Analysis and modeling of resistive switching mechanisms oriented to resistive random-access memory*

Huang Da(黄 达)[a)b)†], Wu Jun-Jie(吴俊杰)[b)], and Tang Yu-Hua(唐玉华)[b)]

[a)] State Key Laboratory of High Performance Computing, National University of Defense Technology, Changsha 410073, China
[b)] School of Computer, National University of Defense Technology, Changsha 410073, China

(Received 14 May 2012; revised manuscript received 21 August 2012)

With the progress of the semiconductor industry, the resistive random-access memory (RAM) has drawn increasing attention. The discovery of the memristor has brought much attention to this study. Research has focused on the resistive switching characteristics of different materials and the analysis of resistive switching mechanisms. We discuss the resistive switching mechanisms of different materials in this paper and analyze the differences of those mechanisms from the view point of circuitry to establish their respective circuit models. Finally, simulations are presented. We give the prospect of using different materials in resistive RAM on account of their resistive switching mechanisms, which are applied to explain their resistive switchings.

Keywords: resistive random-access memory, resistive switching mechanism, circuit model

PACS: 84.32.–y, 89.20.Ff, 84.37.+q **DOI:** 10.1088/1674-1056/22/3/038401

1. Introduction

With the increasing requirements of the speed and capacity of data storage, the traditional dynamic random-access memory (DRAM) encounters its inherent bottleneck. Magnetic RAM, resistive RAM, and phase RAM all could potentially replance DRAM. Compared to magnetic RAM and phase RAM, the resistive RAM has the advantages of programming power and cost-per-cell size.[1] In 2010, the HP lab announced its cooperation with the Hynix company to produce memristor memory, which has the same cost performance as flash, in 2013. Samsung, Panasonic, Fujitsu, as well as the European Interuniversity Microelectronics Center (IMEC) have invested effort in the research of resistive RAM based on memristors since 2010. Choosing the best performing material is key in the research of resistive RAM. The material should have the following characteristics: high ratio of on/off resistance, long duration of maintaining the resistance, and outstanding endurance. Because the structure of resistive RAM is composed of word lines and bit lines in the vertical and the horizontal directions, the reading of the memory cell is likely to be affected by nearby cells that are in low resistance states. As a result, each cell has a rectification effect. Due to applying voltage on the memory cells to read data, the threshold effect of both voltage and current is required. In summary, a high-performance material with resistive switching should possess the characteristics above.

Zhao *et al.*[2] prepared Ag/ZnO/Zn/Pt structure resistive switching devices by radio-frequency magnetron sputtering. Their devices exhibited a good retention property, and the operation voltages were very low: –0.3 V/–0.7 V (off state) and 0.3 V (on state). Xing *et al.*[3] studied the electric-pulse-induced resistive switching effect in $Ti_{0.85}Cr_{0.15}O_x$ (TCO) films grown on Ir–Si substrates by pulsed laser deposition. Such a TCO device exhibited bipolar switching behavior with an electric-pulse-induced resistance ratio as large as 1000% and a threshold voltage smaller than 2 V. Li *et al.*[4] fabricated a WO_3-based resistive random access memory device composed of a thin film of WO_3 sandwiched between a copper top electrode and a platinum bottom electrode by electron beam evaporation at room temperature. That Cu/WO_3/Pt memory device had the characteristics of reproducible resistive switching, low power consumption, multilevel storage possibility, and good data retention. However, at present, no material or device shows absolute predominance in the performance of resistive RAM.

Using an equivalent circuit model to analyze the characteristics of a real experiment is commonly found in physical research. For example, Pan *et al.*[5] constructed the equivalent circuit for the LC resonance giant magneto-impedance effect, and they verified the correctness of the proposed equivalent circuit through a comparison of the circuit simulation results with the real experimental data. Hu *et al.*[6] used an equivalent circuit model to study the SiGe heterojunction bipolar transistor (HBT), the Pspice simulation results of the study provided an important theoretical guidance to the real experiment. There are many studies in the field of building different spice circuit models[7] for different kinds of materials with resistive switching to be fitted with the experimental data, while few works focus on building the equivalent circuit model cor-

*Project supported by the National Natural Science Foundation of China (Grant No. 60921062).
†Corresponding author. E-mail: huangda1109@163.com
© 2013 Chinese Physical Society and IOP Publishing Ltd

responding to the physical characteristics. We discuss the resistive switching mechanisms in our current research. Based on those mechanisms, appropriate circuit models have been established and simulations are performed. In addition, we have estimated different materials used in resistive RAM by studying their resistive switching mechanisms.

