A Compact Model of Drift and Diffusion Memristor Applied in Neuron Circuits Design

Ying Zhao[1, 2], Cong Fang[1], Qiang Li[2], Nianduan Lu[1], Feng Zhang[1*] and Ling Li[1*], *Member, IEEE. Ming Liu*[1], *Fellow, IEEE*

[1] Key Laboratory of Microelectronics Devices and Integrated Technology, Institute of Microelectronics of Chinese Academy of Sciences, Beijing 100029, China
[2] the Institute of Integrated circuits and systems, University of Electronic Science and Technology of China, Chengdu, 610054, China.
* Email: lingli@ime.ac.cn, zhangfeng_ime.ac.cn

***Abstract*—A compact model of memristor for unifying two switch characteristics, drift and diffusion has been proposed, based on the ion dynamic transport theory at the oxide interface layer. The model is verified by measured data in different oxide-material-based drift/diffusion memristors, and well fits DC/AC characteristics of both devices, under parameter variations and temperature evolution. Moreover, the applications of this model in neuron circuits design are shown.**

Keywords—first-principles calculations, boron nitride nanotubes, adsorption effect, small molecule

I. Introduction

Recently, various types of memristors, such as ion drift (drift-type) and diffusion (diffusion-type), are very promising to be candidate for enabling high-density and ultimately scaled synaptic arrays in neuromorphic architectures [1-4]. Especially, the mechanism of diffusion-type memristor is similar to the physical behavior of the biological Ca^{2+}dynamic diffusion. Therefore diffusion-type memristor can improve emulation results of synaptic function and can be widely applied in neuromorphic computing [1]. For neuromorphic circuit design, the compact model of memristor is indispensable. So far, many researches have been done for modeling the switching behavior of memristor, such as based on the sub-circuits [5-15]. However, the physic-based compact model of memristor operating available is still scarce for neuromorphic circuit simulation. To our understanding, the compact model of new-emerging diffusion memristor is also still lacking now. In this work, a physics-based compact model applicable for both drift and diffusion memristors is developed, based on the insight of ion transport theory under the effect of the joule thermal effect, interface energy diffusion, and electric field. Furthermore, the proposed model is used in classical neuron circuit with great accuracy of circuit performance estimation.

II. Theoretical Model

The resistive switch mechanism here is subjected to the creation and breakdown of conductive filament (CF) in oxide layer [2], [16-18]. The SET processes of both drift and diffusion devices are attributed to the dielectric soft

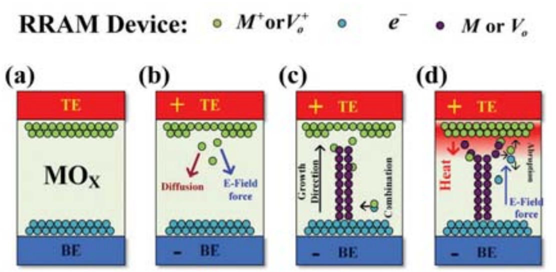

Fig. 1. Schematic physical processes of resistive switching for drift memristor. (a) Initial state. (b)、(c) The SET process: CF formed by applying the positive voltage on TE. (d) The RESET process: the reverse voltage and Joule heat are dominant for CF rupture.

breakdown and the creation of CFs by positive voltage on the Top Electrode (TE), as shown in Fig. 1 and Fig. 2(a)-(c)). Although the RESET process is attributed to the CF rupture, the mechanisms behind are different between the drift and diffusion devices. For the drift one, it is the recombination of vacancies and ions induced by the positive voltage applied on the Bottom Electrode (BE) or Joule heat (Fig. 1(d)). For the diffusion one, it is the particle diffusions toward the minimum energy positions near the device terminals [1] (Fig. 2(d) and (e)).

