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A New Tunneling Barrier Width Model of the Switching Mechanism in Hafnium Oxide-Based Resistive Random Access Memory

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Abstract- In this paper, the switching characteristics of Ti/HfO_2/TiN resistive random access memory (RRAM) have been examined. A novel tunneling barrier width model based on WKB approximation is proposed to explain the pertinent current-voltage characteristic and the origin of the resistance changing in RRAM. It was found that the resistance in high resistance state of RRAM is exponentially related to the reset voltage, and the tunneling barrier width is proportional to the reset voltage. Simulation results show that the TiO_x layer formed at the bottom HfO_2/TiN interface is responsible for the resistance switching. The transient tunnel barrier width changing shows the switching time is related to both ionized charge migration and the redox reaction speed of the conducting filament.

1. Introduction

RRAM has aroused more interests in recent years as a result of its simple structure, better performance, and its compatibility with the current silicon-based IC process and manufacturing. RRAM using binary transition metal oxide dielectric draws much more interests as a result of better device performance, but the physics inside is still vague [1]. Although there are many physical models to describe the RRAM device, such as space-charge-limited-current (SCLC) [2], Schottky barrier thermionic emission [3], direct tunneling [4], and ionic drift & diffusion [5] models etc., none of them can explain well the experimental results, including temperature effect, switching time, and bipolar asymmetry.

In this paper, we will propose a simple and intuitive tunneling model based on WKB approximation [6] to well describe the RRAM switching mechanism. A dedicated simulation is performed to match the model with experimental data. And, based on the model, for the first time, we can determine the critical parameters that affect RRAM on/off ratio and switching time.

2. Device Preparation

The structure of RRAM was the TiN/TiO_x/HfO_x/TiN stack, which was deposited on the Ti/SiO_2/Si substrate. The HfO_2 thin film was deposited by atomic layer deposition (ALD), while all the other thin films were deposited by sputtering methods, as shown in Fig. 1 [7]. The device area is 0.48x0.48 μm^2, and the thickness of HfO_2 layer is 5nm.

3. Results and Discussion

A. Tunneling barrier width model

Fig. 2 shows the typical bipolar switching of RRAM. The positive turn-on process(in the first quadrant) is swept by the currents. The negative turn-off (third quadrant) is done by reset voltages. The relation between HRS (High Resistance State) resistance and reset voltage is shown in Fig. 3. Beyond a certain threshold, the HRS resistance increases first linearly then exponentially with the reset voltage.

Different HRS current-voltage characteristics are shown in Fig. 4. The current seems to be proportional to the square root of the applied voltage, similar to the Schottky thermionic emission [3]. However, from the temperature experiments in Fig. 5, we are aware that the origin of RRAM resistance changing is *not* modulated by the Schottky barrier height, i.e., independent of the barrier height. As such, we propose a new model for RRAM which relates the resistance changing to the modulation of tunneling barrier width based on WKB approximation, Table 1. The tunnel barrier height is set for 0.1eV, effective mass is $9m_0$, and dielectric constants are 46 for TiO_x and 25 for HfO_2 [8-10]. A TiO_x layer is formed at the bottom HfO_2/TiN interface for its lower activation energy than HfO_2 [11]. Fig. 6 shows the formation of the tunnel barrier width *d* and the band diagram of the device. Fig. 7 shows the model simulation perfectly matches with the experimental data, and the equivalent tunnel barrier width is also extracted. The integration can be done under assumptions [6], and after the simplification, we found the RRAM resistance is linear with barrier width when d is small, and then increases exponentially. Comparing with Fig. 3, it also means the tunnel barrier width is proportional to the reset voltage. This can be realized by a critical electric field that enables ion migration. The critical electric field is about 1.2MV/cm.