2. The memristor and its research

Similar to memristors, the characteristic of resistive switching is changing its resistance by an external voltage or current excitation and maintaining its resistance when the excitation disappears. The material with the characteristic of resistive switching can be applied in resistive RAM. We analyze the characteristic from the circuit schematic. Here V is defined as the voltage, i is defined as the current, and $R(x)$ stands for the resistance of the memristor. When the excitation is a current, we have

$$V = R(x)i, \quad \frac{\mathrm{d}x}{\mathrm{d}t} = i. \tag{1}$$

When the excitation is the voltage,

$$V = R(x)i, \quad \frac{\mathrm{d}x}{\mathrm{d}t} = V. \tag{2}$$

Simplifying the two equations, we get

$$x = it + c, \quad x = Vt + c, \tag{3}$$

where c is a constant.

Then q is defined as the electric charge, and φ is defined as the magnetic flux. Because $\int i\,\mathrm{d}t = q$ and $\int V\,\mathrm{d}t = \varphi$, so if the excitation is the current, the resistance is effected by q as follows:

$$V = R(q)i. \tag{4}$$

When the excitation is the voltage,

$$V = R(\varphi)i. \tag{5}$$

When the excitation is the current, the material's resistance with resistive switching is changed by the electric charge, and when the excitation is the voltage, it is changed with the magnetic flux. In fact, due to the material with resistive switching lacking capacitive and inductive characteristics, both voltage and current affect its resistance. In other words, both the electric charge and the magnetic flux change the resistance. We get

$$V = R(q, \varphi)i. \tag{6}$$

In 1971, Leon[8] predicted the existence of the fourth component in a circuit, the memristor, which links the electric charge to the magnetic flux in four variables of voltage, current, magnetic flux, and electric charge. The memristance M is given in

$$\mathrm{d}\varphi = M\,\mathrm{d}q. \tag{7}$$

Because the magnetic flux is the time integral of the voltage, and the electric charge is the time integral of the current. The memristance has the same unit as the resistance. Through comparing the memristance in the formula above with the description of a material with resistive switching, we find that they are twins. Published in 2008, HP labs found resistive switching in the structure of Pt/TiO_2/Pt, which is true to the principle of a memristor.[9] Based on the analysis of the characteristics of resistive switching, the boundary drift model was proposed to simulate the actual physical processes. In fact, bipolar resistive switching (BRS) and unipolar resistive switching (URS) behaviors in Pt/27 nm thick TiO_2/Pt stacks were found in 2007.[10] However, it was HP labs who related their result with the previous mathematical model of a memristor. After that, the application of the memristor was not limited to resistive RAM, but extended to neural network computation, chaos circuit design, FPGA design, CAM design, and so on.

3. Analysis of resistive switching

Two kinds of resistive switchings have been found in materials. They are bipolar resistive switching and unipolar resistive switching.[11] A URS, V_{reset} which transforms the low resistance state (LRS) into the high resistance state (HRS), has the same polarity as V_{set} which transforms the HRS into the LRS. Besides, $V_{\mathrm{reset}} < V_{\mathrm{set}}$. In BRS, we usually find (see Fig. 1)

$$V_{\mathrm{reset}} < 0, \quad V_{\mathrm{set}} > 0. \tag{8}$$

Some studies have concentrated on materials with resistive switching, such as SiO_2, NiO, ZrO_2, TiO_2, perovskite, and organic synthetic materials. The materials usually used as electrodes in the structure of metal–insulator–metal (MIM) include Pt, Au, Cu, Ni, W, Al, and TiN.[12] Choosing different kinds of electrodes and using different materials with different doped materials leads to different conductive mechanisms. This section discusses several resistive switching mechanisms.

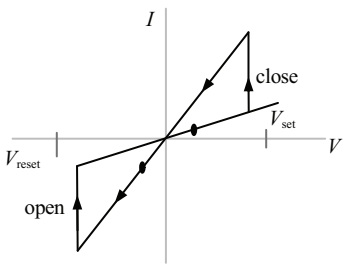


Fig. 1. The I–V curve of BRS.

