A Hybrid Phototransistor Neuromorphic Synapse

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ABSTRACT In this paper, a synaptic transistor based on the indium zinc oxide (IZO)–hafnium oxide (HfO$_2$) thin film structure was demonstrated. Blue light pulses (470 nm) were used as the presynaptic stimulus, the IZO channel was used as the postsynaptic membrane, and the HfO$_2$ electrolyte film was regarded as the synaptic cleft. The synaptic transistor exhibited the behavior of paired-pulse facilitation. With different light power densities, the channel current of the transistor can be regulated to different levels, corresponding to different synaptic weights. In addition, the transistor showed the brain's memory behaviors including the short-term memory and the transition from the short to the long term memory. The synaptic behaviors of the transistor can be explained by the trapping and releasing processes of the photo-generated carriers.

INDEX TERMS Artificial synapse, light-stimulated, IZO, HfO$_2$.

I. INTRODUCTION

Modern computers are based on the von Neumann' architecture, in which the processor and memory are physically separated [1]. The architecture is becoming increasingly inefficient for the intense computation in artificial intelligence (AI), virtual reality (VR) or Internet of Things (IoT), mainly due to the physical separation between the computing cells and memories. In contrast, the human brain is a parallel and reconfigurable network with low power consumption [2]. Therefore, the research of brain-inspired systems is attractive and important to improve the computation capability. The human brain contains $\sim 10^{11}$ neurons connected by $\sim 10^{15}$ synapses. The synapse emulation is a key step to realize the complex neuromorphic computation systems [3]. Many works have been devoted such as the two-terminal resistance random access memory (RRAM) and the three-terminal synaptic transistors [4]–[10]. However, these reported simulated synapses were usually stimulated with electrical signals, which may bring a limited bandwidth and a large RC delay for signal transmission [11], [12].

Recently, the development of optoelectronic devices has achieved many progresses [13]–[16]. Light-waves or photons represents a potential avenue to implement neural networks, which offer robustness, ultrafast speeds, and superior connectivity between discrete computing modules [11]. Light induced transistor using InGaN/GaN quantum-well diodes were demonstrated to mimic synaptic [17], [18]. Although these works are noteworthy, they require highly sophisticated fabrication process, device architectures, or materials. Another effective method for light-stimulated synapse was electric-double layer (EDL) based transistors [19], [20]. The fabrication is simple, but these devices are not stable enough, deeper understanding of their mechanisms needs to be studied to fully take advantages of these new devices. Thus, the demonstration of a light-stimulated synapse with steady and easy preparation is significant for the brain like system in the future.

Here, indium zinc oxide (IZO)-based light-stimulated synaptic transistors gated by an HfO$_2$ layer were demonstrated. Synaptic plasticity and memory behaviors including paired-pulse facilitation (PPF), short-term memory (STM)
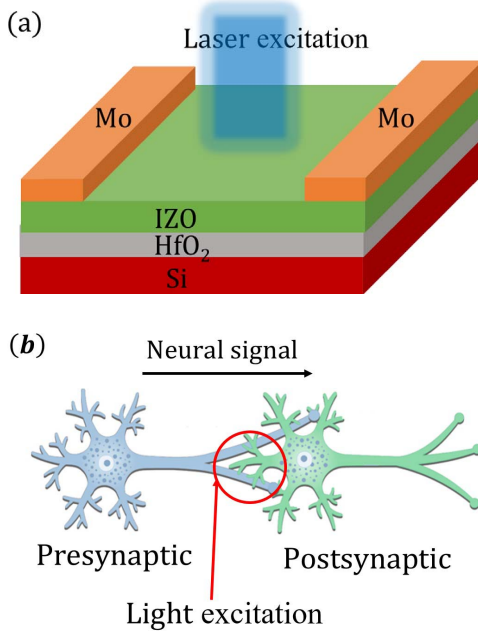
FIGURE 1. (a) Schematic image of the IZO-HfO₂ synaptic transistor with light excitation as stimulus. (b) Simple schematic picture of an artificial synapse.

FIGURE 2. (a) Measured transfer characteristics of the IZO-HfO₂ synaptic transistor with V_{DS} = 2 V. (b) Output characteristics of the synaptic transistor.

FIGURE 3. (a) Photo-carriers generated by light and some of them diffused to IZO/HfO₂ interface and HfO₂ layer. (b) Some of the photo-generated holes were trapped after light illumination, inducing electrons in the IZO channel. (c) More photo-generated holes were generated and trapped by oxygen vacancy when continuous light stimulus were applied. (d) More electrons induced in the IZO channel after the stimulus in (c).

and long-term memory (LTM) were mimicked in this synaptic transistor with light stimulus.

