Supporting Information

Optoelectronic synapse based on $Mg_{0.1}Zn_{0.9}O/TiO_2$ heterojunction for neuromorphic computing

Xuan Gu[1,2], Jiaying Chen[1,2], Tianfu Zhang[3], Zhenhua Tang[1,2], Yanping Jiang[1,2], and Xingui Tang[1,2]*

[1]*School of Physics & Optoelectric Engineering, Guangdong University of Technology, Guangzhou, 510006, China*

[2]*Guangdong Provincial Key Laboratory of Sensing Physics and System Integration Applications, Guangdong University of Technology, Guangzhou, 510006, China*

E-mail: xgtang@gdut.edu.cn (Xingui Tang)

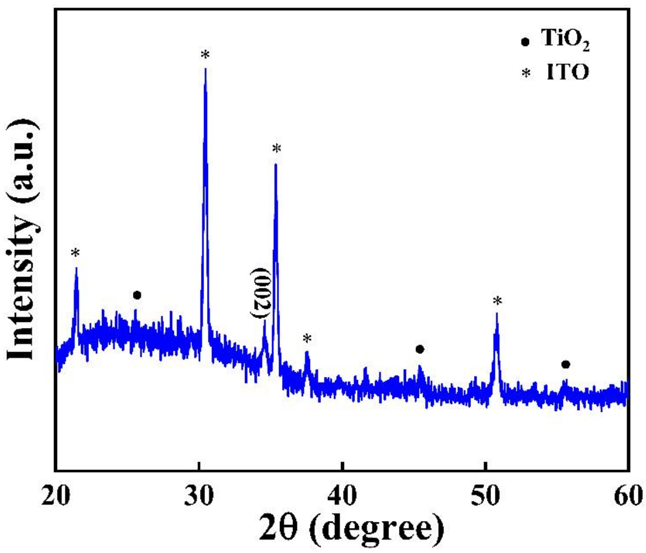

Fig.S1 XRD pattern of the MZO/TiO_2 device.

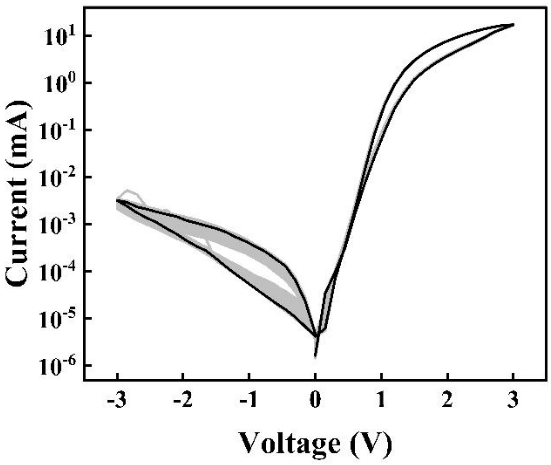

Fig.S2 *I*–*V* cycling characteristics of the MZO/TiO_2 device under 50 consecutive voltage sweeps from −3V to 3V.

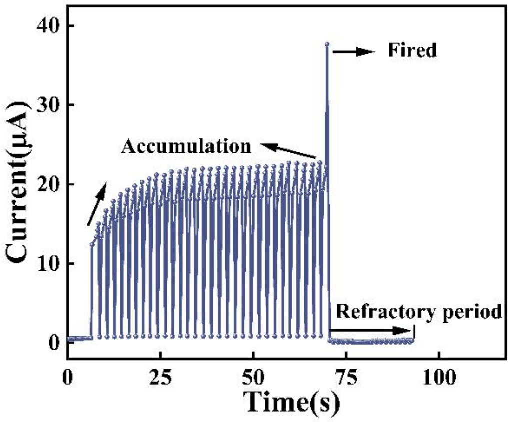

Fig.S3 Emulation of leaky integrate-and-fire (LIF) neuronal behavior by the MZO/TiO_2 device.

