Investigating the Temperature Effects on ZnO, TiO₂, WO₃ and HfO₂ Based Resistive Random Access Memory (RRAM) Devices


1 Computational Electronics and Nanoscience Research Laboratory, School of Nanoscience and Biotechnology, Shivaji University, Kolhapur, 416004, India
2 Department of Chemistry, Shivaji University, Kolhapur, 416004, India
3 Department of Physics, Shivaji University, Kolhapur, 416004, India
4 Department of Electronics, Shivaji University, Kolhapur, 416004, India

(Received 18 June 2016; published online 29 November 2016)

In this paper, we report the effect of filament radius and filament resistivity on the ZnO, TiO₂, WO₃ and HfO₂ based Resistive Random Access Memory (RRAM) devices. We resort to the thermal reaction model of RRAM for the present analysis. The results substantiate decrease in saturated temperature with increase in the radius and resistivity of filament for the investigated RRAM devices. Moreover, a sudden change in the saturated temperature at a lower value of filament radius and resistivity is observed as against the steady change at the medium and higher value of the filament radius and resistivity. Results confirm the dependence of saturated temperature on the filament size and resistivity in RRAM.

Keywords: RRAM, Thermal reaction model, Reliability, Nanoelectronics.

DOI: 10.21272/jnep.8(4(1)).04030 PACS numbers: 73.22. – f, 07.05.Tp.

1. INTRODUCTION

The Resistive Random Access Memory (RRAM) is considered to be a strong candidate which is poised to substitute the conventional flash memories [1]. The RRAM have several advantages over its other counterparts, for instance, high density of data storage, long data retention, low operating voltage, high endurance, fast switching speed and compatibility with conventional CMOS process and so on [1-2]. Generally, physical and chemical mechanism of RRAM is classified in terms of Valency Change Mechanism (VCM) [3-5], Electro-Chemical Metallization (ECM) [6], Thermo-Chemical Mechanism (TCM) [7], Phase Change Mechanism (PCM) [8], and Electrostatic/Electronic Mechanism (EEM) [9] etc. In above all mechanism the resistance of the RRAM switches between two resistance states viz. low resistance state (LRS) and high resistance state (HRS) [10-11]. The popular version of RRAM is known as a memristor which is modeled around the valency change mechanism [12-15].

Temperature plays an important role in resistive switching and many studies have been devoted to finding out the underlying physical mechanism and its effect on memory performance. Recently Shang et al. reported the heterostructure based thermally stable transparent RRAM. The reported device exhibits forming-free bipolar resistive switching behavior at room temperature with good memory performance [16]. Wang et al. reported the thermoelectric Seebeck effect in oxide-based resistive switching memory. They have investigated the intrinsic electronic transport mechanism by measuring thermoelectric Seebeck effects [17]. Yi et al. reported the effect of annealing temperature on graphene oxide-based RRAM. Their results are evident that the lower annealing temperature improves the memory performance of graphene oxide-based RRAM [18]. Fang et al. reported low-temperature switching characteristics and conduction mechanism of HfOx based RRAM. The results suggested that at a lower temperature the switching voltage increases [19]. Tsuruoka et al. reported the effect of temperature on Cu–Ta₂O₅-based atomic switch and investigated the switching mechanism of the developed device. The results reveal that SET and RESET voltage decreases as the temperature increases [20]. Sato et al. reported the thermal reaction model of the metal oxide-based RRAM. This model calculates the temperature of the conductive filament and its corresponding effect on RRAM performance [21].

The present manuscript reports investigations of temperature effect on ZnO, TiO₂, WO₃ and HfO₂ based RRAM devices using thermal reaction model reported in the ref. [21]. The rest of the paper is as follows, after a brief introduction in the first section, the second section deals with the overview of thermal reaction model of RRAM and other computational details. The third section deals with the effect of filament radius and resistivity on the saturated temperature of ZnO, TiO₂, WO₃ and HfO₂ based RRAM devices. At the end conclusion is portrayed.

