

A large memory window and low power consumption self-rectifying memristor for electronic synapse

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Abstract

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A large memory window and low power consumption self-rectifying memristor for electronic synapse

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Self-rectifying memristor has no need for selector devices, but possess the one-way transmission behavior and multi-level non-volatile memory characteristics, which makes it promising candidate for electronic synapse. In this letter, we propose a novel self-rectifying memristor based on Pt/Hf_{0.5}Zr_{0.5}O₂/TiN structure. The devices show large memory window (10⁴) and high rectifying ratio (10⁴), which can block the sneak current in passive crossbar array without any additional hardware overhead. Moreover, the devices demonstrate excellent multi-level states modulation capability, low power consumption, high endurance and long retention. The final benchmark demonstrates that the proposed Pt/Hf_{0.5}Zr_{0.5}O₂/TiN self-rectifying memristor is a promising candidate for electronic synapse application.

Introduction: Due to the simple structure, multi-level operation and non-volatile memory capacity, memristor has been considered as a potential synapse device for constructing brain-inspired computing systems, which is expected to break the von Neumann bottleneck in traditional computing system [1,2]. Nonetheless, the sneak current, flowing through unselected cells in passive crossbar array, will lead to read-out errors and failure of program operations. Though additional selectors (i.e. transistors or diodes) in serial can solve the sneak path issues, they will lower the integration density due to their larger size. The self-rectifying memristor cell, whose nonlinear and asymmetric current-voltage characteristics can greatly suppress the sneak current flowing through the unselected cells, is attracting significant attention because of their simple two-terminal structure and 3D integration ability [3,4]. However, most current type self-rectifying memristors suffer from relatively small memory window and high-power consumption. Thus, new self-rectifying memristor is needed for being a promising candidate in electronic synapse applications.

In this letter, by using the amorphous high- k Zr-doped hafnium oxide as resistive switching material, we propose a novel self-rectifying memristor based on Pt/Hf_{0.5}Zr_{0.5}O₂/TiN structure. Experimental results demonstrate the as-fabricated device has high rectifying ratio (10^4) and large memory window (10^4), which is sufficient to suppress sneak path issue in Mb-level passive crossbar array. Moreover, the devices possess excellent multi-level states, endurance (10^6) and non-volatility (10^3 s) capability. The excellent resistive switching performance can be ascribed to the trap-controlled space charge limited current (SCLC) effect in Hf_{0.5}Zr_{0.5}O₂ films. The final benchmark demonstrates the outstanding self-rectifying performance with previous reported devices.

Devices and experiments: The proposed self-rectifying memristors were fabricated with a 10-nm-thick Hf_{0.5}Zr_{0.5}O₂ (HZO) layer sandwiched between TiN top electrode and Pt bottom electrode, as shown in Fig. 1a. The vertical lines of Pt/Ti (25/5 nm) were deposited on the SiO₂/Si substrate as bottom electrode by e-beam evaporation after the first lithography process. Then a 10-nm-thick HZO layer was deposited on the Pt bottom electrode at a stage temperature of 280 °C. The Hf[N(C₂H₅)CH₃]₄, Zr[N(C₂H₅)CH₃]₄ and H₂O were used as hafnium precursor, Zr precursor and oxygen source, respectively. The hafnium/zirconium ratio was controlled by alternate deposition of one HfO₂ cycle and one ZrO₂ cycles. Finally, the horizontal lines of TiN (30 nm) were deposited by magnetron sputtering. The cell areas of the devices range from 9 μm^2 (3 $\mu\text{m} \times 3 \mu\text{m}$) to 2500 μm^2 (50 $\mu\text{m} \times 50 \mu\text{m}$). During the electrical measurement, the voltage was applied to the Pt bottom electrode and the TiN top electrodes were grounded.