B. Transient measurements

In order to measure the RRAM transient response, Fig. 8 shows a new measurement method, with results in Fig. 9. We found there are three phases in the each curve: First it remains in LRS for a certain time. Second, the width increases linearly with time, and finally it saturates to a certain level. To explain this phenomenon, we propose a switching time model on the basis of tunnel barrier width model. In phase I, the switching time is determined by how fast the oxygen ion confined in the electrode reaches the conduction filament. If the electric field exceeds a critical level, the ion velocity will increase exponentially with the electric field [12]. According to this, the ion migration time has an inverse exponential relation with the reset voltage, Table 3(a). In phase II, there are sufficient oxygen ions surrounding the tip of the conduction filament, so the switching time is dominated by the redox reaction speed. Assuming the total current provides the charges needed for reaction, an estimation of reaction time in Table 3(b) matches with the logarithmic time dependence observed in Fig. 10. The final saturation phase is already explained in the last section. A complete switching time equals to the time for ion migration plus the time for the conduction filament reaching steady state.

In summary, the tunneling barrier width model based on WKB approximation has successfully demonstrated the switching dynamics of HfO_2-based RRAM. The TiO_x layer formed at the bottom HfO_2/TiN interface is the key for resistance switching. For the first time, the transient RRAM switching mechanism has been examined and we have also proposed physical mechanisms to model the switching time properly and the correlation to the ionized charge migration and the redox reaction speed in a conducting filament.

References

[1] R. Waser et al., *Adv. Mater.*, vol. 21, p. 2632, 2009
[2] Q. Liu et al., *APL*, vol. 92, p. 012117, 2008
[3] Z. Wei et al., *Extended Abs. SSDM*, p.1202, 2009
[4] Y. Sakotsubo et al., *Extended Abs. SSDM*, p.1204, 2009
[5] D. Strukov et al., *Nature*, 453, p. 80, 2008
[6] Y. C. Yeo et al., *IEEE EDL*, vol. 21, p. 540, 2000
[7] H. Y. Lee et al., in *IEDM Tech. Dig.*, p.297, 2008
[8] A. C. Arango et al., *Adv. Mater.*, vol. 12, p. 1689, 2000
[9] C. Kormann, *J. Phys. Chem.*, vol. 92, p.5196, 1988
[10] W. J. Zhu, *IEEE EDL*, vol. 23, p. 97, 2002
[11] X. P. Wang, VLSI-TSA, p. 140, 2010
[12] D. B. Strukov, *Appl. Phys. A*, vol. 94, p. 515, 2009

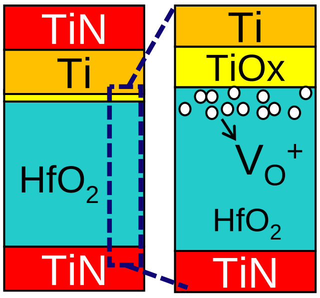


Fig. 1 Schematic of the test device structure. MIM is deposited on Ti/SiO_2/Si substrate.

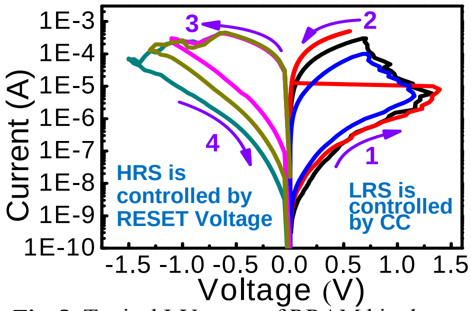


Fig. 2 Typical I-V curve of RRAM bipolar switching with path 1-to-2 in the first quadrant and path 3-to-4 in the 3rd quadrant.

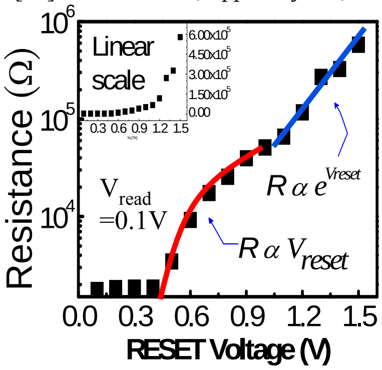


Fig. 3 The relationship between HRS resistance and the RESET voltages. The reset time is 30sec.