The leaky integrate-and-fire (LIF) neuron model is designed to emulate the core physiological mechanisms of charge accumulation dynamics across the cell membrane in biological neurons. From the perspective of bioelectrical activity, neurons receive action potentials from presynaptic neurons through synaptic connections. When the accumulated membrane potential reaches a certain threshold, an output spike is triggered. Continuous presynaptic pulses cause membrane depolarization, and if the depolarization surpasses the threshold, an action potential is generated and propagated to downstream neurons.

Under the stimulation of thirty consecutive pulses with a width of 0.4 s, amplitude of 1 V, and interval of 0.1 s, the MZO/TiO_2 neuromorphic device exhibited an integrative response. Upon receiving the 31st pulse with an amplitude of 11 V, the signal intensity surpassed the threshold, triggering a firing event analogous to the leaky integrate-and-fire (LIF) behavior observed in biological neurons. Subsequently, the device exhibited a spontaneous leakage process and entered a refractory period during the following fourteen pulses (width: 0.4 s, amplitude: 1 V, interval: 0.1 s). Notably, the characteristic leaky integration behavior of neurons enables a potential recovery mechanism when the threshold is not reached. In the absence of sufficient presynaptic input, the membrane potential gradually returns to its resting state through ionic leakage. The LIF model reveals the fundamental signal processing functions of neurons, including synaptic input integration, threshold comparison, and spike generation. Compared with circuit-based implementations, a single-device LIF neuron offers advantages such as lower fabrication cost and simpler operation

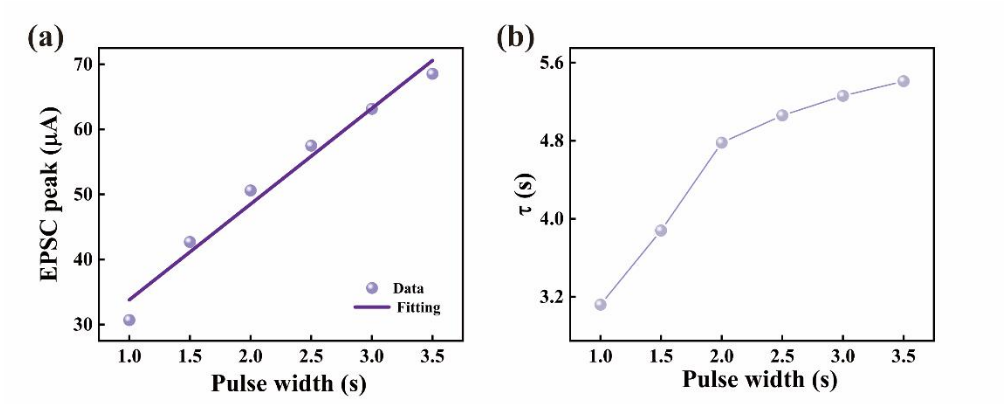

Fig.S4 (a) Variation of EPSC peak under stimulation with different pulse widths; (b) Relaxation time of EPSC under different pulse widths.

As shown in Fig. S4(a), the EPSC peak increases proportionally with the input pulse width, exhibiting a typical feature of spike-width-dependent plasticity (SWDP). Specifically, the EPSC peak shows an approximately linear growth trend as the pulse width increases. Mechanistically, this linear response may be attributed to the ionization of oxygen vacancies in the MZO functional layer: wider pulse stimuli can induce higher ionization efficiency of oxygen vacancies, generating more mobile charge carriers. Notably, under various pulse width conditions, the dynamic variation of EPSC amplitude consistently maintains a stable linear growth behavior. This predictable response characteristic provides a solid foundation for the application of the device in neuromorphic computing.

In Fig. S4(b), the relaxation process of the EPSC follows the equation below:

$$I(t) = \mathrm{I}_0 exp(-\left(\frac{t}{\tau}\right)^{\beta}) \qquad (3)$$

Here, τ represents the relaxation time constant used to evaluate the forgetting rate, and β is the stretch index. The decay of EPSC resembles the Ebbinghaus forgetting curve. As shown in Fig. S4(b), the relaxation time constant τ increases with increasing pulse width, indicating that broader pulse widths may facilitate the transition from short-term memory (STM) to long-term memory (LTM). According to the hypothesis of the Ebbinghaus forgetting curve, human memory fades over time, reflecting how information is lost in the brain as time progresses. The observed increase in τ with pulse width suggests enhanced memory retention, further supporting the potential of the device to emulate the memory dynamics of biological systems.

