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Original Research

Investigation of the synaptic device based on the resistive switching behavior in hafnium oxide

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Abstract

Metal-oxide based electronics synapse is promising for future neuromorphic computation application due to its simple structure and fab-friendly materials. HfO_x resistive switching memory has been demonstrated superior performance such as high speed, low voltage, robust reliability, excellent repeatability, and so on. In this work, the HfO_x synaptic device was investigated based on its resistive switching phenomenon. HfO_x resistive switching device with different electrodes and dopants were fabricated. TiN/Gd:HfO_x/Pt stack exhibited the best synaptic performance, including controllable multilevel ability and low training energy consumption. The training schemes for memory and forgetting were developed.

Keywords: Hafnium oxide (HfO_x); Resistive switching; Memristor; Multilevel cell (MLC); Synapse

1. Introduction

Brain-inspired neuromorphic computing has attracted much attention due to its massive parallelism, adaptivity to complex input information, and tolerance to errors [1]. Synapse is a crucial element in a neural network. Due to the large amount of the synapses in a neural network, it is highly desirable to realize the synaptic function with a simple device structure that has high density and low energy consumption [2]. Recently, metal-oxide based resistive switching memory devices have been demonstrated great advantages for the implementation of the synapse due to their superior performance, low cost, and compatibility with CMOS technology [3,4].

Multilevel ability is one of the key characteristics for synaptic application [2]. Although some of the metal oxides show multilevel resistive switching ability, how to effectively control such behavior is still under investigation [5]. In the meanwhile, the synaptic application requires different operation scheme compared to the memory application. Therefore, it is highly demanded to develop the unique training scheme for the metal-oxide synapses. In this work, we investigate the synaptic training behaviors in hafnium oxide based resistive switching memory devices. Material design methodology is provided to improve the performance of the synaptic device, especially for the multilevel switching ability. Training schemes for the developed synaptic devices are also studied for the high efficient neuromorphic computation application.

2. Experiments

HfO_x based resistive switching devices were fabricated to investigate the synaptic behaviors. About 500 nm SiO_2 film was thermally grown in dry oxygen. Then bottom electrode of Pt/Ti layers with total thickness of 100 nm were deposited by sputtering at room temperature. After that, about 20 nm HfO_x layer was deposited on Pt by reactive sputtering, followed by a furnace annealing at 600 °C in O_2 ambient for 20 min. For doped devices, Gd ions were implanted into the HfO_x layer with the energy of 80 keV, prior to the 800 °C annealing

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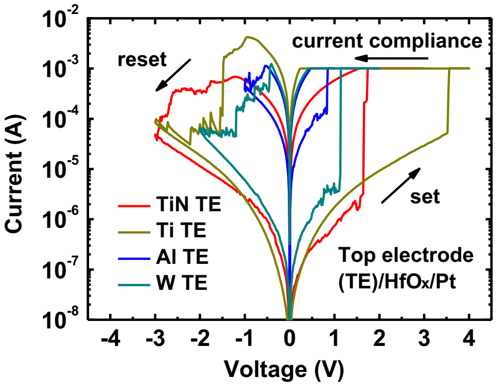

Fig. 1. Typical resistive switching behavior of the HfO_x memory devices with TiN, Ti, Al, and W top electrodes. Set processes require positive voltage, while reset processes require negative voltage for all the devices. Current compliances of 1 mA are applied on all the devices to prevent the occurrence of hard breakdown.

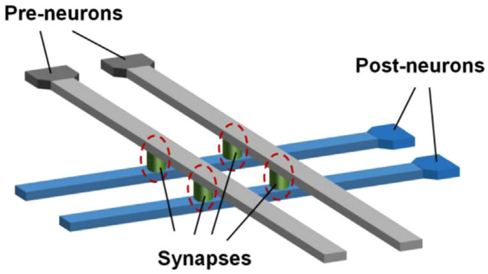

Fig. 2. Schematic of a neural network consisting of two layers of neurons and synapses between the two layers. The synapses are realized using resistive switching devices. The top electrodes of the devices connect to the pre-neurons, while the bottom electrodes of the devices connect to the post-neurons.

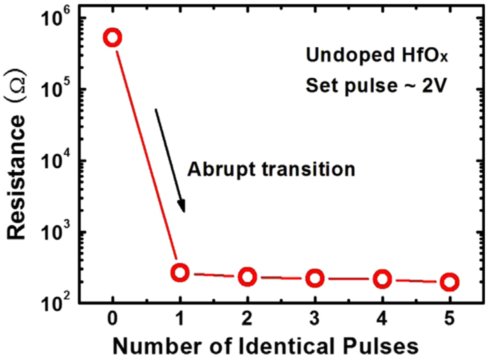

Fig. 3. Resistance as a function of number of identical pulses for TiN/undoped HfO_x/Pt synaptic device during set process. Uncontrollable abrupt resistance transition is observed.

process in N_2 ambient for 5 min to activate the dopants. Finally, top electrodes (TiN, Ti, Al, W) of 100 nm thickness were deposited by sputtering and patterned together with HfO_x layer to form the isolated square with the size varying from 10×10 to $100 \times 100\ \mu m^2$.