II. EXPERIMENTAL DETAILS

The IZO-HfO₂ based synapse is schematically shown in Fig. 1(a), which has the conventional bottom-gate structure. The fabrication process of the device was performed as follows. Firstly, a 30-nm-thick HfO₂ layer was deposited on heavily doped p-type silicon by atomic layer deposition (ALD) method at 200 °C. Next, a 40-nm-thick IZO film as the channel layer was deposited by direct current (DC) sputtering and then patterned (size: 30 μm×100 μm) by lift-off. Finally, a 200-nm-thick molybdenum (Mo) layer was deposited by sputtering at room temperature and then patterned by lift-off to form the source and drain electrodes. The fabricated synapse device was characterized using a semiconductor parameter analyzer (Keysight B1500A). The transfer characteristics were measured in a reverse-sweep mode with the gate voltage (V_{GS}) sweeping from −8 V to 8 V and the drain voltage (V_{DS}) fixed at 2 V.

III. RESULTS AND DISCUSSION

Fig. 1(a) shows the schematic diagram of the IZO based light–stimulated synaptic transistor. Since the IZO film is sensitive to visible light, we chose the blue light pulses (wavelength: 470 nm) as the stimulating signal. The transistor can be seen as an artificial synapse, where the incident light source is used as the pre-synaptic membrane, the IZO channel is used as the post-synaptic membrane, and the HfO₂ electrolyte film is regarded as the synaptic cleft, as shown in Fig. 1(b).
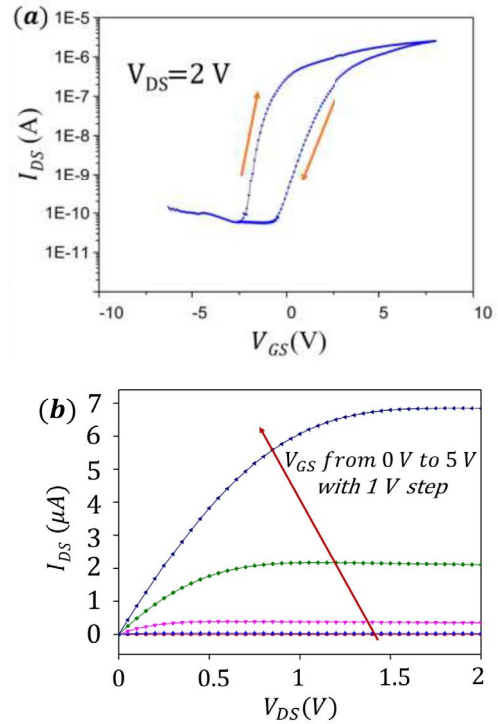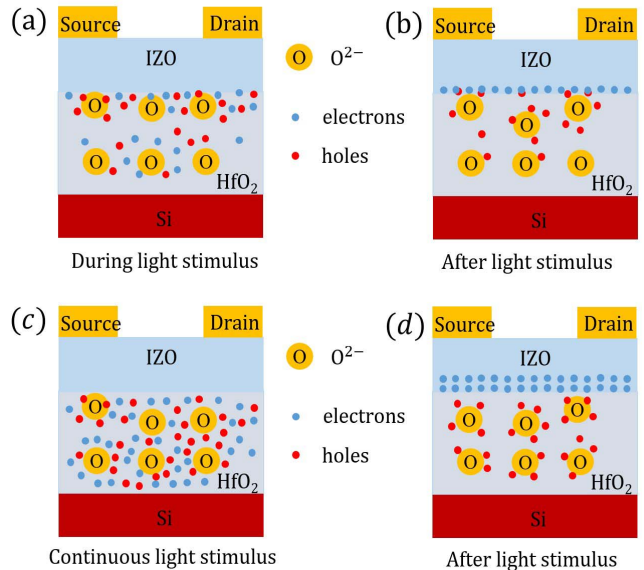
We measured the electrical properties of the transistor without light in the beginning. The transfer curve with V_{DS} = 2 V of the back-gate transistor is shown in Fig. 2(a), by
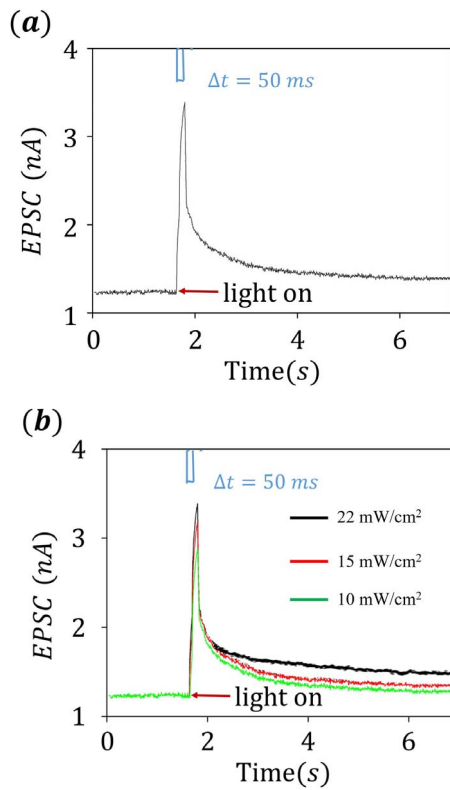
(a)