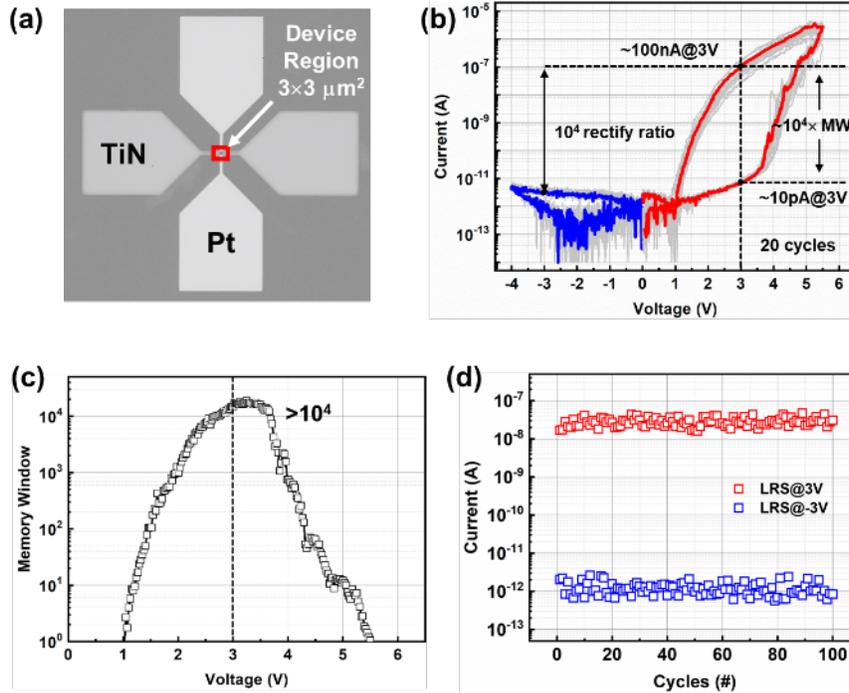


Fig. 1 (a) Device structure of self-rectifying Pt/HZO/TiN device. (b) Typical I - V characteristics in DC-sweeping mode. (c) The memory window with applied positive voltages. (d) The read currents distribution under $\pm 3\text{V}$.

Results and discussion: Fig. 1b shows 20 I - V hysteresis loops of Pt/HZO/TiN device in DC sweeping mode. Notably, no electroforming and no compliance current is needed to trigger the reproducible switching behaviors. The memory window of $\sim 10^4$ and rectify ratio of $\sim 10^4$ can be obtained with 3 V read voltage. The read currents of high resistance state (HRS) and low resistance state (LRS) are ~ 10 pA and ~ 100 nA, indicating the potential for low-power applications. Fig. 1c and 1d show the memory window with applied

positive voltages and the read currents distribution under ± 3 V, respectively. These results further confirm the self-rectifying resistive switching behaviors in the proposed Pt/HZO/TiN device. According to a SPICE-based circuit analysis, where the parasitic wire resistance between adjacent cells is estimated as $R_{\text{wire}} = 10 \Omega/\text{cell}$, the rectify ration of 10^4 and memory window of 10^4 are able to support passive crossbar array integration scale up to Mb-level [5,6].

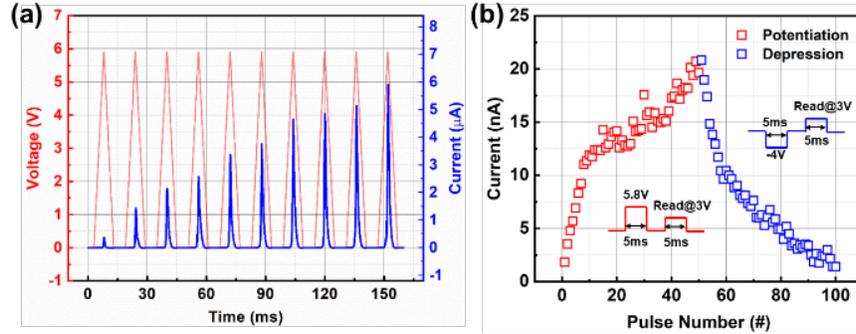


Fig. 2 (a) The I - t and V - t curves under triangle pulses (5.8 V, 10 ms). (b) Potentiation and depression process by positive pulses (5.8 V, 5 ms) and negative pulses (-4 V, 5 ms).

