Thermal effect on endurance performance of 3-dimensional RRAM crossbar array*

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(Received 23 December 2015; revised manuscript received 22 February 2016; published online 5 April 2016)

Three-dimensional (3D) crossbar array architecture is one of the leading candidates for future ultra-high density nonvolatile memory applications. To realize the technological potential, understanding the reliability mechanisms of the 3D RRAM array has become a field of intense research. In this work, the endurance performance of the 3D 1D1R crossbar array under the thermal effect is investigated in terms of numerical simulation. It is revealed that the endurance performance of the 3D 1D1R array would be seriously deteriorated under thermal effects as the feature size scales down to a relatively small value. A possible method to alleviate the thermal effects is provided and verified by numerical simulation.

Keywords: 3-dimensional resistive random access memory (RRAM), thermal effect, endurance performance

PACS: 65.60.+a, 66.30.Xj, 68.35.bg **DOI:** 10.1088/1674-1056/25/5/056501

1. Introduction

Resistive random access memory (RRAM) has attracted increasing attention as potential next-generation nonvolatile memory.[1–6] To achieve the increasing requirements for enormous data densities and nonvolatile storage, some new technologies of memory are of growing interest due to their significant potential for the replacing or complementing existing memory technology.[7–9] High density 3-dimensional (3D) integrated technology in RRAM, such as 3D 1D1R crossbar array (1D1R: one diode one RRAM), is a very promising candidate for future non-volatile memory integration applications, and also is one of the most effective methods to meet the requirement of ultra-high density and ultra-large data storage.[10–12] To compete with the ultra-high density 3D NAND FLASH, a technical modeling of the underlying physical mechanism during operation is very essential. The 1D1R cell usually displays unipolar switching (Set and Reset operation at the same voltage polarity), and the Reset process is controlled by Joule heat.[3,13–15] The physical understanding of the programming and reliability mechanisms in unipolar 1D1R array requires a detailed characterization of the electrical and thermal conduction properties of the memory cell.

It is well known that the Joule heat can result in the temperature increase of the device inside, which can induce the uneven distribution of thermal stress due to the different thermal expansion coefficients for different materials inside the device. Therefore, the Joule heating effect would seriously affect the stability, reliability, and life of semiconductor devices.[16–18] With the increase of the integration level in the 3D integrated RRAM device, which will sharply increase the storage unit number and chip area, the thermal effect caused by Joule heat will become more serious. Especially, with the improving of the storage cell density and hence the distance between the adjacent unit being reduced, the thermal crosstalk of neighboring units will seriously hinder the development and application of 3D integrated RRAM. Therefore, establishing a thermal effect model of 3D integrated RRAM will contribute to further promoting the development of 3D integrated RRAM devices.

In our previous work,[19] the degradation of retention performance under the thermal crosstalk effect and scaling potential of the 3D RRAM array have been systematically investigated. In the present work, we will consider another case, that is, the unit cell adds the electrode component between the RRAM and diode. For this case, with continuously scaling down the feature size, the electrode component will be reduced with the unit cell and finally become filamentous. Due to the filamentous nature of the electrode when the feature size is comparatively small, the thermal reliability of the electrodes should be seriously considered, which could strongly relate to the endurance performance of the integrated array. Otherwise, based on the simulation result, the endurance performance of

*Project supported by the Opening Project of Key Laboratory of Microelectronics Devices & Integrated Technology, Institute of Microelectronics of Chinese Academy of Sciences, the National High Technology Research and Development Program of China (Grant No. 2014AA032901), the National Natural Science Foundation of China (Grant Nos. 61574166, 61334007, 61306117, 61322408, 61221004, and 61274091), Beijing Training Project for the Leading Talents in S&T, China (Grant No. Z151100000315008), and the CAEP Microsystem and THz Science and Technology Foundation, China (Grant No. CAEPMT201504).

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the 3D crossbar array under the thermal effect is analyzed in detail. Possible methods to alleviate these thermal effects are also provided.

2. Theoretical model

To clearly describe the present work, we firstly establish the structure of the 3D integrated RRAM, as shown in Fig. 1. Figure 1(a) shows the schematics of the 1D1R crossbar array structure. Figure 1(b) reveals the unit cell components which are only composed of an RRAM cell (colored in blue) and a diode (colored in red) connected in series, as well as our previous work. In order to introduce the electrode effect, we add the electrode component based on the unit cell component in Fig. 1(b). Figure 1(c) shows the modified 1D1R structure within this work by introducing the electrode component (colored in brown) which connects the RRAM and diode components. Figure 1(d) shows the schematic diagram of typical DC *I*–*V* characteristic including set and reset operations for the 1D1R cell. Both set and reset occur at the same voltage polarity. Otherwise, voltage is applied to the electrode connected with the RRAM cell, while keeping the opposite electrode ground for the set/reset operations.