The key variable of this model is the derivative of x with respect to time, $\frac{dx}{dt}$. After the characteristics of the two-types

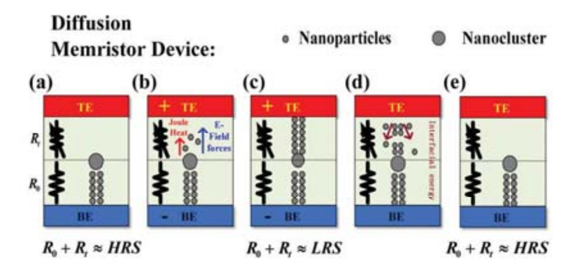

Fig. 2. Schematic physical processes of resistive switching for diffusion memristor (a) Initial state (b) The SET process (c) The CFs connects the electrodes making device in the low resistance state. (d) and (e) The RESET process

memristors reproduced by adjust $\frac{dx}{dt}$, the compact model for circuit design can be made:

$$\frac{dx}{dt} = f(V,T,x) \tag{2}$$

$$x = \int f(V,T,x) + \chi(i)\,dt \tag{3}$$

where x is defined as gap (drift device) or position (diffusion device) between the top of CF and TE and $\chi(i)$ is Gaussian noise sequence. The model makes an assumption of particle normalization based on the thought of mean value, in which $\boldsymbol{x} \cong \sum_{i=0}^{n} \boldsymbol{x}_i$, as shown in Fig.3. The positions of particles inside the devices are normalized to the position of one particle. The resistance variable, $R(x)$, is only relevant to the distance between the positions of particles and TE. Meanwhile, the Ohm's law can be applied between the memristor voltage and current:

$$i_R = \frac{V_R}{R(x)} \tag{4}$$

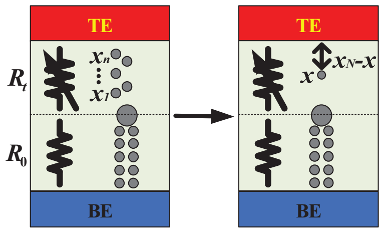

Fig. 3. Equivalent circuit of coupled ohmic-tunneling resistor circuit model.

The derivative of x with respect to time depends on the ion transport rate, i.e. temperature, electric field and other factors. In this work, the electric field force, local joule heat and interfacial minimum potential energy effect are considered, which are defined as f_{drift}, f_{heat}, and $f_{diffusion}$, respectively. The model will represent the drift memristors when f_{drift}, f_{heat} dominant the movement of particles, while the model will be diffusion mode when f_{drift}, f_{heat}, and $f_{diffusion}$ lead.

For drift memristor, according to [17], the developed resistance model is expressed as:

$$\begin{aligned} f(V,T,x) &= f_{drift}(heat) \\ &= -\mu_0 \cdot \left[\exp\left(-\frac{qE_{ag}}{k_B T}\right) \cdot \exp\left(\frac{\gamma d_0 q V_{in}}{L k_B T}\right) \right. \\ &\quad \left. - \exp\left(-\frac{qE_{ar}}{k_B T}\right) \cdot \exp\left(-\frac{\gamma d_0 q V_{in}}{L k_B T}\right) \right] \end{aligned} \tag{5}$$

$$\frac{dT}{dt} = C_{th} \cdot \frac{V_{in}^2}{R_{drift}} - \kappa (T - T_0) \tag{6}$$

$$R_t = \frac{V_{in}}{I_0 \exp(-x/x_0) \sinh(V_{in}/V_0)} \tag{7}$$

where the dynamic temperature effect, $\frac{dT}{dt}$, is included [15], E_{ag} and E_{ar} are activation energy for vacancy generation and vacancy recombination, respectively [10], μ_0, d_0, γ, x_0, I_0 and V_0 are the DC fitting parameters, q is the charge, k_B is the Boltzmann's constant, L is the thickness of resistive layer, V_{in} is the voltage between TE and BE of the memristor, C_{th} is the heat capacitance, κ is the heat transfer coefficient, T_0 is the home temperature.

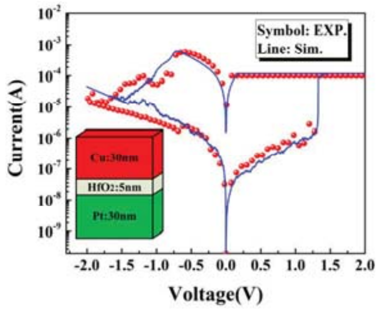

Fig. 4. Comparison between the model calculation and experimental data for DC I-V characteristics of HfO_2 based drift memristor.

