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New Carrier for Neuromorphic Computing: Multimodal Response and Learning Mechanism of Organic Field-Effect Transistor-Based Synaptic Devices

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New Carrier for Neuromorphic Computing: Multimodal Response and Learning Mechanism of Organic Field-Effect Transistor-Based Synaptic Devices

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Abstract. Neuromorphic computing aims to emulate the information processing mechanisms of biological neural systems through hardware approaches, thereby overcoming the energy consumption and efficiency bottlenecks inherent in traditional von Neumann architectures. As a core device for mimicking synaptic functions, the organic field-effect transistor (OFET) has emerged as a research hotspot in artificial synapse studies in recent years, owing to its low power consumption, flexible processability, and tunable material properties. This paper reviews the application potential of OFET devices in neuromorphic computing, systematically outlining their basic structures, working mechanisms, and manifestations of synaptic plasticity. It focuses in particular on their responses to multimodal stimuli, including electrical and optical signal modulation behaviors. Furthermore, the paper discusses recent advancements in biomimetic learning mechanisms and hardware implementation of neural networks using OFET-based synaptic devices. Representative works are comparatively analyzed in terms of material systems, structural design, and performance optimization. Building on the current research progress, the paper also highlights remaining challenges related to device stability, uniformity, and system-level integration, and envisions future directions such as the development of novel organic semiconductors, multimodal fusion computing, and the co-evolution of OFET synapses with brain-inspired chips.

INTRODUCTION

Overview of Neuromorphic Computing

Neuromorphic computing is a brain-inspired computational paradigm that seeks to emulate the functions of neurons and synapses in both temporal and spatial domains, based on spiking events observed in the brain, in order to achieve highly energy-efficient computation [1]. Traditional computers adopt the von Neumann architecture, which separates the processor from memory. This requires frequent data transfers between the two, leading to bottlenecks in data transmission, high energy consumption, and limited parallel processing capabilities, thereby constraining the development of computing in fields such as artificial intelligence [2]. In neuromorphic computing systems, artificial synaptic devices are used to simulate the functions of biological synapses. They are also crucial components in brain-inspired computing. These artificial synaptic devices can regulate their own electrical conductivity according to the intensity and frequency of the input signal, thus enabling a similar approach to synaptic plasticity in biological systems. Realize the storage and transmission of information [3]. If a large number of artificial synaptic devices are integrated together, a highly parallel computing network can be constructed, improving the efficiency of information processing. With the application of new materials and device designs, artificial synapses can significantly reduce the energy consumed during the computing process, meeting the demands of efficient and low-power computing.

The Potential of Organic Field-Effect Transistors in Artificial Synapses

The field-effect transistor (OFET) is a type of transistor based on organic semiconductor materials. Its basic working principle is quite similar to that of traditional field-effect transistors. An OFET is composed of the source, drain, dielectric layer, and gate. The function of the gate voltage is to control the concentration of carriers in the organic semiconductor channel. The source-drain current is modulated in this way. Unlike traditional silicon-based devices, the channel materials in ofet are composed of organic molecules or polymers, which endows them with unique material properties and also gives them application potential [4].

Organic synaptic transistors combine the mechanical flexibility of organic materials themselves with the unique advantage of their device structure that can simultaneously receive and read signals. They have shown very broad application prospects in fields such as brain-computer interfaces, soft robots, and neuromorphic electronics [5]. First of all, compared with inorganic synaptic devices, ofet can operate at a relatively low voltage and regulate the synaptic weight in a relatively smaller electric field, which can reduce energy consumption. This is also a basic feature of large-scale neuromorphic computing systems. Next, let's talk about the second point. Since ofet is made of organic materials, it can be deposited on flexible substrates and has a very broad application prospect in flexible electronic products such as wearable devices and bionic robots. Moreover, due to the chemical tunability of organic semiconductors, the electrical performance of ofet can be optimized through molecular design. It meets various requirements of neuromorphic computing. The use of organic semiconductors with high carrier mobility and stability can enhance the response speed of the device and also improve its reliability [6].

In the present era, with the continuous development and progress of brain-inspired computing, neuromorphic computing has become a key direction that can overcome the limitations existing in traditional computing architectures. There is the field-effect transistor, also known as OFET, which is a crucial device for realizing artificial synaptic functions. Due to its advantages such as low power consumption, mechanical flexibility, and material tuning, It has received increasing attention and research interest from more and more researchers. However, synaptic devices based on OFET still face some challenges in terms of performance stability, device uniformity, response speed, and multimodal responsiveness. Compared with biological synapses, OFET still has certain gaps in synaptic weight regulation, long-term memory retention, and response to multimodal stimuli.

