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A Finite Element Model for Bipolar Resistive Random Access Memory

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Abstract—**The forming, reset and set operation of bipolar resistive random access memory (RRAM) have been predicted by using a finite element (FE) model which includes interface effects. To the best of our knowledge, our bipolar RRAM model is applicable to realistic cell structure optimization because our model is based on the FE method (FEM) unlike precedent models.**

Index Terms—**Realistic cell structure optimization, finite element method (FEM), bipolar resistive random access memory (RRAM).**

I. INTRODUCTION

A resistive random access memory (RRAM) has attracted many researchers' attention as a next-generation high density memory, more specifically a post-NAND flash memory, thanks to its simple structure and excellent three-dimensional stackability [1, 2]. There are two types of RRAM according to their switching mechanisms: one is unipolar and the other is bipolar. This manuscript is contributed to the latter while the former has already been discussed elsewhere [3]. Although most of bipolar RRAM studies have focused on experimental results [4, 5], various pioneering RRAM models have been proposed recently [6-8]. However, all of them have some limitations. For example, interface modified random circuit breaker (RCB) network model can simulate two-dimensional cell structures to obtain the physical insight of RRAM operations and cannot include the effect of spatially nonuniform temperature distribution [6]. Theoretical or analytical models recently proposed by S. Yu *et al.* and D. Ielmini are more accurate in that they include the migration of oxygen vacancies and ions [7, 8]. However, they also fail to simulate realistic cell structures. In this paper, our bipolar RRAM model based on finite element method (FEM) has been proposed for the accurate prediction of forming, reset and set operation in realistic three-dimensional RRAM structures.

II. MODELING METHOD

Fig. 1 shows the flow chart of the proposed FE bipolar RRAM model for forming, reset and set operation cycle categorizing interface and bulk regions unlike our unipolar RRAM model [3]. Because bipolar resistive switching (BRS) is related to an effect at the interface between the electrode and bulk region, in our model, four kinds of local spots have been used to describe the BRS as shown in Fig. 2: an insulating spot in the interface region, conductive spot in the interface region, insulating spot in the bulk region and conductive spot in the bulk region. The simulated cell refers to experimental data in literature [9]. The active area is 0.01 μm^2 and dielectric film thickness is 0.03 μm. Pt electrode and TiO_2 with Ti adhesion layer have been used for BRS. First, a pristine bipolar RRAM cell structure having an interface and bulk region is generated as shown in Fig. 2(a). The introduction of FEM makes the simulation of realistic cell structures feasible by dividing the cell into small nodes. Second, based on both Poisson and heat flow equation, the FEM solver calculates electric field and temperature at each node [10]. Then, by using the

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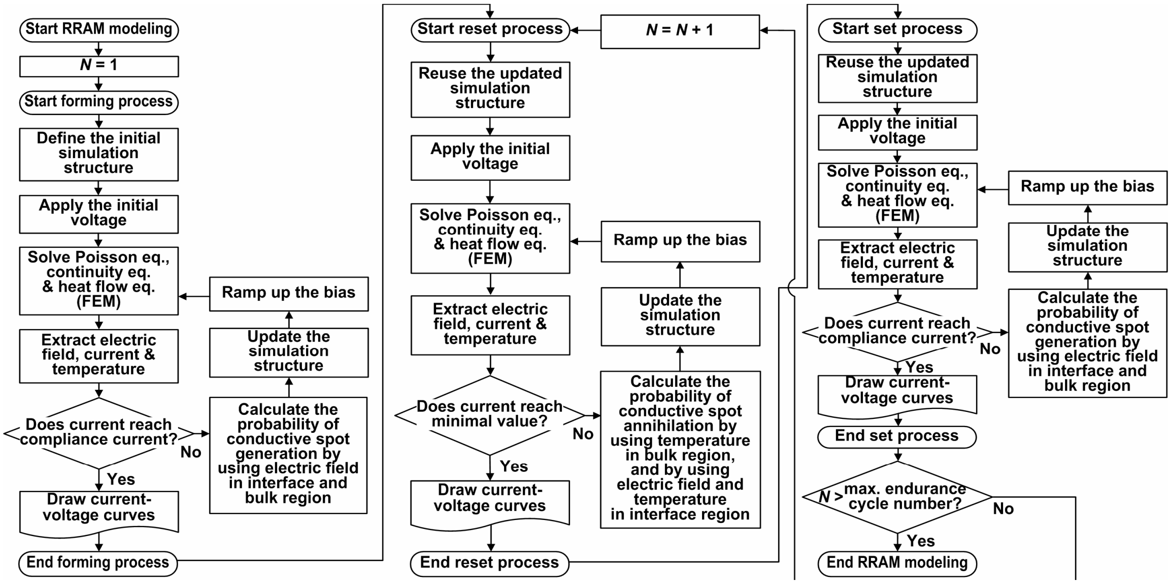