2. THERMAL REACTION MODEL OF RRAM

The temperature of the conductive filament plays an important role in the resistive switching. It is observed that the high current density present in the conductive filament and the aftermaths of temperature effects are unavoidable [22]. Hence, the analysis of temperature effect is of foremost important. Fig. 1 represents the cross-sectional view of the thermal reaction model [21].
The model assumes the cylindrical conducting path present in the active layer (oxidation membrane) of the RRAM. The heating temperature $\Delta T$ can be represented as [21],

$$\Delta T = \frac{1}{(K_r + K)} \frac{V_{\text{reset}}^2}{R}$$  

where, $V_{\text{reset}}$ is the RESET voltage of RRAM, $R$ is a resistivity of the filament, $K_r$ is known as the radial thermal conductance of oxidation membrane and $K$ is the filament thermal conductance and they are given as [21],

$$K_r = \frac{2\pi k'r^4/4}{\log(r_i/r_f)}$$

$$K = \frac{kr_i^2}{1/2}$$

where $k'$ and $k$ are the thermal conductivities of the materials, $r$ is a thickness of oxidation membrane, and $r$ is the radius of the conductive filament. Table 1 represents the various physical parameters for simulation of different RRAM structures.

### Table 1 – Simulation parameters for various RRAM devices

<table>
<thead>
<tr>
<th>MTO materials</th>
<th>Thermal conductivity $k$(W/cm°C)</th>
<th>Thermal conductivity $c$($k$(W/cm°C))</th>
<th>Specific heat $c'$ (J/g°C)</th>
<th>Density of material $\gamma$(g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO</td>
<td>1.2</td>
<td>116</td>
<td>0.5</td>
<td>5.61</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>6.69</td>
<td>21.9</td>
<td>0.6894</td>
<td>4.13</td>
</tr>
<tr>
<td>WO$_3$</td>
<td>1.63</td>
<td>173</td>
<td>0.0780</td>
<td>7.16</td>
</tr>
<tr>
<td>HfO$_2$</td>
<td>1.1</td>
<td>23</td>
<td>0.144</td>
<td>13.31</td>
</tr>
</tbody>
</table>

In the present analysis thickness of the oxidation membrane is kept constant at 200 nm, and reset voltage at 0.5 V. To analyze the saturated temperature behavior of different RRAM devices, we have varied the filament radius in the range of 10 nm to 100 nm with 10 nm as a step size and filament resistivity in the range of 10 $\mu$Ω cm to 100 $\mu$Ω cm with 10 $\mu$Ω cm as a step size. To analyze the effect of filament radius on different RRAM devices, we have taken three observation of filament resistivity in the order of 10 $\mu$Ω cm (low resistivity), 50 $\mu$Ω cm (medium resistivity), and 100 $\mu$Ω cm (high resistivity). Similarly, analyzing the effect of filament resistivity on different RRAM devices, we have chosen three observations for filament radius size in the order of 10 nm (low size), 50 nm (medium size), and 100 nm (high size).

### 3. Result and Discussion

In the present investigation, different RRAM materials are analyzed such as ZnO, TiO$_2$, WO$_3$, and HfO$_2$ owing to their fine memory performance [3-5]. The various physical parameters of above RRAM materials are listed in Table 1. For the first case, the radius of the filament is varied from 10 nm to 100 nm and its effect on the saturated temperature of different RRAM material is analyzed. For each case, the filament resistivity is varied from 10 $\mu$Ω cm to 100 $\mu$Ω cm and its effect on the saturated temperature decreases as the resistivity of the filament increases.

In the present analysis thickness of the oxidation membrane is kept constant at 200 nm, and reset voltage at 0.5 V. To analyze the saturated temperature behavior of different RRAM devices, we have varied the filament radius in the range of 10 nm to 100 nm with 10 nm as a step size and filament resistivity in the range of 10 $\mu$Ω cm to 100 $\mu$Ω cm with 10 $\mu$Ω cm as a step size. To analyze the effect of filament radius on different RRAM devices, we have taken three observation of filament resistivity in the order of 10 $\mu$Ω cm (low resistivity), 50 $\mu$Ω cm (medium resistivity), and 100 $\mu$Ω cm (high resistivity). Similarly, analyzing the effect of filament resistivity on different RRAM devices, we have chosen three observations for filament radius size in the order of 10 nm (low size), 50 nm (medium size), and 100 nm (high size).