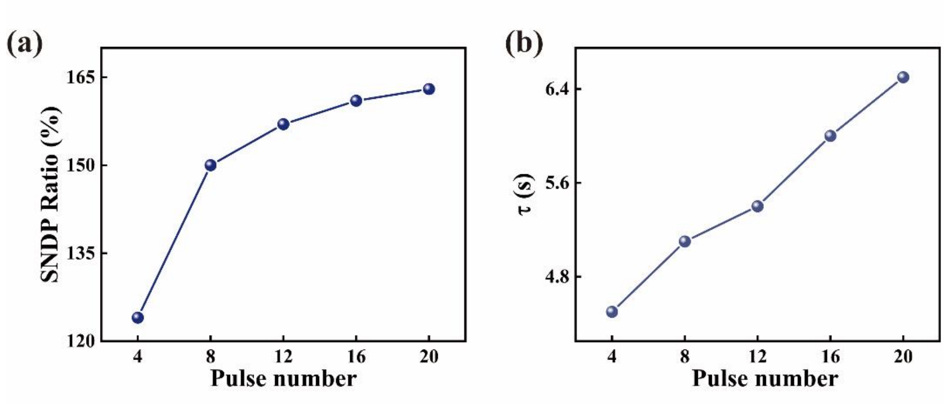

Fig.S5 (a) Ratio of spike-number-dependent plasticity (SNDP); (b) EPSC relaxation time under different numbers of input pulses.

Fig. S5(a) further illustrates the modulation of synaptic weight by the number of input pulses through the calculation of the spike-number-dependent plasticity (SNDP) ratio. The SNDP ratio is defined as A_n/A_1, where A_n is the EPSC peak value induced by the nth pulse, and A_1 is the EPSC peak value induced by the first pulse. It can be observed that when the number of pulses reaches its maximum, the SNDP ratio increases up to 163%.

Similar to Fig. S4(b), Fig. S5(b) shows that the relaxation time constant τ increases with the number of input pulses, indicating an extension of memory retention time. This suggests the potential for the device to realize a transition from STM to LTM.

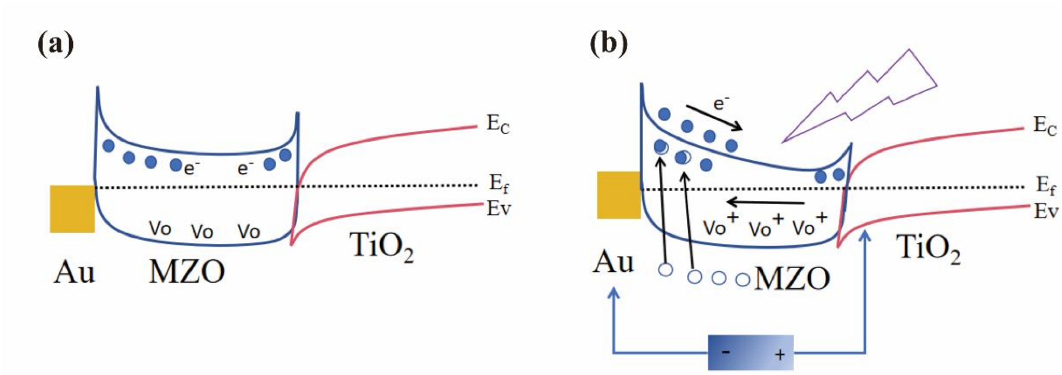

Fig.S6 Schematic illustration of the charge transport mechanism in the Au/MZO/TiO_2/ITO optoelectronic synaptic device under dark and ultraviolet illumination conditions. (a) Energy band diagram of the device in the dark state, showing the formation of interfacial band bending, space charge region, and defect states in the MZO layer. (b) Energy band diagram of the Au/MZO/TiO_2/ITO device under 365 nm ultraviolet illumination, illustrating the generation, separation, trapping, and gradual release of photogenerated carriers regulated by the MZO/TiO_2 heterointerface and defect states associated with oxygen vacancies.