Electrical measurements were performed using Keithley 4200 (for DC measurement) and Agilent 81150 (for AC measurement). A switching box connecting the two equipments was used to select DC signal and AC signal automatically, and then applied the selected electrical signal on the top electrodes of the devices. The bottom electrodes were grounded.

3. Results and discussion

Fig. 1 shows the typical resistive switching I–V curve of the HfO_x devices with different top electrodes (TE). It can be observed that the device with TiN TE shows the best switching performance. For the devices with Ti, Al, and W TE, large current overshoots are observed, which increases the reset current. Especially for Ti TE device, even though a smaller current compliance is applied, the reset current is still larger than 5 mA. Furthermore, the sharp resistance transitions observed in the reset process of Ti and W TE devices make it difficult for the synaptic application. For this reason, we choose the TiN/HfO_x/Pt stack to realize the function of synapse.

The synapse requires multilevel resistance states to represent different synaptic weightings [3]. As illustrated in Fig. 2, in the computing process of a neural network, the pre-neurons generate small pulses and transfer them to the post-neurons through synapses. The post-neurons receive different currents due to the different conductance of the synapses. In the training process of the neural network, both the pre-neurons and post-neurons generate large pulses to adjust the resistance of the synapses. Generally, there are two ways to change the resistance. One way is to control the resistance by varying pulse amplitude, which requires more complex programming pulse generation circuit and leads to lower training efficient. A more preferred way is to modulate the resistance by increasing pulse number. In this case, a series of identical pulses are applied on the device sequentially, and the resistance changes slightly with each pulse. As a result, the multilevel ability under pulse stimulation is important for the synaptic device.

As shown in Fig. 3, the TiN/undoped HfO_x/Pt device do not show gradual resistance transition in set process, which is due to the random and avalanching nature of oxygen vacancy (V_O) generation during set process [6]. To avoid the generation of V_O clusters, we developed a methodology by doping trivalent elements into HfO_x layer in our previous work [5]. In this case, the local formation energy of V_O near the dopants is reduced, and V_O will distribute more uniform in the conductive filament region. In this work, we develop TiN/Gd:HfO_x/Pt device to get the controllable multilevel resistive switching behavior.

For a synaptic training process, set process is corresponding to the memory function of the synapse, which increases the conductance of the device, while reset process is corresponding to the forgetting function of the synapse, which decreases the conductance of the device. Fig. 4 shows the memory function of the TiN/Gd:HfO_x/Pt synaptic device. Gradual resistance transition is observed. The resistance of the device decreases with the pulse number or accumulative pulse time. There are three stages for the resistance transition. At first, the resistance is independent with the increased pulse number. This is attributed to the random nature of V_O generation [6]. Once a V_O generates in the filament gap region, the training

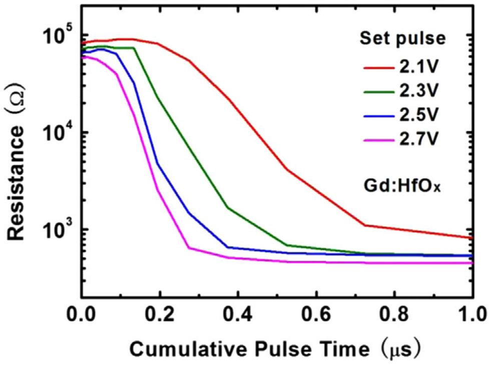

Fig. 4. Resistance as a function of cumulative pulse time for TiN/Gd:HfO$_x$/Pt synaptic device during set process. A series of identical pulses are applied on the device to get the gradual resistance transition. Different amplitudes of pulses are used and shown with different colors of lines.