In our previous work,[19] the electrode connecting the RRAM and diode components is neglected (see Figs. 1(a) and 1(b)). Generally, the electrode area of the diode cell is usually larger compared to the conductive filament of the RRAM component, and the potential drop on the electrode, and hence the Joule heating process of the electrode could be ignored for the sake of simplicity. However, with the feature size scaling down (such as, < 100 nm), the electrode component will reduce and finally become filamentous. The reduced electrode may be comparable with the conductive filament in the RRAM cell, and could not be neglected as a result under the thermal effect, as schematically shown in Fig. 2.

Due to the filamentous nature of the electrode when the feature size is comparatively small, the thermal reliability of the electrode should be seriously considered, as well as the RRAM and diode. In order to clearly exhibit the change of the electrode in a smaller size, we describe the degradation mechanisms of electrode structure, as shown in Fig. 3. The electrode component could be destroyed by Joule heat during the reset transition. However, differing from the conductive filament in the RRAM cell, the destroyed electrode component could not be rehabilitated by "set operation", since the electrode is a kind of metal, such as Pt, Ag, etc. Therefore, the destroyed electrode would deteriorate the operation life time (i.e., endurance performance) of the cross-point array.

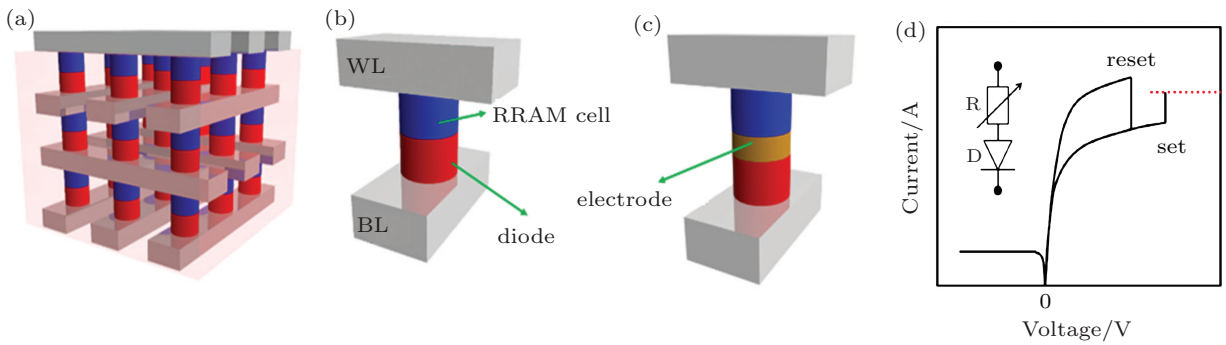


Fig. 1. (color online) (a) Schematic of the 1D1R crossbar array structure; (b) the unit cell composed of a RRAMdevice and a diode connected in series; (c) the unit cell added the electrode component based on the unit cell component in panel (b); and (d) schematic diagram of typical DC *I*–*V* characteristic of a 1D1R cell. In the present work, voltage is applied to the electrode (WL/BL: word lines (WL), bit lines (BL)) that is connected with RRAM cell while keeping the opposite electrode ground for the reset operation.

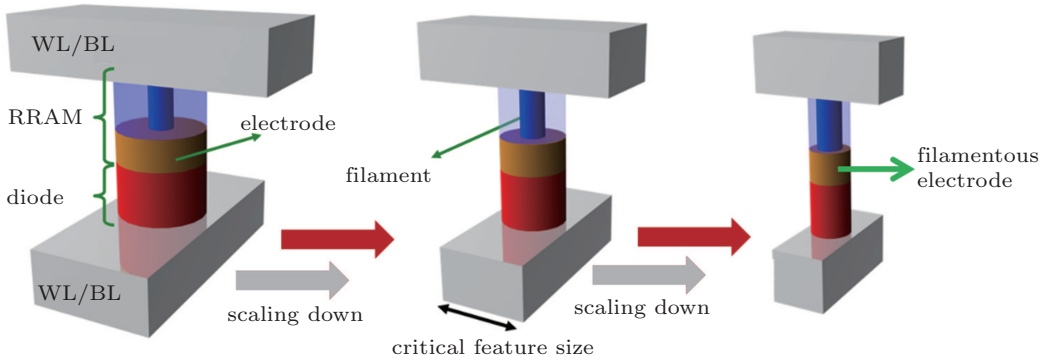


Fig. 2. (color online) Schematics of the 1D1R cell with continuously scaling down the feature size. Electrode component (colored in brown) between the RRAM and diode cells will become filamentous.