3.1. Boundary drift model

HP labs believed that +2 oxygen vacancies in TiO_2 and TiO_{2-x} drift up and down in the electric field formed by positive and negative voltages applied on the electrodes.[9] In the structure of Pt/TiO_{2-x}/Pt, two conductive parts in series are separated, which have different resistances. Due to the drifting of +2 oxygen vacancies, the boundary of the two parts moves, making the overall resistance switching.

This model actually explains the BRS reasonably, but it does not work with the URS. In addition, TiO_2 and TiO_{2-x}, which have the supposed boundaries, are evenly distributed along the direction of up and down electrodes. The process of boundary drifting is supposed to be continuous. In fact, the distributions of TiO_2 and TiO_{2-x} are not so uniform.

3.2. Filament conducting

Different from the boundary drift model, both BRS and URS can be explained by thermo-chemical and valence-change mechanisms with the filament model. With the excitation of voltage or current, inside the material more conductive filaments are formed whose resistance is several orders of magnitude smaller than the original material. When these filaments are connected to both electrodes, the material is in the LRS. When they are disconnected, it will change into the HRS.

For URS, thermo-chemical mechanisms with filament conducting can explain the resistive switching. First of all, filaments are formed by a high voltage with current limitation. This process is generally called the forming process. Now the material is in the LRS. With the applied voltage reaching $V_{\rm reset}$ ($V_{\rm reset} < V_{\rm set}$), a large current causes Joule heat, which makes the filaments disconnected. At this time, the material is in the HRS. When the voltage reaches $V_{\rm set}$ with current limiting, the filaments are re-connected. For BRS, the filaments are composed of valent ions. For example, filaments in Ref. [13], which may be the reason for resistive switching, are composed of oxygen vacancies in ZrO_2. When the positive voltage $V_{\rm set}$ is applied, due to the filaments composed of oxygen vacancies, the material is in the LRS. When the negative voltage $V_{\rm reset}$ is applied, it shows a high resistance because of the disconnected filaments. The difference between filament conducting and boundary drift models is that the filaments instead of the proportion of TiO_2 and TiO_{2-x} cause the resistance switching.

3.3. Ion migration

When Ag,[14] Cu are used as the electrode, Cu_2S, Ag_2S, GeSe are used as the main materials, and Cu, Au[15] are used as the doping materials, the resistive switching is usually explained by the ion migration. The initial resistance of the main materials is high, and it turns to low when the conductive pathway made of Cu or Au ions generated from the doping materials is formed. The ions will be restored to atoms at the other end of the electrode. In this model, the electrodes play a considerable role in the process of ion migration for providing and receiving atoms. The ion migration is similar to the filament conducting in the conductive mechanism, the difference is the process of actual ion migration by electrochemical reaction.

3.4. Schottky barrier model

It is believed that the contact between the electrode and the material plays a major role in resistive switching while the other parts of the material contribute little in this model. The Schottky barrier comes into being when the metal electrode and the material as a whole have the same Fermi level in thermal equilibrium. A potential barrier is formed at the contact surface, and when the electrons from the material to the metal electrode or vice versa should overcome the barrier. This barrier is affected by the voltage on the electrodes. When a positive voltage is applied on the electrode, the barrier falls, while when a negative voltage is applied, it rises. This model[16] can explain the characteristics of BRS. The Schottky barrier can be seen as a voltage-controlled resistor in series which changes with the applied voltage. The change of resistance causes the overall resistive switching. However, it is not useful for URS. In fact, different materials with different doped materials may cause the Schottky barrier, which plays a part or all of the role in resistive switching yet to be confirmed.

3.5. Trap charging and discharging

Inside many kinds of materials, there are irregular positive traps, particularly when they are doped with different materials. Electrons come into the dielectric material with the applied voltage, and they are captured by the traps. The electric field formed by the trapped electrons will affect the conducting, so the overall resistance rises. When the traps release electrons, making the formed electric field weaken, the overall resistance reduces. It is different to how the applied voltage affects electrons entering and jumping traps when different materials and different doped materials are chosen.

