Exploring The Horizon of Neuromorphic Computing: Research Progress of Synaptic Transistor Materials

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Abstract. In recent years, with the rapid development of integrated circuits, Moore's law has become more and more difficult to maintain. The brain-like neuromorphic computing system based on the new brain-like device synaptic transistor provides an alternative way for future computers. At present, a large number of studies have tried to fabricate synaptic transistors with different materials, and simulated synaptic behavior successfully. In this review, the basic structure and function of synaptic transistors are described, and three kinds of materials for fabricating synaptic transistors are classified: organic and non-solid electrolyte materials, inorganic solid materials and organic flexible materials, and their current research is reviewed. The purpose of this review is to provide more research directions for the research in the field by summarizing the current research on the fabrication materials of synaptic transistors. At present, there are still many new materials that have not been tried in the research field of synaptic transistors. Trying to use composite materials and two-dimensional materials is a noteworthy research direction, which is expected to promote the development of a new generation of memory technology and the application in the field of artificial intelligence.

Keywords: Synaptic transistor; Neuromorphic device; Electrolyte material; Neuromorphic computing; Flexible organic materials.

1. Introduction

In recent years, with the rapid development of integrated circuits, traditional CMOS transistors are gradually approaching the physical limit, Moore's Law is becoming more and more difficult to maintain, and the von Neumann bottleneck caused by the separation of memory and computation also restricts the operation speed. How to continue to improve the computing performance of integrated circuits has become a big problem. Synaptic transistor, a novel brain-like device, has considerable potential in the application of artificial brain-like synaptic arrays and is a hot topic in current research [1]. At present, exploring the materials used to fabricate synaptic transistors is one of the main research directions. This review summarizes some cutting-edge research on synaptic transistors, classifies and compares the materials used in them.

In Chapter 2, the basic structure and working principle of synaptic transistors are introduced. From the basic structure, the synaptic transistor is based on the structure of the field effect transistor, replacing the materials used. From the working principle, the ion conduction in the dielectric layer is used to simulate the information transmission between synapses, thus simulating the function of synapses. In Chapter 3, the commonly used materials for fabricating synaptic transistors are classified and compared. In the first section, organic and non-solid electrolyte materials are introduced. This kind of material is easy to form electric double layer phenomenon (EDL), and this kind of material has the most research results, but it is also difficult to integrate. In Section II, inorganic solid materials are introduced, which have better surface and electrical properties, but the fabricated transistors consume more power. In Section III, organic flexible materials are introduced, which have good flexibility and biocompatibility, and have potential applications in the field of wearable devices, artificial intelligence and brain-computer interface.

Synaptic transistors have broad research prospects in computer storage, computing, biology, medicine and other fields. The aim of this review lies in compiling and presenting the current research endeavors pertaining to the materials used in the fabrication of synaptic transistors, so that scholars

in related fields can have more understanding of the current research in the field of synaptic transistor materials and provide more research directions for the research in this field.

2. Basic structure and working principle of synaptic transistor

2.1. Basic structure

In the field of integrated circuits, the traditional metal oxide field effect transistor (MOFET) is a three-terminal device, which is composed of a substrate, a channel layer, an insulating oxide layer, and three metal electrodes: gate, drain and source. Most of the substrate and channel layers are made of silicon doped with different ions. If the gate voltage is different, the amount of current flowing through the drain-source can be changed. The synaptic transistor exhibits a structural resemblance to the conventional field-effect transistor, with notable similarities in their fundamental configurations. To mimic the function of the synapse, the original insulating oxide layer is replaced with a different material, so that it becomes a gate dielectric layer, which can interact with the charge of the gate. The substrate and channel layer will also be replaced by materials other than silicon to achieve the required function. A common kind of synaptic transistor structure is the oxide electric double layer transistor made by Jiang J and Wan Q et al in 2009, which uses electrolyte as gate medium, which is shown in figure 1 [2].