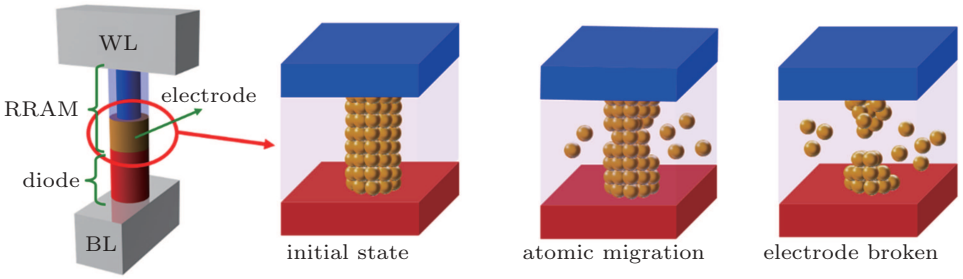


Fig. 3. (color online) Schematics of the 1D1R unit and the degradation mechanisms of electrode structure.

To estimate the operation life time of the cross-point array, the Arrhenius law is usually used as[20,21]

$$t_{\text{life time}} = t_0 \, \mathrm{e}^{qE_\mathrm{a}/kT}, \tag{1}$$

where $t_{\text{life time}}$ is the life time of the electrode component, t_0 is the pre-exponential constant (here $t_0 = 1$ ns), q is the elementary charge, k is the Boltzmann's constant, and E_a is the activation energy of the metal atoms to migrate in isolation material around the electrode region. Here, the life time of the electrode component with $E_\mathrm{a} = 1.5$ eV under $T = 400$ K is assumed to be 10 years. Figure 4 shows the theoretically calculated life time of the electrode component with various activation energy E_a. One can see that the life time of the electrode increases with the increase of activation energy. Since the activation energy is responsible for the atomic migration ability, using the metal with larger activation energy could enhance the operation life time of the electrode component.

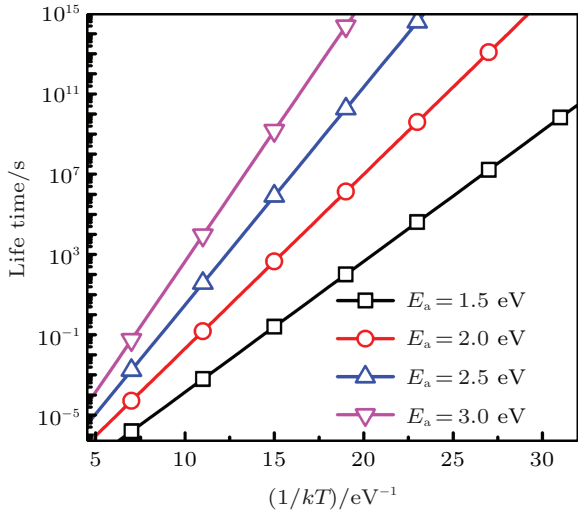


Fig. 4. (color online) Arrhenius plot of the life time of the electrode component for different activation energy. Here, the life time with $E_\mathrm{a} = 1.5$ eV under $T = 400$ K is assumed to be 10 years.

Then, the temperature evolution maps of the cross-sections are simulated in the array structure with the electrode connecting the RRAM and diode components, based on 3D Fourier heat flow equation, expressed as

$$\nabla k_{\text{th}} \nabla T + \sigma |\nabla V|^2 - c\rho \frac{\partial T}{\partial t} = 0, \tag{2}$$

where T is the temperature, k_{th} is the thermal conductivity, c is the thermal capacity, ρ is the mass density of the material in the crossbar array system, V is the imposed voltage, t is the time, and σ is the electric conductivity with the empirical expression as

$$\sigma = \sigma_0/(1 + \alpha(T - T_0)), \tag{3}$$

where α is the temperature coefficient of theresistivity and σ_0 is the electric conductivity at room temperature T_0. Word lines (WL) or bit lines (BL) in the top and bottom layers of 3D array system are assumed to connect with the ideal heat dissipation packaging structure and keep at room temperature T_0 during the calculation, as

