Zinc Tin Oxide Synaptic Transistor with Ion-gel in Different Concentrations for Neuromorphic Application

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ABSTRACT

The component of three-terminal bionic neural based on zinc-tin-oxide semiconductor (ZTO) with Ion-gel in three different concentrations as the insulating layer was fabricated in this paper. We proved the short-term plasticity (STP) characteristic was increased with the addition of [EMIM][TFSI], where the best paired-pulse facilitation (PPF) ratio was 162 %.

1 Introduction

Von Neumann model, as the architecture used by the vast majority of modern computers, has made great contributions to the development of various fields, demonstrating the success of this architecture, but this model of separating memory and processing units leads to a von Neumann bottleneck, especially when performing ultra-fast operations.[1]

As the most powerful processor known so far, the human brain is not only capable of fetching instructions and operating data at the same time, but also its strengths in highly complex visual recognition, language cognition, and ultralow energy consumption [2-3]. If artificial synapses or brain-like computing can be developed, it will become one of the candidates for the development of new generation computer architectures.

Synapse refers to the connection structure in which neurons transmit signals to other cells in an organism, as shown in Fig. 1, which can strengthen or weaken the connections between neurons as needed. In order to quantify the strength of connections between neurons, scientists named it as synaptic weights. At the same time, this phenomenon of regulating neural information transmission through a synapse, which we call synaptic plasticity, can be divided into short-term plasticity (STP) and long-term plasticity (LTP) according to the duration of time.

Short-term plasticity, the most commonly discussed is Paired-pulse facilitation (PPF), when the pre-synapse receives two action potentials of the same intensity and very close in time, the post-synapse produces a response that is stronger than the previous one. This changing current is called the excitatory postsynaptic current (EPSC). The opposite of this phenomenon is paired-pulse depression (PPD).

Zinc-Tin-oxide semiconductor (ZTO), under the research in recent years, its characteristics are not far from IGZO semiconductor [4] and does not use the precious metals indium (In) and gallium (Ga) whose prices are rising year by year. Therefore, we choose this material to make the semiconductor layer.

To make the transistor have the learning ability, we used the ion-gel layer (Ion-gel, hereinafter called IG) made of PVDF-co-HFP and [EMIM][TFSI] as the insulator. The flexible compatibility and the ability to block leakage current are exceptionally good [5]. L, K. Hyung et al. found the transistor had an outstanding capacitance at the low frequency when the weight ratio between the polymer and the ionic liquid was [1:4] [6]. We use a different composite ratio of IG to verify the trend of capacitance. Based on the capacitance result, we try to improve the interface between the dielectric and semiconductor layer for getting better synapse characteristics.

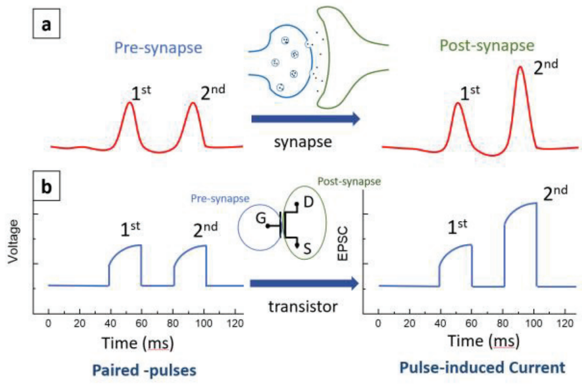

Fig. 1(a) Paired-Pulse Facilitation (PPF) in biological synapses (b) Emulate PPF using electrical signals

2 Experiment

Fig. 2 shows the structure of the transistor that combines a traditional bottom transistor and an IG top transistor. For the bottom transistor, Al was first made as a gate electrode on the standard-cleaned glasses. Sputtered Ti/Al/Ti source/drain electrodes by the thickness of 100 nm were followed. Silicon nitride was deposited as the bottom transistor gate insulator. Make up the semiconductor solution with Zinc acetate and stannous chloride, and used MEA be the chelating agent to configure 0.3 M ZTO. Spin-coated ZTO on the device and annealed at a high temperature of 500 ℃. Then, the procedure of the top bionic transistor was going. The Ion-gel mixed with PVDF-co-HFP, [EMIM][TFSI] and acetone were prepared at weight ratios of [1:2:7], [1:4:7], and [1:6:7], respectively. We use " cut and stick " to manufacture insulator IG [6] (Spin coating on the washed glasses at 500 rpm for 3 sec. Spin-coated ion-gel layers were placed in an oven at 70 ℃ for 2 h to remove the residual solvent). At the end of component fabrication, silver is attached to the IG as a gate electrode.