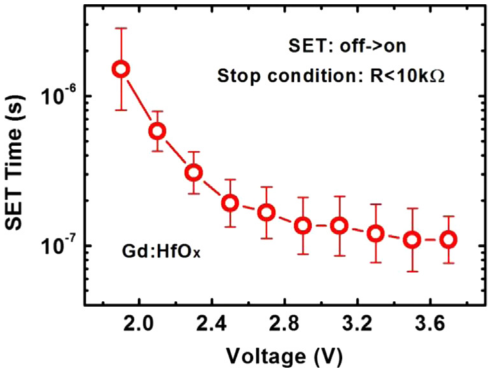

Fig. 5. The extracted set time as a function of pulse voltage.

process goes to the second stage, which exhibits the exponentially decreases of resistance with pulse number. At this stage, the amount of V_O increases quickly, resulting in the formation of conductive filaments between top and bottom electrode. The exponential dependence is attributed to the tunneling current mechanism [3]. When the filaments are connected, the training process goes to the last stage, at which the resistance is saturated. The device has switched from high resistance state (HRS) to low resistance state (LRS). It should be notice that larger pulse amplitude leads to quicker transition of resistance and quicker saturation. This is quite similar to the phenomenon observed in bio-synapse, in which stronger stimulation leads to quicker excitation.

Fig. 5 shows the extracted set time as a function of pulse voltage. The data in Fig. 5 are extracted based on the measured used in Fig. 4. The pulses with the same amplitude are applied on the device. The cumulative pulse time is recorded when the resistance drops below a critical value. In this measurement, the threshold value is set to 10 kΩ. The dots in the figure represent the average values, and the error bars indicate the standard deviations of the measured data. Since V_O are easy to generate under large voltage, filaments grow more quick when voltage is large, which results in the decreased set time with the increased set voltage.

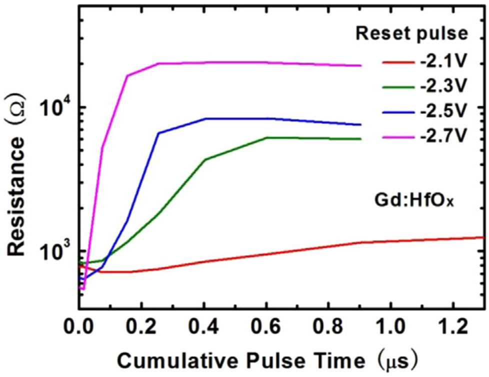

Fig. 6. Resistance as a function of cumulative pulse time for TiN/Gd:HfOx/Pt synaptic device during reset process. A series of identical pulses are applied on the device to get the gradual resistance transition. Different amplitudes of pulses are used and shown with different colors of lines.

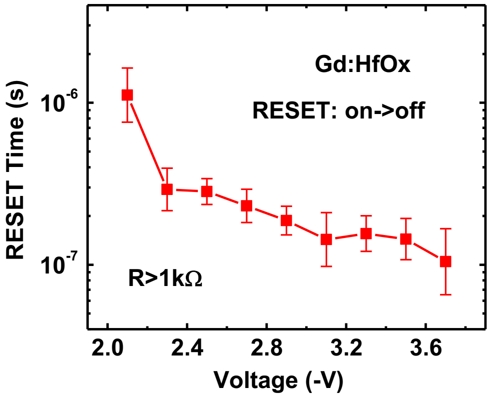

Fig. 7. The extracted reset time as a function of pulse voltage. The data are extracted based on the measured used in Fig. 6. The pulses with the same amplitude are applied on the device. The cumulative pulse time is recorded when the resistance transits above a critical value. In this measurement, the threshold value is set to 1 kΩ.

The forgetting function of the device shows similar behavior. As shown in Fig. 6, gradual resistance transition is observed as the pulse number or accumulative pulse time increases in the reset process. The resistance begins to increase since the first pulse is applied, and goes to saturation after receiving enough pulses. Since the reset process is attributed to the migration of oxygen interstitials and the recombination between oxygen interstitials and V_O, the transition is not as random as set process. Under larger voltage, resistance increases and saturates more quickly due to the faster migration of oxygen interstitials. Different from set process, the saturation resistance varies with pulse amplitude [7]. Larger voltage results in higher saturation resistance, which is attributed to the different distributions of local electric field in the filament gap region. Therefore, only large voltage can switch the device from LRS to HRS. Small voltage training can only finish at a certain intermediate state, results in a small resistance window.

Fig. 7 shows the required reset time as a function of pulse voltage. Reset time also decreases with the increased pulse voltage. Since the large voltage may decrease the number of multilevel states due to the quick saturation, there is a tradeoff between state number and resistance window in the reset process. A moderate reset voltage should be used to get the optimized forgetting function.

4. Summary

HfO_x based electronics synaptic devices are developed. TiN/Gd:HfO_x/Pt is demonstrated to show excellent synaptic performance, such as multilevel ability in both set and reset process, low training current, low operation voltage, fast speed, and good uniformity. The memory and forgetting behaviors of the developed synapse are demonstrated with different pulse conditions. The developed HfO_x based synapses will boost the realization and application of hardware based neuromorphic computation system and artificial neural network.Acknowledgement: This work is supported in part by the NSFC (61404006) and the China Postdoctoral Science Foundation (2014M550013).

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