(b)

FIGURE 4. (a) EPSC of the synaptic transistor triggered by a presynaptic light spike. (b) EPSC of the synaptic transistor with different synapse weights.

(a)

(b)

FIGURE 5. (a) PPF in the synaptic transistor. EPSCs generated by two light spikes with an interval time of 50 ms. (b) PPF of paired presynaptic spikes with different interval times.

sweeping V_{GS} from -8 V to 8 V forward and backward. A clockwise hysteresis of ~ 5 V was observed. The on/off current ratio and threshold voltage under 2 V reading voltage were estimated to be 10^5, and 0.5 V, respectively. This hysteretic phenomenon can be explained as carriers being trapped by the defects like oxygen vacancy in the HfO_2 insulating layer and IZO/HfO_2 interface [21]. The typical output characteristics of the synaptic transistor are shown in Fig. 2(b), by sweeping V_{GS} from 0 V to 5 V with 1 V step.

Photo-carriers were generated in the IZO layer with light illumination and some of them diffused to HfO_2 layer as shown in Fig. 3(a). A photocurrent was produced under the influence of the source-drain voltage, leading to an increased post-synaptic current. Considering the effects of oxygen vacancy in HfO_2 layer and IZO/HfO_2 interface (oxygen vacancy equivalent to oxygen ions with negative charges, O^{2-}). The mechanism of the synaptic transistor can be explained as follows [22]. Some of the photo-generated holes were trapped after light illumination. Furthermore, some oxygen vacancies are not saturated and can trap more holes, as shown in Fig. 3(b). The trapped holes induced electrons in the IZO channel. As a result, the postsynaptic current does not disappear immediately when the light illumination is turned off. A decay of the postsynaptic current will be observed during the off periods of the light pulses. This process was demonstrated to mimic synaptic STM. When
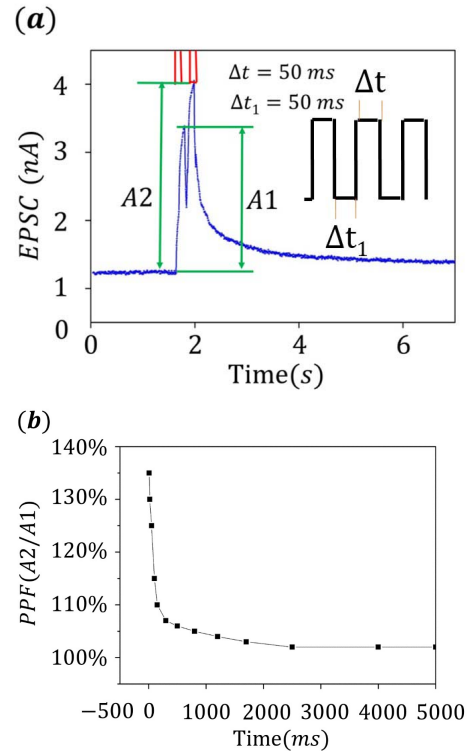
a higher light power was applied (or increasing the time of illumination), more photo-generated holes will be generated and trapped by oxygen vacancy as shown in Fig. 3(c). Fig. 3(d) shows the trapped holes induced more electrons in the IZO channel and result a larger postsynaptic current. The process was demonstrated to mimic synaptic LTM.