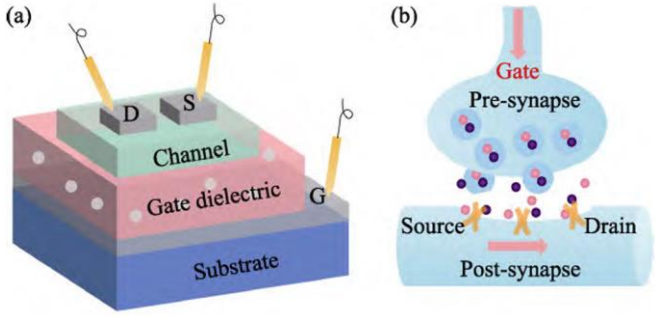


Fig. 1 Structure diagrams of synaptic transistor (a) and synapse (b)[2]

Floating gate transistor is also a kind of synaptic transistor that has been widely studied. Compared with the traditional transistor structure, the gate dielectric layer of floating gate transistor is divided into three parts: charge trapping layer, charge barrier layer and tunneling oxide layer. In addition to double-layer and floating gate, there are many different structures of synaptic transistors, but their structure is based on the traditional field effect transistor [3].

2.2. Working principle

The purpose of studying synaptic transistors is to simulate the behavior of synapses, so it's working principle is to achieve the function of synapses through various methods. Signals are transmitted by electrical currents on neurons and by neurotransmitters across synapses. Thus, the gate can be considered as the presynaptic membrane and the channel layer between the drain-source as the postsynaptic membrane. The gate-dielectric layer was mentioned earlier, which allows the channel layer and the gate to conduct ions but is electrically insulated, much like the synaptic gap. Applying a voltage to the gate causes the active ions to enter the channel layer to change the resistivity and thus the drain-source current, which is the basic principle of the synaptic transistor [3]. Different types of synaptic transistors have different operating principles. For example, floating gate transistors are based on quantum tunneling effect or thermal emission of charge, electric double-layer transistors regulate channel current through capacitive field effect mechanism at the interface between electrolyte and channel. Ferroelectric field effect transistors are based on spontaneous polarization of ferroelectric materials, And the modulation of carrier concentration is achieved by altering the polarization state of the incorporated material, thereby polarizing its state [4]. The schematic of a synaptic device based on a three-terminal transistor is shown in figure 2.

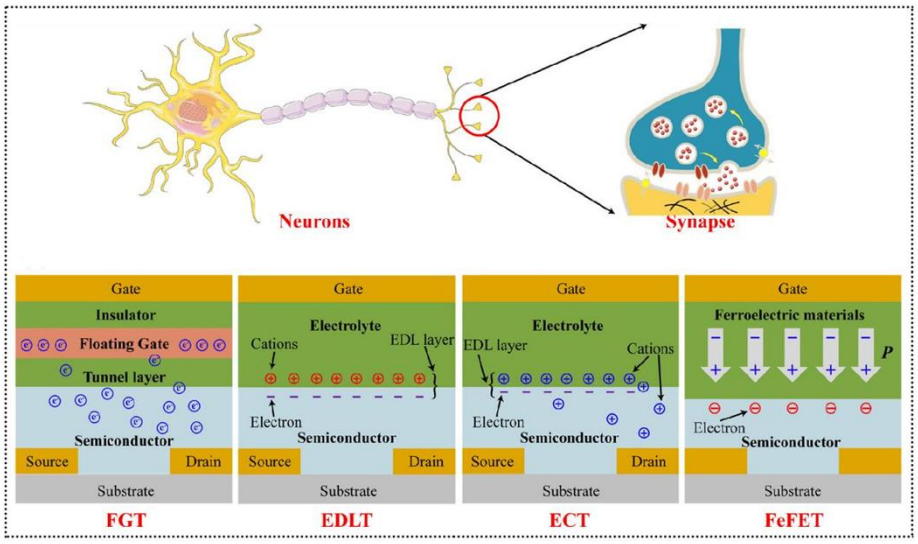


Fig. 2 Schematic of a synaptic device based on a three-terminal transistor [5]

3. Analysis of different materials and application effects

3.1. Synaptic transistors based on organic and non-solid electrolyte material

In most current studies of synaptic transistors, the electrolyte layer as an ion conductor is the key structure for transistor to realize synaptic property simulation. This is because electrolyte-based transistors facilitate the formation of electrical double layer (EDL) phenomena that enable transistors to achieve the basic properties of artificial synapses [6].