The multi-level states modulation capability of self-rectifying Pt/HZO/TiN device is shown in Fig. 2. The I - t and V - t curves of Pt/HZO/TiN device under triangle pulses (5.8 V, 10 ms) are shown in Fig. 2a. The gradual increase of response current demonstrates the potential for multi-level modulation. Then, the identical rectangle pulses (5.8 V, 5 ms) for potentiation and (-4 V, 5 ms) for depression are employed to further investigate the device performance. It should be noted that all the current was readout at the same read pulse (3 V, 5 ms). As seen from Fig. 2b, the read current was gradually tuned up by 50 potentiation pulses and down by 50 depression pulses. The above results confirm the good gradual switching properties of self-rectifying Pt/HZO/TiN device under both potentiation and depression pulses, which can be used to mimic the synaptic behaviors in brain-inspired computing systems.

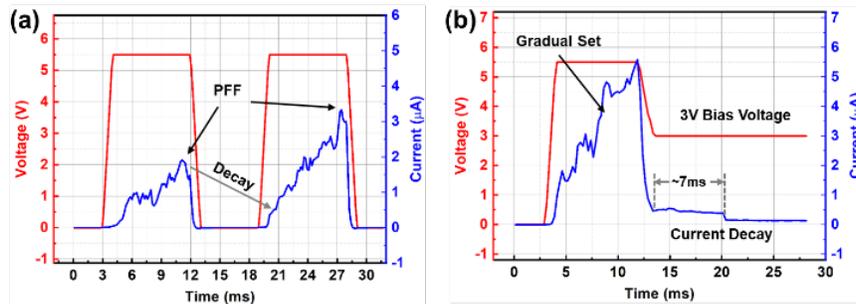


Fig. 3 (a) PPF function under a pair of positive pulses (5.5 V, 10 ms). (b) short-term plasticity after removing the operating pulse.

Pair-pulse facilitation (PPF) is an important short-term synaptic function involved in several neuronal tasks, such as reinforcement learning and information filtering [7]. Fig. 3a shows the experimental demonstration of PPF function in the proposed Pt/HZO/TiN device. When a pair of pulses (5.5 V, 10 ms) was applied to the device, the response current gradually increased during the positive bias, and the maximum response current of the second pulse was clearly larger than the first one. But the current at the beginning of the second pulse is obviously smaller than that at the ending of the first pulse, which means a decay during the pulse interval. Fig. 3b further shows the short-term plasticity of the self-rectifying device. After removing

the operation pulse (5.5 V, 10 ms), the device state can be maintained for about 7 ms, monitoring by the 3 V bias voltage. Thus, the short-term plasticity can also be realized in Pt/HZO/TiN device.

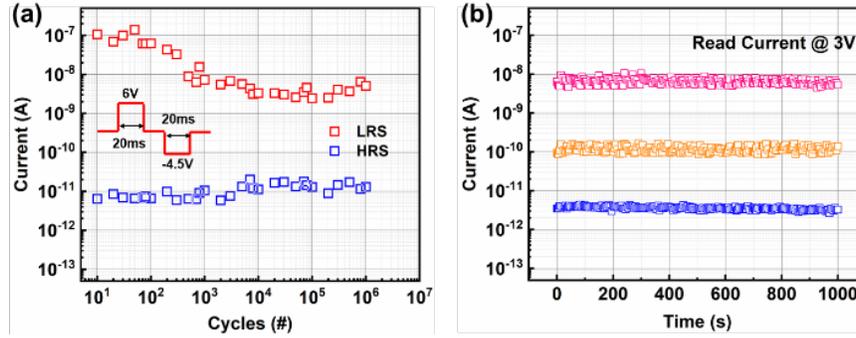


Fig. 4 (a) Endurance property under operation pulses (6 V, 20 ms) and (-4.5 V, 20 ms). (b) Retention property of the representative three conductance states.