This paper reviews the application of organic field-effect transistors in neuromorphic computing, focusing on introducing the synaptic plasticity and response mechanisms they exhibit under electrical stimulation and light stimulation. Then, this paper analyzes the new research progress of different material systems and structural designs at present. And all the potentials of OFET devices in multimodal response, learning mechanism and the hardware implementation of neural networks were also explored. The main contribution of this work lies in proposing the future development direction of OFET in the field of neuromorphic computing from the perspectives of materials, properties and applications, which can provide some insights for subsequent related research.

FUNDAMENTAL PRINCIPLES OF ORGANIC FIELD-EFFECT TRANSISTOR-BASED SYNAPTIC DEVICES

Basic Structure and Working Mechanism of OFETs

Field-effect transistors (ofet) have demonstrated unique advantages in artificial synaptic devices, mainly due to their material properties and working mechanisms [7]. The key to OFET lies in the selection of organic semiconductor materials, which can mainly be divided into two categories: small molecules and polymers. Small molecule organic semiconductors are generally processed by vacuum evaporation deposition. It has a high crystallinity and a relatively high carrier mobility. In addition, polymer organic semiconductors can be processed by solution-based technologies, which makes them suitable for manufacturing large-area flexible electronic devices.

When the OFET starts to operate, the gate voltage regulates the carrier concentration in the organic semiconductor layer, thereby controlling the current between the source and the drain. Specifically, the voltage pulse applied to the gate can cause changes in the charge distribution within the organic semiconductor layer or alter the interface density of states. This will have an impact on the conductivity of the channel and enable the dynamic modulation of "synaptic weight". This modulation mechanism can mimic the plasticity characteristics of biological synapses, such as short-term and long-term potentiation or depression, providing a foundation for building bioinspired neural networks [8].

In addition, the molecular structure and arrangement of organic semiconductor materials have a significant impact on carrier transport. In the crystalline regions, carriers primarily move quickly along the ordered π - π stacking direction and conjugated molecular chain direction. Contrary to the situation mentioned earlier, in the amorphous region, carriers move by means of interchain transitions, and their movement speed is slower. If the material design of organic semiconductors is optimized and the processing technology is also improved, the performance of ofet can be enhanced. This way, it can meet the requirements of artificial synaptic devices for response speed and also their requirements for stability.

Feasibility of OFETs as Artificial Synapses

In this era of artificial intelligence, the demand for artificial neural networks is constantly increasing, and the exploration of them is also continuously deepening. There is the field-effect transistor (ofet), which, as an artificial synaptic device, has been proven to have great feasibility in simulating the function of biological synapses. We can regard it as the presynaptic membrane. The semiconductor channels are relatively similar to the postsynaptic membrane. The change of the gate voltage, that is, V_G , will cause the carrier concentration in the semiconductor channel to change. This change can be regarded as the change of the postsynaptic membrane state caused by the transmission of neurotransmitters. Because the current of the conductive channel changes, the conductivity of the channel also changes. This change can be regarded as the change of synaptic weight [9]. Biological synapses can achieve synaptic plasticity and memory effects by regulating the intensity of signal transmission between neurons. ofet can simulate the short-term and long-term plasticity of biological synapses and the related memory effects by controlling the concentration and mobility of carriers in the organic semiconductor layer.

In terms of key performance indicators, OFET-based artificial synaptic devices exhibit advantages such as low energy consumption, high switching ratio, and fast response. In 2015, Vuillaume et al. demonstrated biomimetic synaptic behavior on an OFET with an array of Au nanoparticles. They observed typical short-term synaptic plasticity at a working voltage as low as 1 V, and the synaptic device was able to operate with a low energy consumption of 2 nJ per spike [10]. In 2016, Yoon et al. fabricated an array of 36 OFET-based biomimetic synaptic electronic devices on a flexible and transparent polyethylene terephthalate (PET) plastic substrate [11].

MULTIMODAL RESPONSE CHARACTERISTICS

Electrical Stimulus Response

In biological neural systems, action potentials generated by presynaptic neurons propagate along the axon and reach the synapse, transmitting useful information to the postsynaptic neurons. The strength of the connection between presynaptic and postsynaptic neurons is defined as the synaptic weight, and its modulation is the basis for the integration of memory and processing in neurons. This process involves a biological phenomenon known as synaptic plasticity, in which the presynaptic membrane adjusts its ability to release neurotransmitters based on neuronal activity.