For the diffusion memristor, according to [1], [20], the interfacial energy for particles diffusion is included and the model is shown as:

$$f(V,T,x) = f_{drift} + f_{heat} + f_{diffusion} \tag{8}$$

$$f_{drift} = \alpha \frac{V_{in}}{L} \tag{9}$$

$$f_{heat} = \sqrt{2\eta k_B T} \tag{10}$$

$$f_{diffusion} = 2\omega_i \cdot \frac{x - x_c}{R_i^2} \cdot \exp\left[-\frac{(x - x_c)^2}{R_i^2}\right] + \pi \cdot \frac{\omega_p}{R_p} \cdot \cos\frac{2\pi x}{R_p} \tag{11}$$

$$\frac{dT}{dt} = C_{th} \cdot \frac{V_{in}^2}{R_{diffusion}} - \kappa (T - T_0) \tag{12}$$

$$R_t = R_b \cdot \left[\exp\left(\frac{x_T - x}{\lambda}\right) - 1 \right] \tag{13}$$

where α is the electric field fitting factor, η is the particle viscosity coefficient, x_c is the location of cluster[1], [21], x_T is the location of top electrode in diffusion memristor, ω_i is the interfacial energy barrier, ω_p is the pinning potential, R_i and R_p are location fitting parameters, λ is the effective tunneling length, R_b is the resistance state fitting parameter of the diffusion memristor..

III. Results and Discussion

To verify the improved model, the DC and AC simulations are carried out in different device modes, and the simulation results are compared with the experimental results. Fig. 4 shows the comparison between experimental

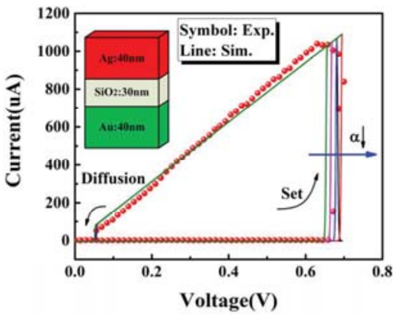

Fig.5. The DC characteristic comparison of the SiO_2 based diffusion memristor and its model.

data and model simulation of drift memristor devices with HfO_2 material as resistive layer. The model agrees well with the measured data. This model is most useful in modeling the behavior of the diffusion memristor while the interfacial energy is applied. Fig. 5 displays the I-V characteristic comparison of the diffusion memristor and its model.

Besides, the transient characteristics of the real devices and the model are shown in Fig. 6. It can be seen from the distributions of the high and low resistance in Fig. 6(c), the R_{OFF}/R_{ON} window is larger than 100, consistent with the experimental transient simulation results in Fig.6 (b), and the transition time shows the same magnitude as shown in Fig. 6(a). In Fig. 7, the model can reproduce the transient characteristics of diffusion memristor with great accuracy with the magnitude of diffusion time matching the experimental result.

Moreover, it is proved that the diffusion memristor can be used as the neuron-device [1, 20, 2]. The integrate-and-fire (IF) model circuit in Fig. 9 is constructed by the diffusion memristors [22]. The response behaviors are consistent with the traditional CMOS circuit shown in Fig. 8, indicating that the IF circuit can be fully implemented using diffusion memristor device compact model.

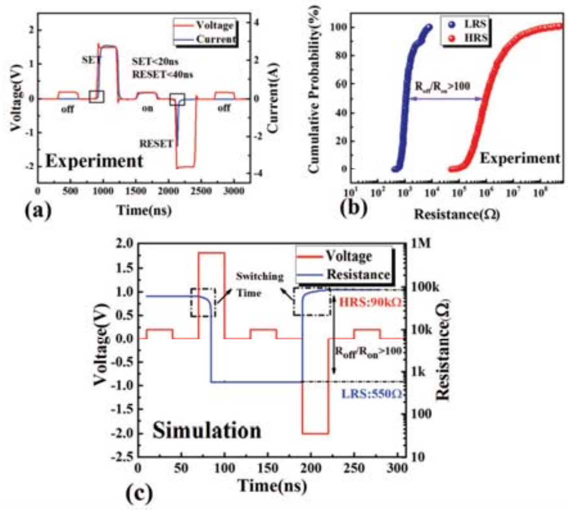

Fig. 6. Verification of drift memristor for transient: (a) Experimental transition characteristics: transition time (both SET and RESET) less than 40ns. (b) High and low resistance distribution of real device: the R_{OFF}/R_{ON} window is greater than 100. (c) Simulations transition characteristics: transition time (both SET and RESET) less than 40ns and the R_{OFF}/R_{ON} window is greater than 100.