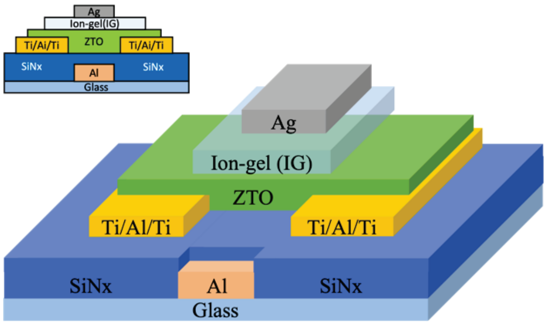

Fig. 2 Device configuration.

3 Results and Discussion

3.x Transistor characteristic

For the sake of comparing systematically, all the transistors' channel width/length are fixed at 500 μm/50 μm. Then the samples with different ratios of IG are characterized carefully by applying appropriate gate and drain voltages, and the results are compared with the control device without IG. Fig. 3 and Table 1 show the comparison results between the top bionic transistor with identified IG ratio of 1:4:7 and the bottom traditional transistor with SiN_x as gate insulating layer.

It can be seen from Fig. 3 that the operating range, drain (V_d=0.5 V) and gate (V_g=0~1 V) voltage of the top bionic device with IG, is considerably lower than that of the bottom device with SiN_x (V_d=5 V, V_g=-5~30 V). Also, in Table 1, the threshold voltage (V_{th}) of using IG as the insulating layer is maintained at about 0.2 V, and the Subthreshold slope (S.S.) is about 0.1 V/dec. Ion-gel greatly reduces operating voltage when compared to conventional gate insulators.

This result is in line with the theoretical expectation. After the ions in the IG are driven by the voltage at the gate terminal, anions and cations are separated toward two opposite sides in the ion-gel layer, then a double-layer capacitor structure is formed, which would induce a large internal electrical field and thus reduces the voltage required for operating transistor and achieve good transistor characteristics.

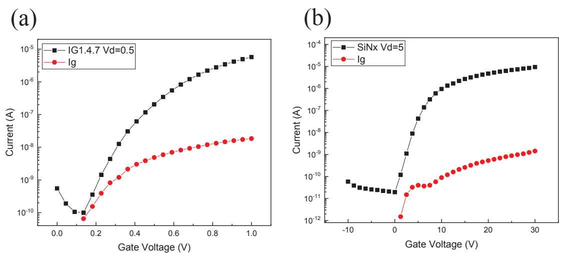

Fig. 3 The transfer curves of transistors with Ion-gel and SiN_x gate insulators, respectively. (a) Ion-gel. (b) SiN_x

Table. 1 The transistor's On/Off ratio, Subthreshold slope, Threshold voltage in different gate insulators

insulator	V_{th} (V)	On/Off ratio	S.S. (V/dec)
SiN_x	1.45	4.7×10^5	1.43
IG 1.2.7	0.25	2.5×10^4	0.12
IG 1.4.7	0.13	5.7×10^4	0.09
IG 1.6.7	0.26	5.6×10^5	0.07

Using constant drain voltage (V_d=0.5 V) and sweeping gate voltage (0~1 V) to characterize the hysteresis curves of different IG ratio devices, results as shown in Fig. 4.

Devices prepared with other ratio [1:2:7] and [1:6:7] of IG also reveal lower operating voltage, and the values of V_{th} are very close to the result of transistors with conventional gate insulators. However, the hysteresis window is similar for all the samples.

From the highest drain current value of each hysteresis curve, it can be found that the current value increases with the increase of ion concentration in IG. The highest drain current of the device with IG of 1:6:7 ratio is about 10^{-4} A, while the other sample, such as the IG of 1:2:7 ratio, is about 10^{-5} A. The reason which may come from the high concentration of IG with more ions, forming a larger double-layer capacitor to increase the internal electrical field and deduce more channel conduction carriers, thereby increasing the overall current value. Indeed, about the effect of the ion liquid and how by modulating the number of ions to influence the transistor's characteristics still need more research to clarify related mechanisms. In this paper, the results of the three conditions seem similar.