3.6. Space-charge-limited conduction[17]

Defects as well as grain boundaries (e.g., oxygen vacancies in TiO_2) have their own electric fields. These fields have impacts on the electronic transmission. The space-charge-limited conduction (SCLC) mechanism was proposed in 1940. With further research, many improved models were proposed. It is believed that the conduction should be divided into four sections. The first is the Ohm conduction in the HRS (low applid voltage state). The second section is the trap center, in which the trap (mentioned as defects and grain boundaries) attracts sufficient electrons so the electron center is formed impeding the electronic transmission, as a result, it is in the HRS.

The third section is trap-filled limited, in which the untrapped electrons can no longer be attracted by the trap, so the resistance is slightly lower. The fourth section is trap-free, in which not only the untrapped electrons can no longer be attracted but also the trapped electrons, so the formed center disappears, as a result, it is in the LRS. In this section, the applied voltage is $V_{\rm set}$. Compared to trap charging and discharging, the initial state is HRS in this model, while it is LRS in trap charging and discharging.

Besides the six resistive switching mechanisms mentioned above, there are other models to explain different materials with different doping materials. In fact, not only the material and the doping material selected, but also the chosen electrode and the thickness of the main material may lead to different mechanisms.[18] Much effort has been invested in analyzing from the view point of electrochemical and physical principles. In this paper, we try to analyze the differences of these mechanisms from the view point of circuitry to establish their respective circuit models.

4. Circuit analysis of resistive switching

Through the analysis of the mechanisms in the previous section, we know that the internal electrochemical or physical changes cause the overall resistance changing. From the circuit analysis, the changing part of resistance $R_{\rm x}$ and the fixed part of resistance $R_{\rm t}$ have different distributions, typically in the relationships of series and parallel, as shown in Fig. 2.

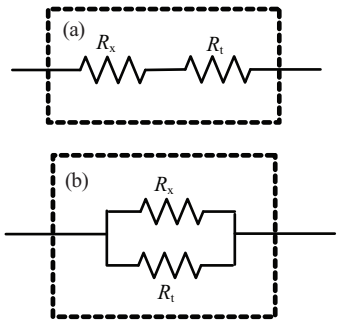


Fig. 2. Schematic diagrams of (a) series and (b) parallel resistive switching circuits.

The boundary drift model uses the circuit model in series in Fig. 2(a). It is believed that

$$R_{\rm total} = R_{\rm on}\frac{\omega(t)}{D} + R_{\rm off}\left(1 - \frac{\omega(t)}{D}\right), \tag{9}$$

where $R_{\rm on}$ and $R_{\rm off}$ represent the resistances of TiO_{2-x} and TiO_2, respectively. The order of magnitude of on–off ratio is usually larger than three, and the equivalent series resistance in the circuit model is

$$R_{\rm t} = 0, \quad R_{\rm x} \in [0, R_{\rm off}], \tag{10}$$

where $R_{\rm x}$ is the resistance of the formed filament, and $R_{\rm t}$ is the resistance of the original material.

From the circuit analysis, the filament conducting has a different circuit model. The resistance of the original dielectric material is high, and the resistance of the filament is low. The two parts are in parallel, and the overall resistance is $R = R_{\rm x}R_{\rm t}/(R_{\rm x} + R_{\rm t})$.

In LRS, we have

$$R_{\rm on} = \left.\frac{R_{\rm x}R_{\rm t}}{R_{\rm x} + R_{\rm t}}\right|_{R_{\rm x} \ll R_{\rm t}} \approx R_{\rm x}. \tag{11}$$

When the filament is disconnected, we have

$$R_{\rm off} = \left.\frac{R_{\rm x}R_{\rm t}}{R_{\rm x} + R_{\rm t}}\right|_{R_{\rm x} \approx R_{\rm t}}, \tag{12}$$

at this time, $R_{\rm x}$ has the same order of magnitude with $R_{\rm t}$.

Similar to filament conduction, the ion migration model is suited to the circuit model in parallel. In addition, the actual structure of filaments or ion conductive pathways is not necessarily geometrically regular, there are many nodes, blobs, and links between filaments.[19] In the circuit model in parallel, the definition of $R_{\rm x}$ refers to the entire resistance of filaments or ion conductive pathways, and therefore it is applicable.