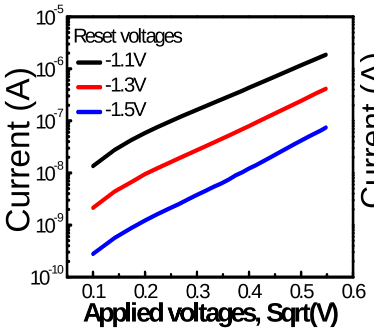


Fig. 4 I-V characteristics for different reset voltages. The maximum sweep voltage is 0.3V to avoid possible resistance switching.

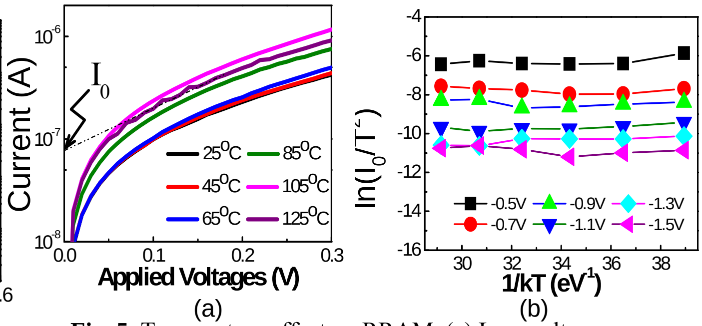


Fig. 5 Temperature effect on RRAM. (a) Low voltage sweep shows the slope is independent of the temperature. (b) The slope of each line indicates that Schottky barrier height is approximately zero for every reset voltage.

$$I_{RRAM} = \frac{Aq^2}{16\pi^2\hbar\varepsilon_{TiOx}\phi_i}\cdot\frac{V_A}{d_{TiOx}}\exp\left[-2\int_0^{d_{TiOx}}\frac{\sqrt{2m^*q|E-V|}}{\hbar}dx\right]$$

$$|E-V| = \phi_i - \frac{q^2}{16\pi\varepsilon_{TiOx}x} - q\frac{V_{TiOx}}{d_{TiOx}}x$$

$$V_{TiOx} = \frac{V_A}{1+\dfrac{\varepsilon_{TiOx}}{\varepsilon_{HfO2}}\dfrac{d_{HfO2}}{d_{TiOx}}}$$

A : device area
V_A : Applied voltage across two electrodes
E : electron energy
V : barrier potential

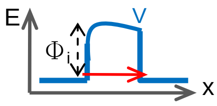


Table 1 Proposed RRAM current model using WKB approximation. Image force effect is also considered. The inset illustrates the tunnel barrier height used in the integration.

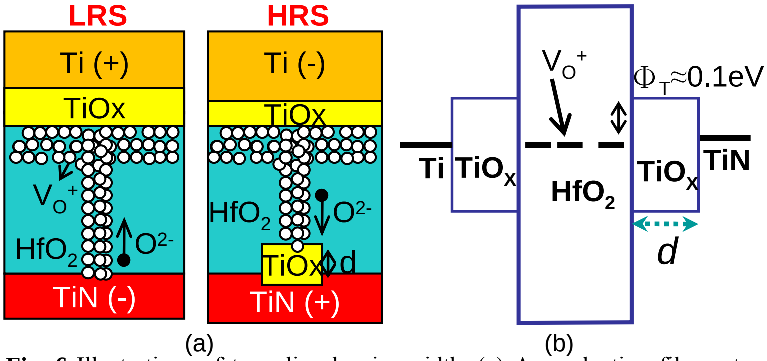


Fig. 6 Illustrations of tunneling barrier width. (a) A conduction filament constructed by oxygen vacancies depleted in HRS, leaving a TiO_X region. (b) The band diagram in HRS of the experimental device.

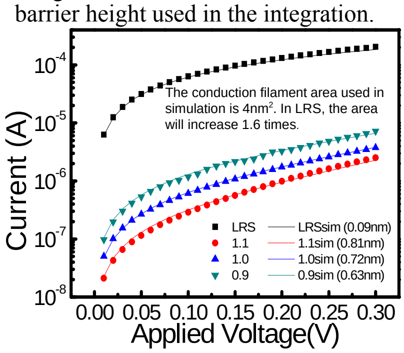


Fig. 7 The experimental and simulation results for RRAM low field currents at different HRS states.