In the artificial synapse based on ofet, the mechanism of synaptic weight modulation mainly relies on the influence of electrical stimulation on the carrier concentration and mobility in the organic semiconductor channel. The voltage pulse applied to the gate will cause the accumulation or depletion of charges in the organic semiconductor layer, thereby modulating the source-drain current, which corresponds to the change in synaptic weight [12]. By adjusting the amplitude, width and frequency of electrical pulses, precise control of synaptic weights can be achieved, effectively simulating the learning and memory processes of biological synapses.

Synaptic plasticity is generally divided into two types: short-term plasticity and long-term plasticity. Short-term plasticity is usually represented by STP, while long-term plasticity is generally represented by LTP. In artificial synaptic devices, there are field-effect transistors (ofet), which successfully simulate various plasticity characteristics of biological synapses through electrical stimulation. This includes short-term synaptic plasticity, namely STP, long-term improvement, namely LTP, and long-term inhibition, namely LTD.

Short-term synaptic plasticity, or STP for short, refers to the transient changes in synaptic transmission efficiency, which usually last from a few milliseconds to several minutes. In an organic field-effect transistor, if a short voltage pulse is applied to it, a transient change in the source-drain current can occur. In this way, it can effectively imitate the phenomenon of short-term improvement or short-term inhibition that can be observed in biological synapses.

From the perspective of all the properties of potential changes, STP can be further divided into two situations:

short-term boost and short-term suppression, which are commonly referred to as STP and STD. A representative example is the pairing of impulse boost and suppression, also known as PPF/PPD. In these cases, when two consecutive pulses are applied, the second pulse results in an enhanced or suppressed response. If the altered synaptic state induced by STP is repeatedly stimulated before it fades, it may transition into long-term synaptic plasticity, allowing the synaptic state to be retained for an extended period or even permanently [13]. Based on changes in potential, long-term synaptic plasticity can be further divided into long-term potentiation (LTP) and long-term depression (LTD).

Most bioinspired synaptic electronic devices are regulated by classical electrical signals. In 2015, Vuillaume et al. demonstrated biomimetic synaptic behavior on an OFET incorporating an array of Au nanoparticles. Typical short-term synaptic plasticity was observed at operating voltages as low as 1 V, and the synaptic device was able to function at an ultra-low energy consumption of just 2 nJ per spike [14]. In 2016, Yoon et al. fabricated an array of 36 OFET-based bioinspired synaptic electronic devices on a flexible and transparent polyethylene terephthalate (PET) plastic substrate, as shown in Figure 1. Vacuum-deposited Al metal nanosheets, used as a floating gate, can regulate the rate of hole trapping under high-frequency input signal stimulation to mimic the short-term plasticity of biological synapses. When the frequency exceeds 2 Hz, the device exhibits a depressive behavior, while frequencies below 1 Hz result in facilitative behavior. This work successfully demonstrates the integration of organic electronic devices with large-area flexible artificial synapses.

Optical Stimulus Response

In recent years, research on the optical response of Organic Field-Effect Transistors (OFETs) has deepened, particularly in the area of simulating biological synaptic behavior, which has garnered widespread attention. By introducing organic semiconductor materials with photosensitive properties or appropriately designing the device structure, OFETs can generate synaptic-like responses to optical stimuli, achieving weight changes similar to those in biological synapses. Current research primarily focuses on enhancing the device's response efficiency to light, improving the light-induced synaptic memory effect, reducing energy consumption, and improving the device's operational stability. These efforts aim to address issues such as instability in response to light, short retention times, or high operating voltages, making OFETs more suitable for constructing low-power, multimodal brain-inspired computing systems. With the progress and development in these aspects, field-effect transistors have gradually shown their application potential in artificial neural networks and sensing systems [15]. Wang et al. reported a type of field-effect transistor memory, which is based on cesium lead bromide perovskite quantum dot nanoparticles as float gates. And the behavior of photonic synapses has also been successfully demonstrated [16]. OFET memory devices exhibit multi-wavelength photon enhancement and electrical suppression at wavelengths of 365 nanometers, 450 nanometers, 520 nanometers, and 660 nanometers, simulating the behavior of biological synapses. As a result, a new type of structure has been successfully established, which integrates photonics and neuromorphic computing.