The Schottky barrier model, the trap charging and discharging model, as well as the SCLC model are different, but in fact they are suited to the circuit model in series. It is believed that the resistance change of the interface plays a major role in resistive switching in the Schottky barrier model. The relationship between the interface and the intermediate part of the material is in series, and it is similar to a variable resistor in series which is controlled by the applied voltage. Due to the changed electric fields inside the models of trap charging and discharging and SCLC, the changes of electron conduction lead to resistive switching. It can still be seen as a variable resistor in series, which is related to the changed electric field.

In summary, resistive switching is caused by proportion changes of the conductive and the less conductive parts in the above mechanisms, and these changes are in the physical or chemical structure of the material. It can be modeled that the distribution of a resistor in series or parallel is fixed only the variable resistor changes with the applied voltage.

For the variable resistor $R_{\rm x}$, we have

$$V = R_{\rm x}(q, \varphi)i. \tag{13}$$

We define $R_{\rm x}(q, \varphi)$ as a function related with resistive switching. In further analysis, the resistive switching function should satisfy

$$\dot{R}_{\rm x} = f(u, i, t), \tag{14}$$

where u and i denote the voltage and the current at time t, respectively. Function f represents the change related to the excitation of voltage and current as well as time t. Function f used in different mechanisms is similar, while it has different

parameters and different distributions of resistors in series or parallel.

To accord with real physical or chemical changes, different mechanisms may be the combinations of both resistors in series and parallel in circuit modeling. There are two methods to simplify the model. One is the equivalent transformation of the circuit. We can equivalently transform the value of changeless resistor R_t so the circuit is transformed from a complex circuit to resistors in series or parallel without changing the variable resistor R_x. The other is choosing the dominant distribution of resistors and modeling with resistors in series or parallel. In the remainder of this section, simulations of the differences of resistors in series or parallel in resistive switching will be present.

For the BRS in Fig. 1, the main difference with voltage-controlled resistor in the I–V characteristics is the memory of the original state. For instance, in the region from –2 V to 2 V in Fig. 1, it can be in the HRS or the LRS, which differs from the voltage-controlled resistor, while in other regions we can use it instead.

In the environment of Hspice, we use the existing model and the parameters of a memristor[20] to represent function f and the corresponding parameters. This experiment is used to show the difference of the distributions of resistors in series or parallel by simulating the memristor in series or parallel with a real resistor. The value of resistor is $R = 10^7\ \Omega$, the I–V curve of simulation is shown in Fig. 3.

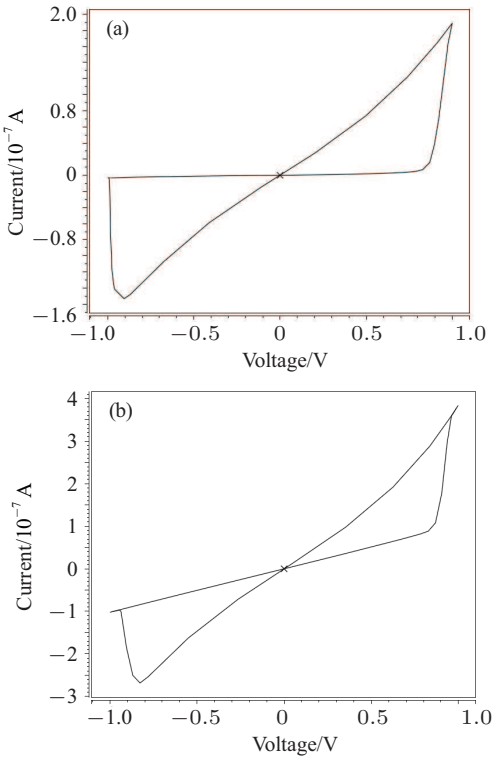


Fig. 3. The I–V curves of the distributions of (a) series and (b) parallel with the same parameters.

It can be seen that the distribution of series is dominant in the ratio of on/off resistance by using the same function f and the same parameters. Since the resistance of the distribution of series is higher than that of parallel, the average current of series is smaller, which requires lower power of reading and writing data by using the same voltage.

