d) Current compliance unit

Fig. 2. HSPICE netlists of behavioral ReRAM model.

show test-fixture examples for simulating pulse responses and I-V characteristics of the ReRAM model. Initial conditions of the ReRAM model (node voltages "u" and "v") are given by the ".ic" card in the test-fixture subcircuits ($v|_{t=0} = 0$, $u|_{t=0} = -1$ for initially OFF state, and $u|_{t=0} = 1$ for ON state). Measurement system's (parameter analyzer's) current compliance circuit, which is used in measuring I-V characteristics, is emulated by a subcircuit shown in Fig. 2 (d), where an external voltage source is connected to node "vin", and node "vout" is connected to the target (*i.e.*, our ReRAM subcircuit). If the current flowing out of node "vout" exceeds a given threshold current that is defined by current source "ic" in the subcircuit, the output current is compliant to the threshold current (*i.e.*, node voltage of "vout" is fixed over the limited states).

In the following simulations, β, initial values of u and v were set at 10^6, -1 (OFF state) and 0, respectively. We first demonstrate an intrinsic temporal ON/OFF switching ability of the proposed ReRAM model by applying narrow voltage pulses [frequency: 200 kHz, pulse width: 0.5 μs, amplitudes: 3 V (on pulse) and 1 V (off pulse), current compliance in the voltage pulser: none]. Figure 3 (a) shows the pulse responses simulated by a test fixture shown in Fig. 2 (b) ($\tau_1 = 100$ ns). The ReRAM model was able to be turned on (or off) by applying voltage pulses of amplitude 3 (V) [or 1 (V)], as observed in typical unipolar ReRAMs [1].

Figure 3 (b) plots transient responses of the ReRAM model for transient sweep of V_{ReRAM} (I_c in the figure) simulated by a test fixture with a current-
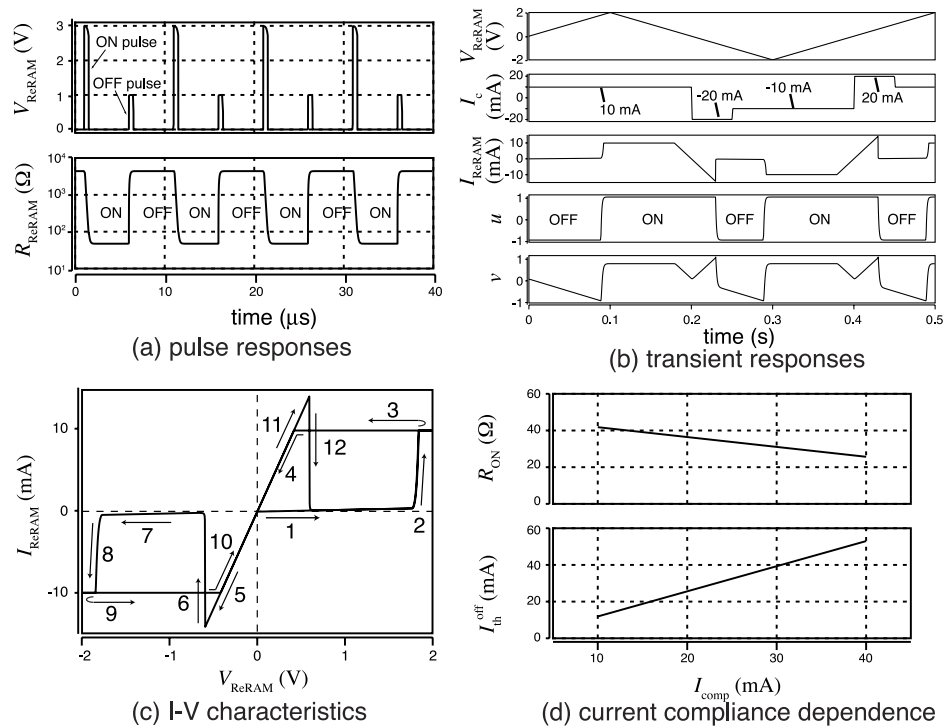
Fig. 3. Simulated results (HSPICE).

compliance unit shown in Figs. 2 (c) and (d). Here τ_1 was set at $1\,\text{ms}$ for fast simulation. The compliance current was essentially set at $\pm 10\,\text{mA}$, but was set at $\pm 20\,\text{mA}$ during the expected ON→OFF transition [I_{ReRAM} does not exceed this value ($20\,\text{mA}$), which meant that the current compliance was disabled during the term]. The I_{ReRAM}-V_{ReRAM} characteristic extracted from Fig. 3 (b) is plotted in Fig. 3 (c). Finally, the dependence of the model's ON resistance and OFF threshold current on the compliance current is presented in Fig. 3 (d).

4 Conclusion

We proposed a behavioral model of a resistive RAM (ReRAM) device having a dependence of ON resistance and OFF threshold current on values of compliance current. The model was described by a set of nonlinear differential equations which could be integrated on any numerical or circuit simulator. As an example, we integrated the model on HSPICE, and showed the typical characteristics. The results agreed well with experimental results of fabricated ReRAMs of TiO_2 thin films.

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