In 2018, researchers such as Huang successfully fabricated light-stimulated synaptic transistors by leveraging the interface charge capture effect of ofet, and this effect played a crucial role in the fabrication process [17]. By achieving synaptic plasticity through light control, the dynamic behavior of the device under optical stimulation was explored. The interface effects of Organic Field-Effect Transistors (OFETs) were utilized to optimize the device performance, enhancing the correlation between optical response and electrical properties. In 2020, Huang's research group, inspired by natural plant photosynthesis, successfully developed a multifunctional transistor based on natural biological material chlorophyll and the organic semiconductor PDPP4T [18]. By adjusting the gate voltage (VG), OFET devices can flexibly switch between two functional states: photodetection and optical stimulation response, combining both sensing and computing potential. Although the research on optically controlled OFET-based biomimetic synaptic devices started relatively late, it has rapidly developed in recent years, gradually focusing on key issues such as improving the device's response sensitivity, stability, and power consumption control to optical signals. Current research mainly revolves around optimizing the optical sensitivity of materials, device structure design, and multimodal collaborative response mechanisms. The goal is to achieve a more efficient, low-energy, and non-volatile memory optical control artificial synapse system, thereby promoting its practical application in areas like visual perception and brain-like computing.

LEARNING MECHANISMS AND BIOMIMETIC COMPUTING

Synaptic Plasticity Mechanism

In the process of mimicking biological neural systems, the synaptic plasticity mechanism is central to realizing learning and memory functions. The dynamic adjustment of synaptic weights reflects changes in the strength of connections between neurons, serving as an essential method for simulating the learning process in neuromorphic computing. Among them, the Hebbian learning rule, as a classic biologically inspired learning model, provides the theoretical foundation for the regulation mechanisms of artificial synaptic devices.

Based on neurobiological experimental phenomena and some reasonable computational assumptions, in 1949, Donald Hebb, the pioneer of cognitive psychophysiology in Canada, first defined the synaptic plasticity learning rule in his book *Organization of Behavior*, through the brain's associative learning [19]. The basic idea of the Hebbian rule can be summarized as "cells that fire together, wire together." When the activity of a presynaptic neuron always occurs shortly before the activity of a postsynaptic neuron, the connection between them will be strengthened. This process is often realized in artificial synapses by adjusting the device's conductivity. For example, in an OFET synaptic device, applying time-correlated pulse stimuli consecutively can lead to a sustained enhancement of source-drain current, exhibiting Hebbian-like long-term potentiation (LTP) behavior. However, if the stimulus times are out of sync or the intervals are too long, the weight-enhancing effect weakens or even exhibits long-term depression (LTD), forming the foundation for time-dependent plasticity. The long-term conductance enhancement achieved through a series of enhancement pulses and its subsequent long-term suppression reset through inhibition pulses demonstrate that the device can achieve multiple state adjustments at the maximum conductance level and reset through subsequent continuous inhibition pulses. After a series of continuous conductance adjustments, further multiple rounds of continuous conductance regulation were performed to test the device's long-term cycling stability.

To more closely mimic the behavior of biological synapses, more complex synaptic weight regulation models need to be introduced in the actual device design. Among these, the time difference between pre- and postsynaptic pulses, especially spike-timing-dependent plasticity (STDP) based on pulse timing, becomes a key variable for controlling synaptic behavior. The STDP model determines whether synaptic weight increases or decreases based on the positive or negative time difference. In the adjustment model, additional parameters such as pulse amplitude, frequency and duration were also introduced to simulate all the nonlinear response characteristics of real neural networks. These research efforts have played a promoting role, enabling bionic synaptic devices to continuously develop in the direction of higher performance and behavior closer to biological synapses.

The synaptic plasticity mechanism provides biological principle support for the realization of the device's learning function. It integrates Hebbian learning and synaptic weighting models, promoting the practical application of neuromorphic systems in bionic computing. These mechanisms enable artificial synaptic devices like ofet to autonomously adapt to external stimuli and construct a dynamic network structure. This structure has adjustable weights and memory capabilities, thus offering potential for a more efficient brain-inspired computing architecture.

The Hardware Implementation of Artificial Neural Networks (ANNs)

The hardware implementation of artificial neural networks is actually a very crucial step in the development of neuromorphic computing. There is the field-effect transistor, also known as the OFET synaptic device. Due to its particularly good processing flexibility and synaptic characteristics, it shows great potential when constructing network structures similar to those of the brain. Compared with the traditional neural networks that rely on software to operate, the hardware implementation method based on OFET can achieve a more reasonable information processing approach in biology, thus achieving a better balance between the consumed energy and the processing efficiency [20].