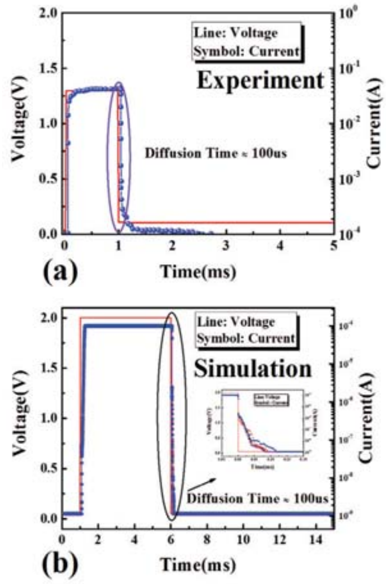

Fig. 7. Verification of diffusion memristor for transient: (a)Experimental transition characteristics: Diffusion time is about 100ns. (b) Simulations transition characteristics: the magnitude of diffusion time is the same as experimental result.

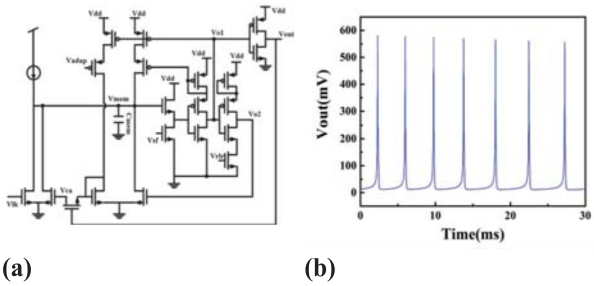

Fig. 8. (a)The traditional CMOS integrated fire (IF) circuit. (b)CMOS IF circuit simulation results.

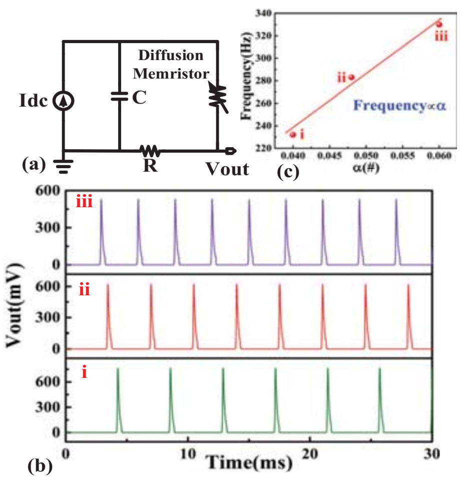

Fig. 9. (a)The new integrated circuit using the diffusion memristor devices. (b)Simulation results with different E-field factors. (c)IF circuit frequency is proportional to E-field factors.

IV. Conclusion

A compact model applicable for both drift and diffusion memristor is presented which can compensate the lack of the diffusion memristor model of neuromorphic device. The model can reproduce the DC and AC characteristics of the device accurately comparable with the measurements of the experiments. The Verilog-A model for SPICE can been used for neuromorphic circuit design. Moreover, it is found that diffusion memristor is more suitable for neuromorphic circuit. The effect from device threshold voltage and parameters variations on the circuit performance were discussed.

ACKNOWLEDGMENT

This work is supported by the National Key Research Plan of China (no. 2018YFB0407500), the National Natural Science Foundation of China (no.61704143, no 61474134, and no. 61720106013), Young and Middle-aged Teacher Education Research Project of Fujian Province (Grant No. JAT170428).

REFERENCES

[1] Zhongrui Wang, Saumil Joshi, Sergey Savel Ev, Hao Jiang, Rivu Midya, Peng Lin, Miao Hu, Ning Ge, John Paul Strachan, Zhiyong Li, Qing Wu, Mark Barnell, Geng Lin Li, Huolin L Xin, R Stanley Williams, Qiangfei Xia, Jianhua Yang, "Memristors with diffusive dynamics as synaptic emulators for neuromorphic computing", *Nature Materials*, vol. 16, no. 1, pp. 101-108, Sep. 2016, doi: 10.1038/nmat4756.