The endurance and long-term retention property are also investigated, as shown in Fig. 4. The fatigue could be observed at $10^2 \sim 10^3$ endurance cycles, but no dielectric breakdown was observed even after 10^6 pulses, as shown in Fig. 4a. Three representative conductance states were selected for retention tests, and each state was monitored by a 3 V bias every 5 seconds. As seen from Fig. 4b, all the three states successfully lasted 1000 seconds without noticeable degradation at room temperature.

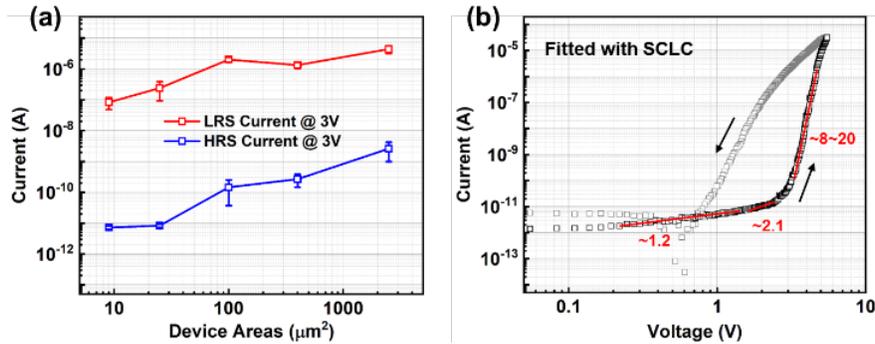


Fig. 5 (a) Area dependence of the read current. (b) Fitted I - V curves with SCLC conduction mechanisms.

Then, the underlying mechanism of the self-rectifying Pt/HZO/TiN device is investigated. Fig. 5a shows the area dependence of read currents in LRS and HRS, respectively. The read current for each device area were obtained from 20 switching cycles. As the device area increase from $9 \mu\text{m}^2$ to $2500 \mu\text{m}^2$, the read currents of both LRS and HRS increase approximately linearly, indicating an interface-type rather than localization-type resistive switching behavior. Fig. 5b shows the fitted I - V curves with SCLC conduction mechanism. A typical I - V characteristic plotted in a log-log curve for SCLC is bounded by the three limited curves, ohm's law ($I \propto V$), traps filled limit current ($I \propto V^2$) and Child's law. The result in Fig. 5b is consistent with the features of SCLC conduction mechanism.

Finally, a benchmark especially on rectify ratio, memory window, read power and endurance is provided in Table 1. Compared with previous self-rectifying devices, the proposed Pt/HZO/TiN devices in our work show competitive advantages, such as the largest memory window, lowest read power in HRS state.

Table 1. Performance benchmarking between our self-rectifying device and previous results.

	Device Structure	Rectifying Ratio	Memory Window	Read Power (HRS, nW)	Endurance
1 [8]	TiN/Al-HfO _x /SiO ₂ /Si	300	~7	0.2	10 ⁵
2 [3]	Pt/C/NbO _x /TiN	10 ⁶	~25	100	~3×10 ³
3 [2]	Ru/HSO/Al ₂ O ₃ /HSO/TiN	10 ⁴	~5	0.8	10 ⁶
This work	Pt/HZO/TiN	10⁴	10⁴	0.03	10⁶

Conclusion: In summary, we have proposed a novel self-rectifying memristor based on Pt/HZO/TiN structure. The devices show large memory window (10⁴) and low power consumption (0.03 nW @ HRS). These properties make the devices especially suitable for low-power artificial synapse and embedded non-volatile memory applications.

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Conflict of interest: There is no conflict of interest in this paper.

Data availability statement: Data available on request from the authors (the data that support the findings of this study are available from the corresponding author upon reasonable request).

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