$$T - T_0|_{\text{BC}} = 0. \tag{4}$$

3. Results and discussion

The array structure with various sizes from $3 \times 3 \times 1$ to $3 \times 3 \times 3$ block array, respectively, is shown in Figs. 5(a)–5(c), at which the Pt electrode component (thickness is 30 nm, and radius is 12 nm) connects the RRAM and diode. Figure 5(d)–5(f) illustrates the temperature evolution maps of the cross-sections (blue planes) in Figs. 5(a)–5(d). Here the critical feature size used for analysis is 30 nm. The other input parameters are the same as those in Ref. [19]. The programmed cells are connected with the diodes in green color (on state). Otherwise, the electrode can be treated as a metallic conductive filament, being similar to our previous work based on the Arrhenius plot used to evaluate the endurance performance under the thermal effect.[19] By connecting the temperature at $t = 50$ ns in the electrode of the programmed bit and the characteristic reset time t_{reset}, endurance cycles $n_{\text{endurance}}$ can be described as

$$n_{\text{endurance}} = t_{\text{life time}}/(t_{\text{reset}} - 50 \text{ ns}), \tag{5}$$

which corresponds to a sequence of $n_{\text{endurance}}$ program/erase pulses, t_{reset} is the typical reset time of RRAM equal to 100 ns.[19] In other words, the thermal effect deteriorates the reliability of the electrode component which serves as the interconnections between the RRAM and diode in the 1D1R

unit, and the 1D1R unit may no longer function due to the failure of electrode structure after the consecutive program/erase cycles of $n_{\text{endurance}}$. Here, the self-heating effect due to the application of a set pulse to the programmed bit is neglected, since the temperature is far lower than that in the reset case due to the lower programming current. The highest temperatures at $t = 50$ ns in the electrode region of the programmed cells are 667 K, 705 K, and 910 K, respectively. The corresponding electric resistivity of electrode components is referenced from Pt interconnects (width: ∼30 nm).

By connecting Eqs. (1) and (5), the endurance performance of the programmed cellcan be calculated. Figure 6 shows the estimation of the endurance performance of the programmed cell for different array blocks in Fig. 5. The same evaluation method in terms of the Arrhenius plot in Fig. 4 is adopted. As can be seen from Fig. 6 that, with $E_a = 1.5$ eV, the electrode cell would be destroyed after 1×10^8 consecutive program/erase cycles due to the thermal effect (maximum endurance is 1×10^8 cycles).

Degradation of the electrode is mainly attributed to the metal atom dissipation to the surrounding isolation material. The adoption of the isolation material around the electrode region with higheractivation energy E_a of metal atom migration, which could suppress the dissipation of the electrode material under the Joule heating effect, is a possible method to increase the array endurance performance. As shown in Fig. 6, with the activation energy E_a increasing from 1.5 eV to 3 eV, the endurance performance can be increased by orders of magnitude (e.g., 10 orders of magnitude from 1×10^7 cycles to 1×10^{17} cycles for the $3 \times 3 \times 3$ array block).