[2] Leon O Chua, "Memristor—the missing circuit element", *IEEE Transactions on Circuit Theory*, vol. 18, no. 5, pp. 507-519, 1971, doi: 10.1109/TCT.1971.1083337.

[3] Sung Hyun Jo, Ting Chang, Idongesit Ebong, Bhavitavya B Bhadviya, Pinaki Mazumder, Wei Lu, "Nanoscale memristor device as synapse in neuromorphic systems", *Nano Lett.* vol.10, no. 4, pp. 1297–1301, March. 2010, doi: 10.1021/nl904092h.

[4] Mirko Prezioso, Farnood Merrikhbayat, Brian J Hoskins, Gina C Adam, Konstantin K Likharev, Dmitri B Strukov, "Training and operation of an integrated neuromorphic network based on metal-oxide memristors", *Nature*, vol. 521, pp. 61–64, May. 2015, doi: 10.1038/nature14441.

[5] Yuning Zhao, J J Hu, Peng Huang, F Yuan, Yang Chai, Xiaoyan Liu, Jinfeng Kang, "A physics-based compact model for material- and operation-oriented switching behaviors of CBRAM", *Electron Devices Meeting IEEE*, 2017:7.6.1-7.6.4. doi: 10.1109/IEDM.2016.7838370.

[6] Sen Liu, Wei Wang, QingJiang Li, XiaoLong Zhao, Nan Li, Hui Xu, Qi Liu, Ming Liu, "Highly improved resistive switching performances of the self-doped Pt/HfO 2 :Cu/Cu devices by atomic layer deposition", Science China Physics Mechanics & Astronomy, vol. 59, no. 12, pp. 127311, Dec. 2016, doi: 10.1007/s11433-016-0389-9.

[7] Jinfeng Kang, Bin Gao, Peng Huang, Haitong Li, Yudi Zhao, Zhe Chen, Changze Liu, L F Liu, Xiaoyan Liu, "Oxide-based RRAM: requirements and challenges of modeling and simulation", IEEE International Electron Devices Meeting IEEE, 2015:5.4.1-5.4.4. doi: 10.1109/IEDM.2015.7409634.

[8] Zizhen Jiang, Yi Wu, Shimeng Yu, Lin Yang, Kay Song, Zia Karim, H S Philip Wong, "A compact model for metal–oxide resistive random access memory with experiment verification", *IEEE Transactions on Electron Devices,* vol. 63, no. 5, pp.1884-1892, 2016, doi: 10.1109/TED.2016.2545412.

[9] Haitong Li, Zizhen Jiang, Peng Huang, Y Wu, Hongyu Chen, Bin Gao, Xiaoyan Liu, Jinfeng Kang, H S P Wong, "Variation-aware, reliability-emphasized design and optimization of RRAM using SPICE model", Design, Automation & Test in Europe Conference & Exhibition IEEE, 2015:1425-1430. doi: 10.7873/DATE.2015.0362.

[10] Zizhen Jiang, Ziwen Wang, Xin Zheng, Scott W Fong, Shengjun Qin, Hongyu Chen, Chiyui Ahn, Ji Cao, Yoshio Nishi, H S Philip Wong, "Microsecond transient thermal behavior of HfOx-based resistive random access memory using a micro thermal stage (MTS)", Electron Devices Meeting IEEE, 2017:21.3.1-21.3.4. doi: 10.1109/IEDM.2016.7838465.

[11] Dalibor Biolek, Zdenek Kolka, Viera Biolkova, Zdenek Biolek, "Memristor models for SPICE simulation of extremely large memristive networks", IEEE International Symposium on Circuits and Systems IEEE, 2016:389-392. doi: 10.1109/ISCAS.2016.7527252.

[12] Ting Chang, Sung-Hyun Jo, Kuk-Hwan Kim, Patrick Sheridan, Siddharth Gaba, Wei Lu, "Synaptic behaviors and modeling of a metal oxide memristive device", *Applied Physics A Materials Science & Processing*, vol. 102, no. 4, pp. 857-863, 2011, doi: 10.1007/s00339-011-6296-1.