2023 in a study by Qiu et al., The In2O3 synaptic transistor based on glass substrate was fabricated by using the non-toxic water induction method and sol-gel technology. The basic biological synaptic behavior was successfully simulated by the motion relaxation characteristics of the ions in the electrolyte, and high image recognition accuracy was obtained by neural network simulation. This study provides an experimental basis for the development of environmentally friendly, economical and high-performance neuromorphic electronic devices using sol-gel technology [4].

In another study, Zhang's team utilized organic and liquid electrolytes as gate dielectric layers. They used lignin and polyvinyl alcohol (PVA) to make films. Lignin possesses numerous advantages in electrolytes, encompassing biodegradability, robust physical and chemical stability, and cost-effectiveness. PVA is a non-toxic and biodegradable polymer. The blends of PVA/lignin demonstrate superior ionic conductivity and a noteworthy increase in specific capacitance. Furthermore, the arrays proposed in this research exhibit remarkable uniformity, offering valuable insights for the integration of large-scale arrays of EGTs [7].

Research from Wang's group proposes the utilization of lithium perchlorate (LiClO4) and polyethylene oxide as an electrolyte that can conduct ions to fabricate a MoS2 synaptic transistor. The gate control ability of this transistor is significantly enhanced due to the EDL effect, surpassing that of conventional gate dielectric materials, while operating at lower voltages. In addition, compared to the commonly used electrolyte material polyvinyl alcohol (PVA), PEO/LiClO4 electrolyte offers environmental friendliness, non-toxicity, ease of preparation, and ensures optimal performance of electricity. This study successfully simulated a range of metrics that could represent synaptic behavior, such as different plasticity and filtering. These achievements indicates that it is possible for the 2D MoS2 synaptic transistor to construct a new artificial neural network in the future. It also shows good prospect in computing and storage applications [8].

In most current studies of synaptic transistors, the electrolyte layer as an ion conductor is the key structure for transistor to realize synaptic property simulation. Recently, significant progress has been achieved in the development of electrolyte-based synaptic transistors based on ionic liquids or organic

materials. However, organic and non-solid materials may lead to poor interface contact and rough surface of the film, resulting in too many defects and reducing the electrical stability and performance of the device. In addition, these materials have poor compatibility with technologies such as lithography, which is not conducive to large-scale industrial production [6].

3.2. Synaptic Transistors based on inorganic solid materials

Compared with organic and non-solid materials used as electrolyte bases, the synaptic transistors based on inorganic solid materials have better electrical stability and performance due to their good smooth surface and interface contact. Furthermore, inorganic solid materials exhibit greater suitability for industrial-scale film formation techniques. Up to now, several oxide-based transistors have been successfully implemented to simulate synaptic function [6].

In order to explore potential materials for synaptic transistors and reduce the cost of the fabrication process, Zhou's team proposed to fabricate Gd2O3 thin films in aqueous solution and use them as dielectric for thin film transistors. Gd2O3 stands out as a lanthanide oxide boasting a high K value. The In2O3/ Gd2O3-TFT prepared in this study realized a series of basic functions of artificial synapses. They conduct a test on the signal memory and gain behavior of the transistor, achieving the goal of simulating synaptic function such as short-term plasticity. When they applied a variety of pulses to the gate end, the device indicates different EPCS responses and its short-term memory for pulse spurts is also enhanced. In2O3/ Gd2O3-TFT also shows potential in high-frequency filtering and other applications, as well as the perception of light stimuli [6].