The excitatory post synaptic current (EPSC), an essential function of biological synapses, was mimicked by the delay characteristic of HfO_2 layer, as shown in Fig. 4(a). A spike of postsynaptic current was generated when a presynaptic spike was applied, and gradually decayed to its initial level in a short-term time after the light was turned off, due to some holes diffused to IZO channel and recombined with electrons. On the other hand, some holes were trapped, resulting the postsynaptic current a little bigger than initial current after light stimulation as shown in Fig. 4(a), where the power density is 22 mW/cm². When the light power reduced to 15 mW/cm² and 10 mW/cm² (the stimulation time is same), as shown in Fig. 4(b), the EPSC changed accordingly. Thus, many synaptic weights that can be represented by various EPSC, which can be obtained by adjusting the light power, this phenomenon is similar to the process in neural computing.

Based on the analyses above, there will be an accumulation of the trapped holes, leading to an increase in the postsynaptic current with an increasing number of the light pulses. When two consecutive presynaptic spikes are applied,
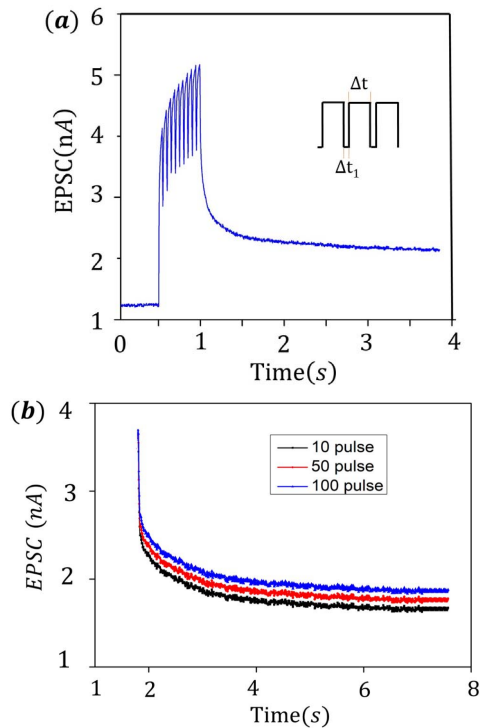
FIGURE 6. (a) EPSCs triggered by 10 stimulus spikes. (b) The realization of the synaptic transistor transitioned from STM to LTM.

the second EPSC will be enhanced as shown in Fig. 5(a). The power density is also 22 mW/cm². Δt is the duration time of one pulse, Δt_1 is an interval time of two pulses. We choose $\Delta t = \Delta t_1 = 50$ ms in Fig. 5(a). This phenomenon can be used to mimic the PPF in the nerve systems [23]. PPF is a form of short-term synaptic plasticity that plays a significant role in learning and information processing in human brain.

Two presynaptic light pulse were applied to the IZO layer with an interval time of 50 ms, and the EPSC driven by the second spike was 130% larger than that by the first spike. The EPSC amplitude gradually decreased with the spike train frequency as shown in Fig. 5(b). The longer the interval time between two presynaptic spikes is, the less facilitation will be. The PPF ratio was reduced to nearly 100% when $\Delta t = 3000$ ms.

Synaptic plasticity is important in biological synapses, which can be classified into two types by the retention time, STM and LTM, respectively. The STM is a short temporal potentiation of the synaptic connection, which lasts for as brief as a few minutes or even less. The LTM is a permanent change of the synaptic connection, which usually lasts for hours to years. The plasticity level could be strengthened through a process of rehearsal. In our case, synaptic transistors could be implemented to mimic such psychological functions by changing the number of the light pulses. Fig. 6(a) shows the postsynaptic current change when 10 light pulses (22 mW/cm², 50 ms) are applied on the IZO channel. The interval time of two pulses is 10 ms.

The postsynaptic current increased step by step, and finally a permanent higher value than initial state was obtained. Such permanent higher current can be regarded as a "LTM" state. The STM process stimulated by a transient light pulse is mostly due to the reversible modulation by mobile holes, whereas the LTM process is due to the irreversible doping by trapped holes under a continuous pulse as demonstrated in Fig. 6(b). The EPSC change recorded after the last pulse of the light stimulus series of 10, 50, and 100 pulses, respectively. STM was changed to LTM by more stimulating light pulses. Persistent electric doping of the IZO channel corresponds to the construction of new proteins for LTM processes in biological systems.

IV. CONCLUSION

In summary, a light-stimulated synaptic transistor based on IZO-HfO₂ was first demonstrated using standard lithography process, indicating the possibility of its integration into complex circuits. EPSC, PPF, STM and LTM were also mimicked in the synaptic transistor. Although the device is initial and needed an extended investigation, the advantages of the new electronic synapse can have significant applications and become important in the near future.

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