[13] Hsu, Kai Hsiang, W. W. Ding, M. H. Chiang, "A compact SPICE model for bipolar resistive switching memory", Electron Devices and Solid-State Circuits IEEE, 2013:1-2. doi: 10.1109/EDSSC.2013.6628127.

[14] Fernando Garciaredondo, Robert P Gowers, Albert Crespoyepes, Marisa Lopezvallejo, Liudi Jiang, "SPICE compact modeling of bipolar/unipolar memristor switching governed by electrical thresholds", IEEE Transactions on Circuits & Systems I Regular Papers, vol. 63, no. 8, pp. 1255-1264, July. 2016, doi: 10.1109/TCSI.2016.2564703.

[15] Hatem, Firas Odai, "A SPICE model of the Ta2O5/TaOx bi-layered RRAM", IEEE International Symposium on Circuits & Systems IEEE, pp. 1487-1498, Aug. 2017, doi: 10.1109/TCSI.2016.2579503.

[16] Rainer Waser, Masakazu Aono, "Nanoionics-based resistive switching memories", *Nat. Mater*. vol. 6, no. 11, pp. 833–840, Nov. 2007, doi: 10.1038/nmat2023.

[17] Zizhen Jiang, Shimeng Yu, Yi Wu, Jesse H Engel, Ximeng Guan, H S Philip Wong, "Verilog-A compact model for oxide-based resistive random access memory (RRAM)", International Conference on Simulation of Semiconductor Processes and Devices IEEE, 2014:41-44. doi: 10.1109/SISPAD.2014.6931558.

[18] Rivu Midya, Zhongrui Wang, J W Zhang, Sergey Savelev, Can Li, Mingyi Rao, Moon Hyung Jang, Saumil Joshi, Hao Jiang, Peng Lin, Kate J Norris, Ning Ge, Qing Wu, Mark Barnell, Zhiyong Li, Huolin L Xin, R Stanley Williams, Qiangfei Xia, Jianhua Yang, "Anatomy of Ag/Hafnia-Based selectors with 1010 nonlinearity", Advanced Materials, vol. 29, no. 12, pp. 1604457, 2017, doi: 10.1002/adma.2016.04457.

[19] Pai Yu Chen, Shimeng Yu, "Compact Modeling of RRAM Devices and Its Applications in 1T1R and 1S1R Array Design", IEEE *Transactions on Electron Devices*, vol. 62, no. 12, pp. 4022-4028, 2015, doi: 10.1109/TED.2045.2492421.

[20] Zhongrui Wang, Saumil Joshi, Sergey Savel'ev, Wenhao Song, Rivu Midya, Yunning Li, Mingyi Rao, Peng Yan, Shiva Asapu, Ye Zhuo, Hao Jiang, Peng Lin, Can Li, Jung Ho Yoon, Navnidhi K. Upadhyay, Jiaming Zhang, Miao Hu, John Paul Strachan, Mark Barnell, Qing Wu, Huaqiang Wu, R. Stanley Williams, Qiangfei Xia & J. Joshua Yang, "Fully memristive neural network for pattern classification with unsupervised learning", Nature Electronics, vol. 1, no. 2, pp. 137-145, Feb. 2018, doi: 10.1038/s41928-018-0023-2.

[21] Rivu Midya, Zhongrui Wang, J W Zhang, Sergey Savelev, Can Li, Mingyi Rao, Moon Hyung Jang, Saumil Joshi, Hao Jiang, Peng Lin, Kate J Norris, Ning Ge, Qing Wu, Mark Barnell, Zhiyong Li, Huolin L Xin, R Stanley Williams, Qiangfei Xia, Jianhua Yang, "Anatomy of Ag/Hafnia-Based selectors with 1010 nonlinearity", Advanced Materials, vol. 29, no. 12, pp. 1604457, 2017, doi: 10.1002/adma.2016.04457.

[22] Xumeng Zhang, Wei Wang, Qi Liu, Xiaolong Zhao, Jinsong Wei, Rongrong Cao, Zhihong Yao, Xiaoli Zhu, Feng Zhang, Hangbing Lv, Shibing Long, Ming Liu, "An artificial neuron based on a threshold switching memristor", IEEE Electron Device Lett., vol. 39, no. 2, pp. 308-311, Feb. 2018, doi: 10.1109/led.2017.278275.