Fig. 1. Flow chart of the proposed unified model of a bipolar RRAM cell for forming, reset and set operation.

calculated electric field and temperature at each node, the probability which determines the generation or annihilation of conductive spots is calculated. The generation of a conductive spot is governed by electric field in unipolar resistive switching (URS) [11] and BRS [12]. On the other hand, their annihilation is ruled by Joule heating [13] in URS and by recombination between oxygen vacancies and oxygen ions [14] in BRS. In this work, it has been assumed that BRS occurs in the interface and URS occurs in the bulk region [6]. For the generation of conductive spots in the interface and bulk regions, $1/E$ model [15] has been introduced. For the annihilation of conductive spots in the bulk regions, Arrhenius equation [13] has been used to describe Joule heating. For the annihilation of conductive spots in the interface region, both $1/E$ model describing the drift of oxygen ions and Arrhenius equation [14] describing the diffusion of oxygen ions have been solved. Fourth, reflecting the calculated probability values at each node, the RRAM cell structure is updated. Fig. 2(b) shows that a few conductive spots are generated in the early stage of forming operation. Fifth, steps #2-4 are repeated with applied voltage increasing until a conductive filament (CF) is formed between the top and bottom electrode as shown in Figs. 2(a)-(d). In order to evaluate the current through the CF, the current continuity equation is solved. Subsequently, forming operation is followed by reset operation. Conductive spots begin to be annihilated and most of them are located in the interface region following the calculated probability values. Similar to the forming operation, the reset operation is repeated with applied voltage ramping up until a CF is disconnected as shown in Fig. 2(e). Seventh, the set operation follows the reset operation, which is analogous to the forming operation. The set operation is repeated with applied voltage increasing until a CF is restored as shown in Fig. 2(f). Finally, the reset-set operation cycle shown in steps # 6 and 7 is repeated until endurance cycle number (N) reaches its defined value.

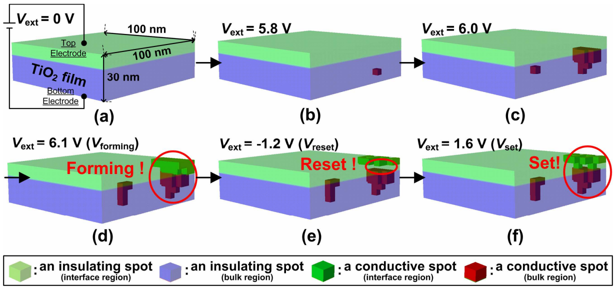

Fig. 2. Schematics of a bipolar TiO$_2$ RRAM cell in single-bit operation (a) Pristine state without initial defects, (b)-(c) Conductive spots randomly generated by probability function, (d) Post-forming state, (e) Post-reset state, (f) Post-set state.

Fig. 3(a) shows the simulated I-V curves of the bipolar RRAM cell. Although there is a difference between the simulated and experimental I-V curves [9] due to the fact that Schottky barrier is not considered in this model, simulation data reflect experimental ones. Fig. 3(b)

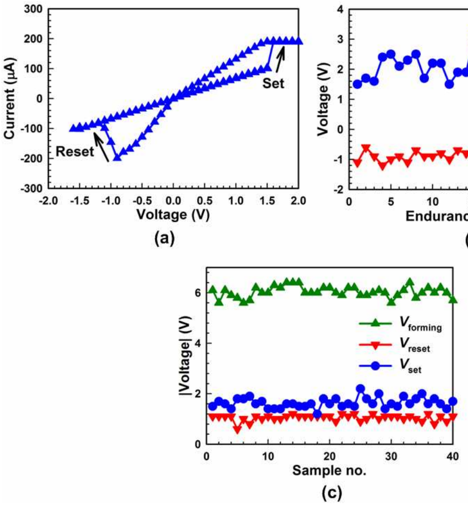

Fig. 3. (a) Simulated *I-V* curves of a bipolar TiO_2 RRAM cell, (b) Simulated V_{reset} and V_{set} distribution after 30 endurance cycles of a bipolar TiO_2 RRAM cell, (c) Simulated $V_{forming}$, V_{reset} and V_{set} distribution of 40 bipolar TiO_2 RRAM cells.

shows the simulated reset voltage (V_{reset}) and set voltage (V_{set}) distribution of a bipolar TiO_2 RRAM cell after 30 endurance cycles. Fig. 3(c) shows the simulated forming voltage ($V_{forming}$), V_{reset} and V_{set} distribution of 40 TiO_2 RRAM cells. It should be noted that bipolar RRAM cells have more uniform V_{reset} and V_{set} than unipolar RRAM cells [3] because the set and reset operation occur only at the thin interface region in the case of the former.