5. Conclusions

Materials used in resistive RAM should meet practical requirements in several important aspects. The first is the retention time of data, which is the key characteristic of non-volatile memory. The second is endurance. The third is the threshold effect and the rectification effect demanded by the structure of resistive RAM. The retention time of data and the endurance depend on the experimental preparation of different materials with different parameters. It is difficult to estimate their advantages and disadvantages by considering the resistive switching mechanisms, while the threshold effect and the rectification effect can be presumed broadly by the mechanisms. The excitation in the boundary drift model is the electric field caused by the applied voltage, and different boundary represents different resistance. With a different positive or negative voltage, the boundary drifts in a different direction. So the threshold effect and the rectification effect do not exist. In the filament conducting model, it is the same with the rectification effect. For URS, it should have the threshold effect by thermo-chemical mechanisms for the Joule heat causing the filaments to disconnect, which cannot be generated by the voltage below threshold. In ion migration, the conducting process relates to the doping materials and the materials of electrodes. As a result, the endurance should be similar.

In summary, the study of resistive switching mechanisms is one of the important areas of research on resistive RAM.[21] That is because high reliable resistive RAM should be produced with the theoretical basis of mechanisms. In this paper, we discuss the different characteristics of resistive switching mechanisms and analyze the differences of those mechanisms from the view point of circuitry. The corresponding circuit models are established, and simulations are performed. This work provides a basis for further simulation and validation of the characteristics of different resistive switching mechanisms.

References

[1] Wang Y, Jia S and Gan X W 2011 *Acta Scientiarum Naturalium Universitatis Pekinensis* **47** 565 (in Chinese)
[2] Zhao J W, Liu F J, Huang H Q, Hu Z F and Zhang X Q 2012 *Chin. Phys. B* **21** 065201
[3] Xing Z W, Chen X, Wu N J and Ignatiev A 2011 *Chin. Phys. B* **20** 097703
[4] Li Y T, Long S B, Lu H B, Liu Q, Wang Q, Wang Y, Zhang S, Lian W T, Liu S and Liu M 2011 *Chin. Phys. B* **20** 017305
[5] Pan H L, Cheng J K, Zhao Z J, He J K, Ruan J Z, Yang X L and Yuan W Z 2008 *Acta Phys. Sin.* **57** 3230 (in Chinese)

[6] Hu H Y, Zhang H M, Lu Y, Dai X Y, Hou H, Ou J F, Wang W and Wang X Y 2006 *Acta Phys. Sin.* **55** 403 (in Chinese)
[7] Biolek Z, Biolek D and Biokova V 2009 *Radioengineering* **18** 210
[8] Chua L 1971 *IEEE Trans. Circuit Theory* **CT-18** 507
[9] Stanley W R 2008 *IEEE Spectrum* **45** 28
[10] Jeong D S, Schroeder H and Waser R 2007 *IEEE Spectrum* **10** G51
[11] Yang Y C, Pan F, Liu Q, Liu M and Zeng F 2009 *Nano Lett.* **9** 1636
[12] Li H S 2011 *Unipolar Resistive Switching Investigation of ZrO_2 and ZrO_2-NiO Dielectric Layer* (MS Thesis) (Taiwan: National Taiwan University of Science and Technology) (in Chinese)
[13] Li Y T, Long S B, Zhang M H, Liu Q, Shao L B, Zhang S, Wang Y, Zuo Q Y, Liu S and Liu M 2010 *IEEE Electron Device Letters* **31** 117
[14] Guo X, Schindler C, Menzel S and Waser R 2007 *Appl. Phys. Lett.* **91** 133513
[15] Schindler C, Thermadam S C, Waser R and Kozicki M N 2007 *IEEE Trans. Electron Devices* **54** 2762
[16] Lee M H, Kim K M, Kim G H, Seok J Y, Song S J, Yoon J H and Hwang C S 2010 *Appl. Phys. Lett.* **96** 219901
[17] Xia Y D, He W Y, Chen L, Meng X K and Liu Z G 2007 *Nano Lett.* **90** 022907
[18] Kim S H and Choi Y K 2009 *IEEE Trans. Electron Devices* **56** 3049
[19] Lee S B, Chae S C, Chang S H, Lee J S, Seo S, Kahng B and Noh T W 2008 *Appl. Phys. Lett.* **93** 212105
[20] Zhou J and Huang D 2012 *Chin. Phys. B* **21** 048401
[21] Li Y T, Liu M, Long S B, Liu Q, Zhang S, Wang Y, Zuo Q Y, Wang Q, Hu Y and Liu S 2009 *Micronanoelectronic Technology* **46** 134 (in Chinese)