Optimized Filamentary RRAM for Neuromorphic Hardware

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RRAM devices with analog switching behavior is particularly important for neuromorphic hardware. However, abrupt switching is often observed in some filamentary RRAM devices [1], which harms the performance of neuromorphic network. In this work, the impacts of electric field and temperature on analog switching behaviors are elucidated, and then a new device structure is proposed for filamentary RRAM to realize analog behaviors. Based on the proposed method, excellent analog behaviors are realized on a RRAM array.

Generally, electric field and thermal effect dominate the formation and rupture of conductive filament (CF). If CF formation is mainly controlled by electric field, single filament is easily formed, resulting in abrupt switching. In contrast, if thermal effect is the domination factor, multiple CFs are most probably to form, resulting in the improved analog switching.[2] Based on this understanding, we design a new device structure with a low thermal conductivity layer capping on the switching layer. We experimentally demonstrate the proposed improvement methodology. A TiN/TaO_x/HfO_x/TiN RRAM (the inset of Fig.1a) is fabricated. Then the electrical performance is investigated. The DC I-V (Fig. 1a) curves of the developed device exhibit gradual switching both in potentiation and depression processes. During pulse measurement (Fig.1b), the conductance is modulated by applying identical pulse trains. Analog switching characteristics with 10x window is realized in the fabricated device using 50ns pulses. Almost all the cells on the array exhibit analog switching behaviors. From these experiments, the developed new device structure is shown to be a good candidate for the optimization of analog switching behaviors.

To validate our hypothesis, a temperature distribution simulation and an oxygen vacancy (Vo) distribution simulation of metal/HfO_x structure and TaO_x/HfO_x structure are performed. From the results, the local temperature increases significantly in TaO_x/HfO_x RRAM compared to metal/HfO_x RRAM. The distribution of Vo is more uniform in TaO_x/HfO_x RRAM, so multiple CFs are formed. The developed RRAM array can be used to realize neuromorphic network, as shown in Fig.2. Analog Vector-Matrix Multiplication operation can be easily calculation on this neuromorphic hardware.

In summary, this work studies the mechanisms of analog switching in filamentary RRAM. A thermal modulation method is proposed and demonstrated to optimize the analog switching. A fab-friendly TaO_x/HfO_x based analog RRAM array is developed. The proposed methodology provides a valuable guideline for designing high performance and large-scale RRAM based neuromorphic hardware.

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[1] Z. Chen, IEDM 2015,467

[2] H. Wu, IEDM 2017, 274.

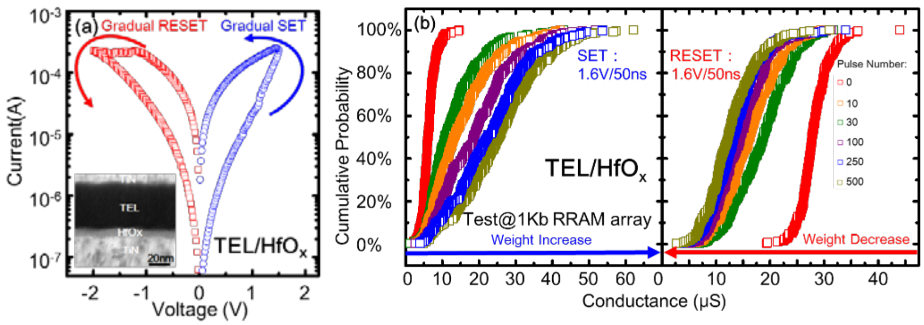

Figure 1: (a) IV curve of TaO_x/HfO_x RRAM. (b) Conductance of TaO_x/HfO_x RRAM changes with the number of identical pulses.

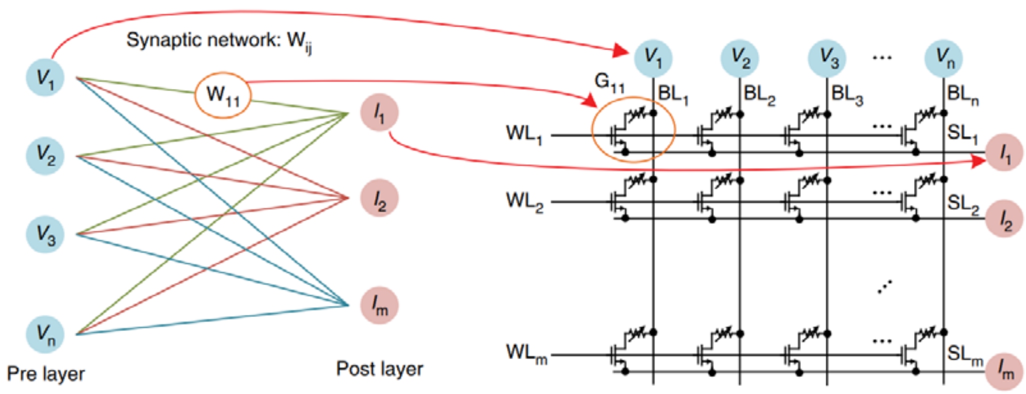

Figure 2: Mapping of neural network to a 1T1R RRAM array.