In 2023, Taebin Lim's group proposed a coplanar amorphous InGaZnO TFT. The observed ferroelectric-like behavior arises from the electron transportation through the gap states and the trapping of positive charges within the Al2O3 layer. In the transistor a SiO2 layer is used to charge, which facilitates the induction of surface charges with prolonged retention characteristics. Thus, if the transistor continues to be studied, it can be feasible to develop high-density neuromorphic devices [9].

In another study, Zhang's group proposed a novel synaptic transistor, which relies on metal hydroxyl defects in the inverse channel, unlike conventional synaptic transistors that use a gate dielectric for weight modulation. After an electrical stimulation at the gate, within those defects the electron will be captured and release simultaneously. This phenomenon leads to a change of the density of channel carrier and subsequently results in weight modulation. Characterized by the high-speed carrier and minimal subthreshold swing, the device demonstrates impressive electrical performance. Furthermore, it effectively emulates fundamental synaptic functions, showing properties such as EPSC and PPF. Moreover, the Ann composed of this transistor is highly accurate when it is identifying various datasets. This system is hoped to be used in neuromorphic computing for higher speed [10].

There is still much room to explore the research of synaptic transistors using inorganic solid materials. Solid-state electrolyte-based synaptic transistors offer the prospect of large-scale integration, albeit with the common challenge of high energy consumption among individual transistors within the array. Reducing energy consumption is an important direction in the research of inorganic solid materials [6].

3.3. Synaptic transistors using flexible organic materials

In recent years, increasing attention has been drawn to brain-like synaptic devices that exhibit exceptional flexibility and remarkable transparency. In addition to the great advantages of synaptic transistor itself in parallel information storage and processing, its ultra-flexible and transparent attributes significantly broaden the application fields for electronic devices, while maintaining their original functionality. Therefore, ultra-flexible transparent electronic devices with biomimetic neuron functions are hoped to establish wearable AI neuromorphic devices [11].

In 2023, Xu Han's team fabricated an organic synaptic transistor (OST) with ultra-flexibility and transparency. An insulating layer, composed of a natural starch, is the key to achieve the performance.

The team successfully simulated a variety of synaptic behaviors, such as EPSC and PPF, as well as the ability to learn to experience. With an ultra-thin thickness about 5 nm, these devices are able to be attached to any curved surfaces in different ways, even at the blade edge where the bending radius is smaller than 4μm, while maintaining basic synaptic functions and showing excellent mechanical properties. This research establishes the feasibility of developing ultra-flexible and transparent neuromorphic electronics in the future, marking a significant stride towards the next generation of artificial intelligence. It holds immense potential for future advancements in biomedicine and wearable displays. [11].

The study by Xu Qian et al. implements a dopamine-mediated biohybrid artificial synapse, using a fully printed OECT device. Those electrodes are all printed with silver ink to ensure that it can be thin enough. Then the active channels are printed with different kind of ink, including polystyrene sulfonate ink and functional poly. A more important point in this study is that OECT can deliver a direct response to dopamine molecules even if an external gate voltage is applied, which means it has long-term plasticity. The results of this study offer a possible route to bioelectronic interfaces [12].

Another study from Qiu proposed an organic flexible electrochemical synaptic transistor, realizing the recognition of dopamine neurotransmitters through REDOX reactions. Without dopng, the transistor showed the short-term plasticity, including IPSC, EPSC and PPD. By incorporating dopamine, the conductance of the channel can be permanently modulated. Moreover, the device responds stably and constantly to dopamine stimulation in various bending states. These achievements can provide avenues for research to study further in synaptic transistor that can directly interact with human body [13].

The pursuit of synaptic devices with ultra-flexibility are still a significant challenge, primarily because of the constraints posed by ultra-thin device structures and the need for highly transparent materials. Therefore, there is still much room for research in the field of biological interaction and wearable devices.