In the present analysis thickness of the oxidation membrane is kept constant at 200 nm, and reset voltage at 0.5 V. To analyze the saturated temperature behavior of different RRAM devices, we have varied the filament radius in the range of 10 nm to 100 nm with 10 nm as a step size and filament resistivity in the range of 10 $\mu$Ω cm to 100 $\mu$Ω cm with 10 $\mu$Ω cm as a step size. To analyze the effect of filament radius on different RRAM devices, we have taken three observation of filament resistivity in the order of 10 $\mu$Ω cm (low resistivity), 50 $\mu$Ω cm (medium resistivity), and 100 $\mu$Ω cm (high resistivity). Similarly, analyzing the effect of filament resistivity on different RRAM devices, we have chosen three observations for filament radius size in the order of 10 nm (low size), 50 nm (medium size), and 100 nm (high size).
**Fig. 2** – Effect of the radius of the filament on the saturated temperature of (a) ZnO; (b) TiO₂; (c) WO₃; and (d) HfO₂ based RRAM.

**Fig. 3** – Effect of the resistivity of the filament on the saturated temperature of (a) ZnO; (b) TiO₂; (c) WO₃; and (d) HfO₂ based RRAM.
Table 2 – Saturated temperature change factor for the change in the filament resistivity value

<table>
<thead>
<tr>
<th>RRAM Material</th>
<th>Saturated Temperature Change Factor for 10 μm to 50 μm cm</th>
<th>Saturated Temperature Change Factor for 50 μm to 100 μm cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO</td>
<td>5.0022</td>
<td>1.9997</td>
</tr>
<tr>
<td>TiO₂</td>
<td>5.0050</td>
<td>1.9983</td>
</tr>
<tr>
<td>WO₃</td>
<td>5.0066</td>
<td>1.9988</td>
</tr>
<tr>
<td>HfO₂</td>
<td>5.0031</td>
<td>1.9994</td>
</tr>
</tbody>
</table>

Table 3 – Saturated temperature change factor for the change in the filament radius value

<table>
<thead>
<tr>
<th>RRAM Material</th>
<th>Saturated Temperature Change Factor for 10 nm to 50 nm</th>
<th>Saturated Temperature Change Factor for 50 nm to 100 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnO</td>
<td>23.3900</td>
<td>3.9908</td>
</tr>
<tr>
<td>TiO₂</td>
<td>8.9945</td>
<td>3.7538</td>
</tr>
<tr>
<td>WO₃</td>
<td>23.5772</td>
<td>3.9927</td>
</tr>
<tr>
<td>HfO₂</td>
<td>19.0357</td>
<td>3.9540</td>
</tr>
</tbody>
</table>

Table 2 and 3 represents the saturated temperature change factor for the change in the filament resistivity and radius of different materials. The results prompt that, the rate of change in the saturated temperature is higher for the lower resistivity whereas it becomes small for higher filament resistivity. The variation in the filament radius shows same behavior for ZnO, WO₃ and HfO₂ based RRAM devices however TiO₂ material shows a small variation in the change factor. This is attributed to the higher thermal conductivity and specific heat capacity of TiO₂ as compared to other ones taken in this investigation. The results showcase that the saturated temperature is the filament size and resistivity dependent property.

4. CONCLUSION

In the present investigation, we have thoroughly investigated the thermal reaction model of RRAM device for different material and consequently correlated the relationship between saturated temperature, filament radius, and resistivity. The saturated temperature is one of the important property of high performance RRAM and it is associated with the device reliability. The higher value of the saturated temperature degrades the device reliability [22]. At the higher temperature more sensitive detection circuitry is required to read and write operations of RRAM [5, 21-22]. The results suggest that the saturated temperature decreases as the radius and resistivity of the conductive filament increases. The results also indicate that there is a sudden change in the saturated temperature for the lower value of filament radius and resistivity whereas steady change is observed for the medium and higher value of the filament radius and resistivity. Results confirm the saturated temperature is filament size and resistivity dependent property. All these investigations and results thereof are definitely significant in the application scenario of RRAMs.

REFERENCES