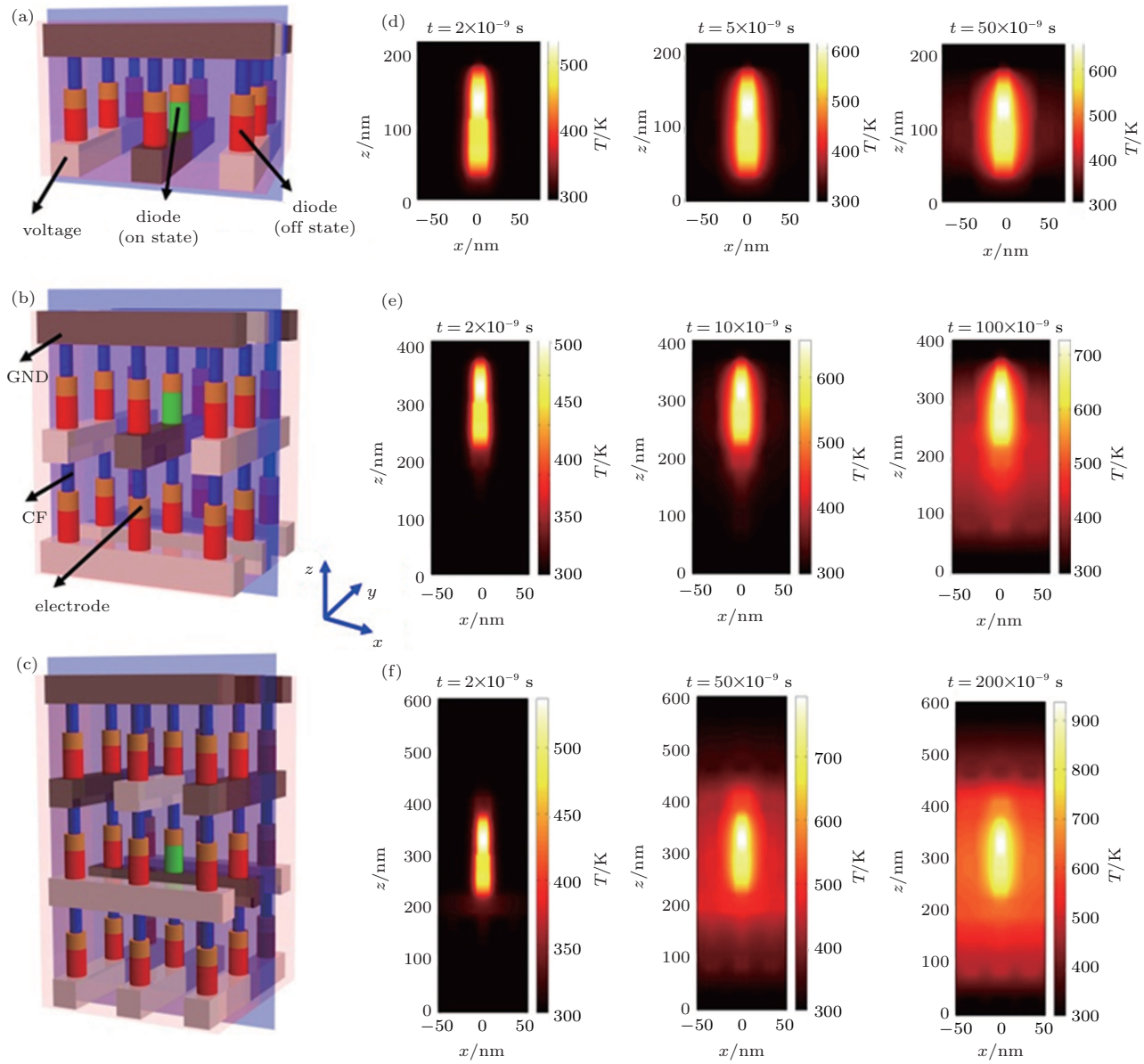


Fig. 5. (color online) (a)–(c) Schematics of the array structure including the Pt electrode component with various sizes from $3 \times 3 \times 1$ to $3 \times 3 \times 3$ block array, respectively. (d)–(f) Temperature maps of the cross-sections (blue planes) in (a)–(c). The programmed RRAMs are connected with diodes in green color.

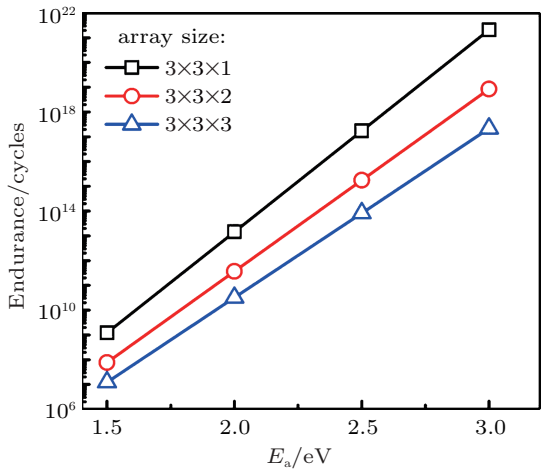


Fig. 6. (color online) Calculated endurance dependence on E_a of different array blocks with $3\times3\times1$, $3\times3\times2$, and $3\times3\times3$ array size, respectively.

4. Conclusion

The endurance performance under the thermal effect of the 3D RRAM array was analyzed in detail based on the numerical simulation, which originates from the thermal reliability degradation of the electrode component at relative small feature size. Based on the proposed theoretical methods, with array size increasing, the thermal effect on the endurance performance gets more severe. Using isolating material with higher activation energy of metal atom migration around the electrode material region could increase the endurance characteristics of the array and hence further promote the scaling potential. The simulated results reveal that with the activation energy E_a increasing from 1.5 eV to 3 eV, the endurance performance can be increased by 10 orders of magnitude.

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