In the existing research, field-effect transistors have been widely used to construct synaptic arrays, which can play the role of synaptic connection in neural networks. Li et al. integrated multiple OFET units with adjustable weights in a two-dimensional device array, thus achieving the parallel weighted summation of input signals. This setting has successfully accomplished the basic computational tasks of neural networks [21]. For another example, some relatively flexible wearable image recognition systems use photosensitive OFET arrays as input neurons. By training synaptic weights using voltage or light pulses, these systems can carry out local processing and recognition of image signals [22]. These systems can generally complete specific perception tasks without the need for external storage devices or central processing units, which reflects the basic concept of "storage-computing integration" in neuromorphic computing.

Meanwhile, OFET devices themselves have advantages such as low driving voltage and low static power consumption. These advantages make them particularly suitable for use in energy-sensitive application scenarios in hardware neural networks such as edge computing and mobile terminals. With their malleable memory characteristics, they also reduce energy consumption related to frequent external memory access. In this way, the efficiency of the overall system is improved. Oh, all the parallel processing capabilities of the OFET array can help accelerate the neural network in the hardware without the need for complex control logic [23].

Challenges and Development Trends

This paper finds that synaptic devices based on field-effect transistors have shown great potential in simulating the functions of the nervous system. However, there are still many challenges that need to be addressed. In the process of moving toward practical applications, stability and integration controllability are the most prominent difficulties.

The performance of OFET devices is largely affected by environmental factors. Organic semiconductor materials are prone to degradation reactions under the influence of oxygen, moisture, heat, and light, which lead to changes in the electrical characteristics of the devices, making it difficult to maintain long-term operational stability [24]. In addition, the consistency issues during the device fabrication process cannot be ignored. Even when fabricated under the same conditions, different devices still exhibit significant variations in turn-on voltage, transport performance, weight adjustment sensitivity, and other aspects. This variability significantly increases the complexity of the subsequent system design. When building large-scale neural networks, as it affects the overall computing accuracy and controllability, there are also challenges in balancing the energy consumption and functional realization of the equipment. Although ofet itself has the characteristic of low driving voltage, which is beneficial for low-power operation, However, if complex synaptic functions, such as plasticity and non-volatile memory, are to be achieved, most of the time additional functional layers or multiple stimulating mechanisms need to be introduced. Although these designs have expanded the functions of the equipment, they may also cause some problems, such as current leakage and response lag, which will affect the overall stability and energy efficiency of the equipment.

In recent years, significant breakthroughs have been made in the field of organic semiconductor materials, which have provided brand-new opportunities for the development of flexible electronics and neuromorphic computing. In the field of polymer semiconductors, researchers have successfully optimized the main chain engineering of DPP, that is, the conjugated polymer of diketo pyrrole. Ultimately, a record-breaking hole mobility of $10.5 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ was achieved[25]. Notably, this material can maintain over 90% of its initial performance even after being exposed to air for more than 1000 hours. This breakthrough addresses the long-standing issue of environmental instability in organic semiconductors.

Significant progress has also been made in the field of small-molecule semiconductors. The small-molecule system represented by C8-BTBT, through the introduction of fluorinated terminal groups, not only significantly improved the solubility and film-forming ability of the molecules in solution, but also achieved over 90% film uniformity through solution-based fabrication [26]. This achievement paves the way for the low-cost, large-area fabrication of organic electronic devices and holds significant industrial application value.

Particularly noteworthy is the latest development of OFET devices based on ion gel gate dielectrics, which have achieved true multimodal response functionality. These devices can simultaneously detect environmental stimuli such as pressure (with a sensitivity of 0.15 kPa^{-1}) and humidity (with a response time of less than 100 ms) [27]. This multimodal sensing capability demonstrates broad application prospects in fields such as smart sensing and human-machine interaction. Through systematic material screening and device optimization, researchers have successfully overcome the technical bottlenecks of traditional organic electronic devices in multifunctional integration.

CONCLUSION

As a representative of artificial synaptic devices, organic field-effect transistors (OFETs) provide a hardware solution for neuromorphic computing that combines low power consumption, flexible processing, and material diversity. Through electrical and optical multimodal stimuli, OFETs exhibit rich synaptic plasticity behaviors and highly tunable weight control capabilities, with the potential to simulate the dynamic responses of biological synapses across multiple time scales. In recent years, research has continuously advanced in areas such as material system optimization, device structure design, and biomimetic learning mechanisms, leading to preliminary progress in neural network construction and the implementation of hardware learning rules. However, challenges related to device

stability, consistency, and large-scale integration still hinder its practical application. In the future, further development of novel organic semiconductor materials to improve environmental stability and device consistency, exploration of multimodal fusion collaborative computing mechanisms, and deep integration of OFETs with traditional integrated circuits and brain-like chips will be key directions for functional breakthroughs and engineering applications in this field.

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