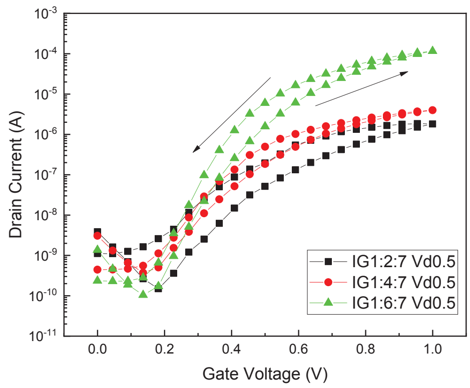

Fig. 4 The hysteresis curves of transistors with different IG of PVDF:EMIM:Aceton concentrations ratios.

Furthermore, according to the experimental results, when the trend of the hysteresis curve is clockwise, an inhibitory memory effect will be presented in the measurement of bionic-related characteristics, and the current will decay with the continuous stimulation of the voltage. On the contrary, when the trend of the hysteresis curve is counterclockwise, the bionic synapse transistor will exhibit an excitatory memory effect, and the current will increase as the voltage is continuously stimulated. The hysteresis trend of our samples is counterclockwise, so the synaptic characteristics of this element in the subsequent measurement are excitatory.

Overall, the device with IG of 1:4:7 ratio has a better value of other devices. This tendency may be explained by the double-layer capacitor, too. Although a mass of ions in IG may enhance the characteristics of the devices, it makes the ions more likely to aggregate into clusters, making the response to voltage worse and increasing the threshold voltage as the device with IG of 1:6:7 ratio showed. On the other side, we also found that the higher the concentration ratio of devices, the worse the reproducibility in fabrication. The solution with high concentration is hard to completely dissolve and too sticky, which makes it difficult to evenly coat and control the film thickness. In contrast, IG of 1:4:7 ratio has relatively stable quality and reproducibility.

3.y Synaptic Characteristics

In the nervous system, EPSCs can be triggered by the voltage spikes from the presynaptic neurons, which are converted to establish spatial and temporal correlated functions by the postsynaptic neurons. [7] Fig 5 shows the EPSC response of the presynaptic voltage, which performs the excitatory characteristics of the bionic transistor. The post-synaptic voltage is fixed at V_{post}=0.5 V, and two stimulation voltages are continuously given to the pre-synapse, where the peak voltage is V_{pre} = 1.0 V, the low peak is V_{pre} = 0.0 V, the interval time (△t) is 10 ms, and the duration pulse duration time (td) is 20 ms. It can be observed that the currents of excitatory post-synaptic currents (EPSC) change under two consecutive pulses, and their values are sequentially A1 and A2. Divide these two values to obtain the paired-pulse facilitation (PPF ratio) of this element, as shown in the following formula.

$$PPF\ ratio = \frac{A_2}{A_1} \times 100\%$$

A reasonable explanation for the increase in EPSC is proposed on the accumulated ions of the double-layer capacitor structure. The first presynaptic spikes accumulate ions at the ZTO/Ion-gel interface so that the next stimulation can accumulate more ions, form a more complete electronic channel, and increase the current. [8]

Fig 6 shows the PPF ratio generated by different ion ratio samples for different interval times (Δt). We observed that the gain ratio produced by the component can reach 162 % when the measurement interval Δt is 20 ms, for the device prepared with [1:4:7] of IG ratio. However, as the time interval (Δt) increases to 100 ms, its gain decreases to 114 %. The mechanism of PPF behavior is explained as follows. As the time is long enough for the ions to return to charge equilibrium, the effect of the first spike gradually disappeared, and the EPSC change caused by the first spike could be restored to its original state. [8]

In addition, we also found that the PPF value produced by IG of 1:4:7 is slightly higher than that of the other samples. The PPF ratio of the device with IG of 1:6:7 ratio is significantly lower than the other two, and the ratio value is between 110% and 100%, which can be regarded as no gain. We speculate that the excess ions in IG of 1:6:7 ratio will saturate the channel current, which causes the channel to no longer be stimulated by the gate voltage. Therefore, it shows the result that PPF does not change with interval time.