$$I_{RRAM} = \frac{Aq^2}{16\pi^2\hbar\varepsilon_{TiOx}\phi_i'}\cdot\frac{V_A}{d_{TiOx}}\exp\left[-\frac{4\sqrt{2qm^*}\left(\phi_i'\right)^{3/2}d_{TiOx}}{3\hbar|V_{TiOx}|}\left[1-\left(1-\frac{|V_{TiOx}|}{\phi_i'}\right)^{3/2}\right]\right]$$

$$= \frac{Aq^2}{16\pi^2\hbar\varepsilon_{TiOx}\phi_i'}\cdot\frac{V_A}{d_{TiOx}}\exp\left[-\frac{2\sqrt{2qm^*\phi_i'}}{\hbar}d_{TiOx}\right]$$

$$R = \frac{V_{read}}{I_{RRAM}} \propto d_{TiOx}\exp\left[\frac{2\sqrt{2qm^*\phi_i'}}{\hbar}d_{TiOx}\right] \quad \text{where} \quad \phi_i' = \phi_i - \sqrt{\frac{qV_{TiOx}}{4\pi\varepsilon_{TiOx}d_{TiOx}}}$$

Table 2 An analytical function of RRAM current with applied voltage, derived by the integration shown in Table 1 with reasonable assumptions.

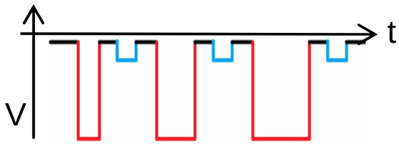


Fig. 8 Transient measurement method. After applying a short, width-changing pulse (red), a small voltage was used (blue) to read the current state and use the equation in Table 2 to calculate *d*.

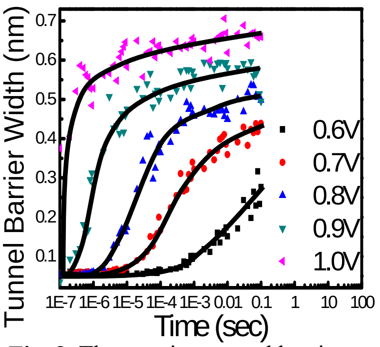


Fig. 9 The transient tunnel barrier width changes with time for various applying biases.

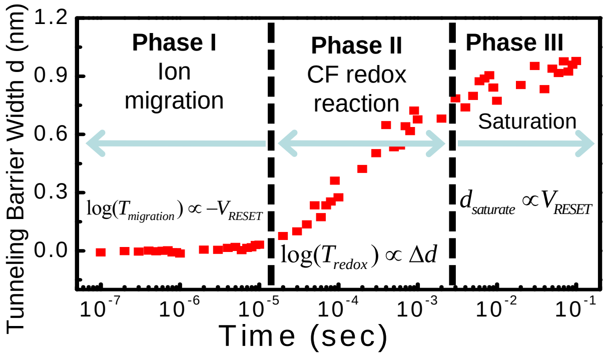


Fig. 10 A three phase switching time dependence was found. A complete switching time equals to $T_{migration}+T_{redox}$.

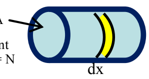
(a) $v = \mu E_0 e^{E/E_0}$ if $E \sim E_0$

$$T_{migration} = \frac{d_0}{v} = \frac{d_0}{\mu E_0\exp\left(V/d_0E_0\right)}$$

where d_0 is the LRS tunnel barrier width

(b) Conduction filament area = A

Assuming conduction filament has constant charge density = N



Total charges in the yellow region = NAdx

$$= \int_x^{x+dx} I(x)dt = \int_x^{x+dx} I(x)dx\frac{dt}{dx} = \int_x^{x+dx} I_0\exp(-\gamma x)dx\frac{dt}{dx}$$

$\because$ dx is very small $\therefore \exp(-\gamma dx)\approx 1-\gamma dx$

$$\Rightarrow T_{redox} = \frac{NA}{I_0\gamma}\left(\exp(\gamma d)-1\right)\approx\frac{NA}{I_0\gamma}\exp(\gamma d)$$

Table 3 The switching time models for both (a) ion migration region and (b) critical field (CF) redox reaction region.