4. Conlusion

At present, the research of synaptic transistor is attracting attention. There have been a large number of studies trying to use various materials to fabricate synaptic transistor, and basically realize the function of synapse. The materials for fabricating synaptic transistors can be mainly divided into organic and non-solid electrolytes, inorganic solid materials and flexible organic materials. Synaptic transistors based on organic and non-solid electrolyte materials are the most widely studied type, and the gate dielectric layer formed by them can effectively transfer ions. However, these synaptic transistors lack good electrical stability and are incompatible with traditional lithography technology, so they are difficult to be integrated on a large scale. Synaptic transistors made of inorganic solid materials are easier to integrate but have high power consumption. Synaptic transistors made of flexible organic materials have better biocompatibility and have great potential in the field of biosensing and wearable devices.

However, the performance of synaptic transistors is still inefficient, which cannot meet the needs of large-scale artificial neural networks. Limited by the materials and fabrication methods used, large-scale integration is still difficult. Therefore, finding materials with lower cost, easier preparation and more excellent performance is the primary direction of current research on synaptic transistors. In order to prepare synaptic transistors with better performance, some studies begin to combine different materials, such as Min et al. 's research, which proposed a polycrystalline silicon channel thin film synaptic transistor using organic-inorganic hybrid EDL gate dielectrics. With the rapid development of materials science, many new materials have become potential research objects. For example, the two-dimensional material graphene has unique physical characteristics. Takuya Ishibashi proposed the quantum transport simulation of synaptic field-effect transistors utilizing two-dimensional semiconductors in his research.

In a word, as new microelectronic devices, there are still many materials not yet tried in the research field of synaptic transistors. As a new generation of brain-like devices, synaptic transistors have broad research prospects.

References

[1] Bai S, Tao G, Guangdong Z, et al. Synaptic devices based neuromorphic computing applications in artificial intelligence. Materials Today Physics, 2021, 18 (prepublish): 100393-.

[2] YANG Yang, CUI Hangyuan, ZHU Ying et al. Research Progress of Flexible Neuromorphic Transistors. Journal of Inorganic Materials, 2023, 38(04): 367-377.

[3] Yanfei Zhao. Artificial Synapses and Neuromorphic Computing Based on Three-terminal Organic Transistors. Lanzhou University, 2023.

[4] Haiyang Qiu. Fabrication and Properties of Ion Gate Metal Oxide Synaptic Transistors. Qindao University, 2023.

[5] Sun F, Lu Q, Feng S, et al. Flexible artificial sensory systems based on neuromorphic devices. ACS Nano, 2021, 15(3): 3875-3899.

[6] Youhang Zhou. Study on Performance Improvement of Metal Oxide Thin Film Transistors Fabricated by Aqueous Solution Process. Shanghai University, 2021.

[7] Zhang W, Li J, Cheng L, et al. Synaptic Transistor Arrays Based on PVA/Lignin Composite Electrolyte Films. IEEE Transactions on Electron Devices, 2023.

[8] Wang Y, Yang Y, He Z, et al. Laterally coupled 2D MoS 2 synaptic transistor with ion gating. IEEE Electron Device Letters, 2020, 41(9): 1424-1427.

[9] Lim T, Bae J, Han B, et al. Artificial Synaptic InGaZnO Thin-Film Transistor with Long Retention Behavior Using Al 2 O 3/SiO 2 Gate Insulator. IEEE Transactions on Electron Devices, 2022, 70(1): 135-139.

[10] Zhang C, Yang B F, Wang D, et al. InGaZnO Synaptic Transistor Using Metal-Hydroxyl Traps at Back Channel for Weight Modulation. IEEE Transactions on Electron Devices, 2023.

[11] Han X, Zhang J, Zeng T, et al. Super-flexible, transparent synaptic transistors based on pullulan for neuromorphic electronics. IEEE Electron Device Letters, 2023, 44(4): 606-609.

[12] Xu Q, Chen J, Li Y, et al. Fully Printed Dual-Gate Organic Electrochemical Synaptic Transistor with Neurotransmitter-Mediated Plasticity. IEEE Electron Device Letters, 2023.

[13] Qiu J, Cao J, Liu X, et al. A flexible organic electrochemical synaptic transistor with dopamine-mediated plasticity. IEEE Electron Device Letters, 2022, 44(1): 176-179.