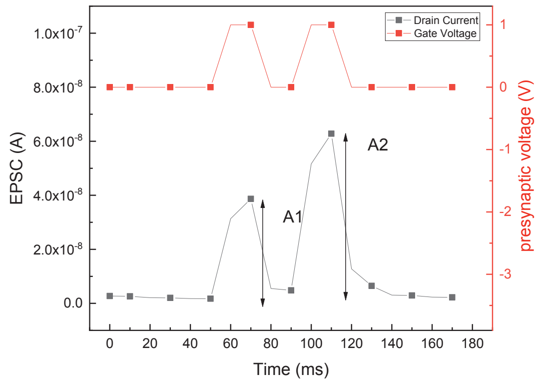

Fig. 5 The PPF measured with two successive presynaptic pulse (V_{pre} = 1.0 V, V_{post} = 0.5 V, t_d = 20 ms and Δt = 20~200 ms).

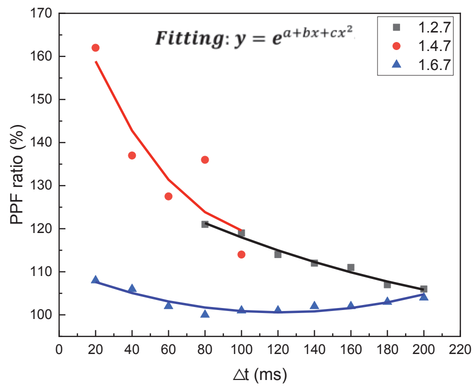

Fig. 6 The PPF ratio of bionic transistors with different IG concentrations.

Fig. 7 is the result of the corresponding drain current (I_d) generated by continuously giving the presynaptic the same pulse stimulation as above. It can be found that as the stimulation is continuously given, the current has a trend of gradually rising and reaching saturation, and each maximum gain is 234 %, 230 %, and 115 % in turn, which verifies that the synaptic transistors we made also have the same long-term synaptic plasticity (LTP) properties as real synapses.

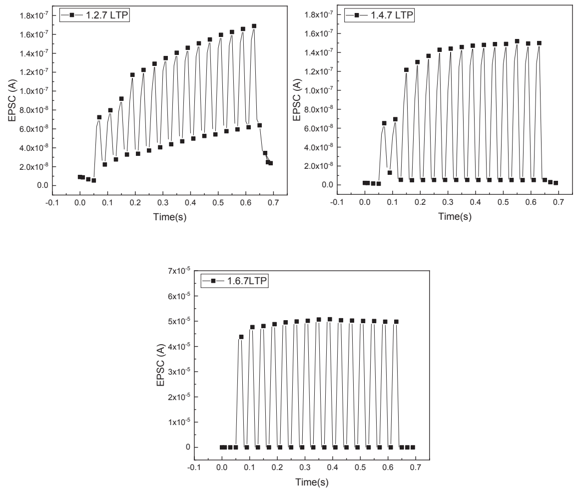

Fig. 7 The LTP (long-term plasticity) of bionic transistors with different IG concentrations.

4 Conclusions

We have successfully fabricated a three-terminal transistor that can simulate neural synapses, which can accomplish the effects of short-term memory (STP) and long-term memory (LTP). According to the research, we prove that it has a better PPF ratio of 162% for the synaptic transistor when the ion-gel layer was mixed with PVDF-co-HFP and [EMIM][TFSI], which weight ratio is 1:4. It means that this concentration is more suitable for the insulating layer of synaptic transistors than other concentrations of the ion-gel layer, which can produce memory effect for stimuli more efficiently.

The ion-gel layer is a material with many complex structures. Unlike ordinary materials, it has more complex internal reactions. Ion-gel can effectively reduce the operating voltage to 0.5 V and produce a double capacitor layer to increase the memory effect of components. So, the results of this experiment determine the material ratio of the ion-gel, which will be of great help to us in the study of bionic synaptic elements in the future. The weight ratio of 1:4:7 will be the basis for our research.

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