III. APPLICATIONS

Various issues of RRAM can be analyzed by using the proposed FE model. Some examples will be presented: multi-bit operation and initial defect effects. In order to boost memory density multi-bit operation needs to be introduced. It has been reported that RRAM cells can be operated in a multi-bit mode [16]. Fig. 4 exemplifies the multi-bit operation of a bipolar RRAM cell: forming, reset and set operation. In the forming operation, as shown in Figs. 4(a) and 5(a) the proposed model successfully shows that an RRAM cell can have more than two CFs which correspond to three storage levels by adjusting forming current [17]. Next, in the reset operation, as shown in Figs. 4(b), (c) and 5(b), the phased reduction of reset current [18] is observed because two CFs are annihilated in turn. Finally, in the set operation, as shown in Figs. 4(d), (e) and 5(c), disconnected CFs are restored in turn by adjusting set compliance current. From now on, the effects of initial defects on a bipolar RRAM cell will be discussed. Resistive switching behavior such as $V_{forming}$ is strongly dependent on initial defects [18]. Figs. 6(a) and (b) show that the average value of $|V_{forming}|$ (<$|V_{forming}|$>) increases while its standard deviation ($\sigma V_{forming}$) decreases as initial

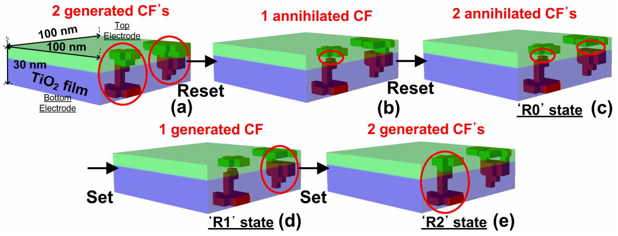

Fig. 4. Schematics of a bipolar TiO_2 RRAM cell in multi-bit operation (a) Post-forming state, (b)-(c) Reset operation: two CFs are disconnected, (d)-(e) Set operation: one or two CFs are restored by adjusting set compliance current.

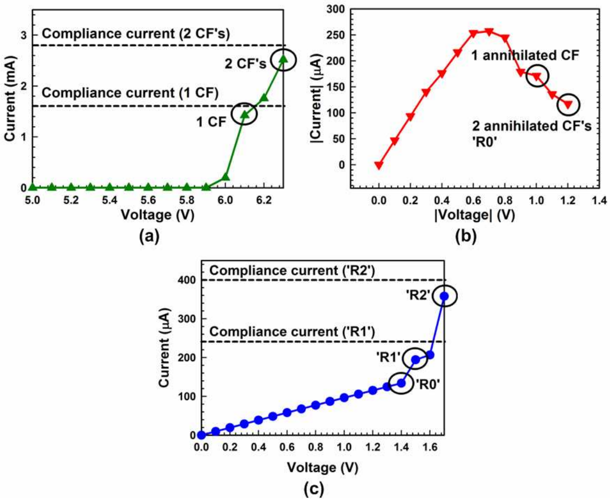

Fig. 5. (a) Simulated multi-bit forming operation by adjusting forming compliance current, (b) Simulated multi-bit forming operation. The phased reduction of reset current is observed, (c) Simulated multi-bit set operation by adjusting set compliance current.

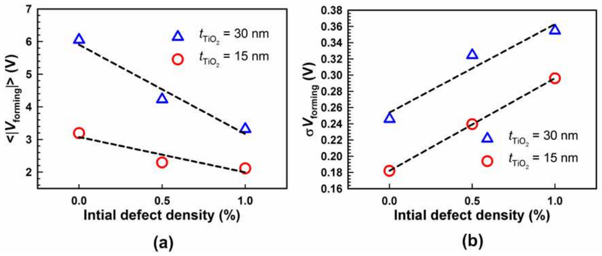

Fig. 6. (a) Effect of initial defect density on the average values of $|V_{forming}|$, (b) Effect of initial defect density on the standard deviation values of $V_{forming}$. The active area is 0.01 μm^2. 40 RRAM devices have been used.

defect density decreases. It is because the number of partially-connected CFs decreases in a pristine cell as initial defect density is reduced. Considering that the number of initial defects decreases with the reduction of cell volume, more uniform V_{foming} distribution is expected in the case of a small-sized RRAM cell [19].

IV. SUMMARY

The unified model for bipolar RRAM has been proposed for forming, reset and set operation considering interface effects. Unlike conventional RRAM models, the proposed model based on FEM can simulate realistic cell structure with higher accuracy and characterize various kinds of technical issues of RRAM: multi-bit operation and initial defect effects.

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