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Research and Applications of Organic Electrochemical Transistors

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Abstract. Organic electrochemical transistors (OECT) exhibit great potential for achieving high-sensitivity sensing and breaking through the "von Neumann bottleneck" to realize low-power neuromorphic computing. This paper reviews the research progress in materials and devices of organic electrochemical transistors over the past five years. It summarizes the research status of active layer materials for OECT based on mixed ionic-electronic conductors, including conjugated polymers, oligomers, and small molecules, starting from effective multifunctional molecular design and structural regulation strategies. Based on the structure and working mechanism of OECT devices, this paper introduces the application directions of OECT technology in physiological signal monitoring, biochemical sensing, and bionic neuromorphology. Finally, the key challenges remaining for OECT technology in the field of bioelectronics and its future development directions are discussed.

Keywords: Organic electrochemical transistor, physiological signal monitoring, biochemical sensor, bionic neurology

1. Introduction

The transistor represents one of the most significant technological breakthroughs in electronic components of the 20th century. It overcomes the inherent drawbacks of vacuum tubes, including large volume, high power consumption, short service life and the requirement for preheating. As the most fundamental building block of integrated circuits and microprocessors, the transistor is widely utilized in the fabrication of radio transmitters and receivers. Its high-frequency characteristics and fast switching speed render it a core technology for wireless communication, which gave rise to the modern information technology revolution.

The organic electrochemical transistor (OECT) is an emerging transistor technology based on mixed ion-electron transport, which was first reported by Wrighton et al. from the University of Washington in the 1980s [1]. The advent of OECT enables efficient conduction of valid information in bioelectronics. The mixed characteristics of electronic and ionic conductivity in organic materials make OECT an ideal candidate for converting physiological signals into electrical signals. As a typical bioelectronic device, OECT possesses unique charge and ion transport properties, which enable it to serve as an ideal interface to connect artificial electronics relying on charge transport with biological systems that function based on chemical signals [2].

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This review aims to summarize the current research status and existing challenges of OECT devices, and provide insights into the future application directions of OECT technology.

2. Research progress

2.1. Working principle

The structure of a typical organic electrochemical transistor is illustrated in Figure 1, which consists of a gate electrode, an electrolyte layer containing mobile anions and cations, a source electrode, a drain electrode, an ion-permeable organic semiconductor layer, and a substrate.Unlike field-effect transistors that form channel charges via electrostatic induction from the gate electric field, organic electrochemical transistors involve electrochemical redox reactions between ions and organic semiconductor materials. Their working mechanism is described as follows (taking organic semiconductor materials operated in the accumulation mode as an example): Under the action of a negative gate voltage, anions in the electrolyte penetrate into the organic semiconductor layer and undergo reversible redox reactions with the material, thereby increasing the hole concentration in the semiconductor layer and outputting a relatively large channel current under the source-drain voltage; when the negative gate voltage is removed, the anions in the semiconductor layer spontaneously return to the electrolyte, leading to a decrease in the hole concentration of the semiconductor layer, an extremely weak channel current output, and the device enters the off-state [3].

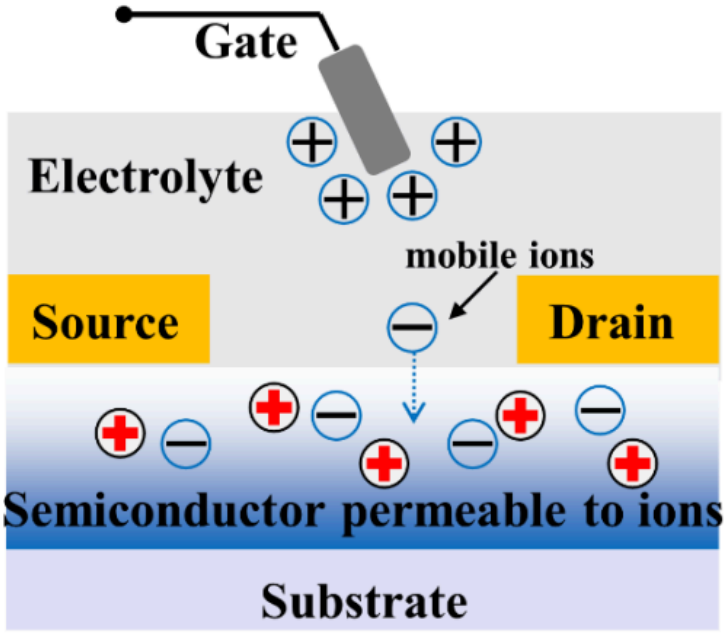

Figure 1. Schematic diagram of a typical vertical electrochemical transistor structure [3]

The most prominent characteristic of organic electrochemical transistors is their bulk-response working nature, that is, electrochemical doping/dedoping and ion/charge transport occur throughout the entire channel [4]. Since effective channel charges can fill the entire semiconductor layer, organic electrochemical transistors exhibit the highest capacitance among thin-film transistors, reaching up to 500 uF/cm², which is 1000 times that of conventional field-effect transistors [5]. Accordingly, organic electrochemical transistors can effectively regulate channel current and realize

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effective amplification/storage of output signals even at an operating voltage lower than 1 V, which compensates for the deficiencies of field-effect transistors [6]. Meanwhile, these properties also make organic electrochemical transistors suitable for detection/sensing signal applications.

2.2. Research on small-molecule materials for organic electrochemical transistors

Organic mixed ionic-electronic conductors with coupled ionic-electronic transport properties are critical materials for organic electrochemical transistor (OECT) devices [7]. From the perspective of molecular weight, OECT active layer materials can be classified into small-molecule materials and polymeric materials. Compared with polymeric materials, small-molecule materials are easy to purify, possess definite molecular structures and molecular weights, and eliminate batch-to-batch variation. Devices fabricated with different batches of small-molecule materials exhibit stable performance, which is more conducive to material structure optimization, device performance improvement, and the establishment of accurate structure-activity relationships.

At present, most research on OECT active layer materials focuses on polymeric materials, while high-performance small-molecule active layer materials remain relatively scarce. No systematic structure-activity relationship has been established for this category of materials, which constrains their application and development. Compared with p-type small-molecule materials, the design and development of high-performance n-type materials lag further behind. This is because n-type materials generally require strong electron-deficient building blocks to lower molecular energy levels, but the introduction of such building blocks reduces the chemical activity of the molecules and makes structural modification difficult, resulting in very few reports of high-performance n-type small-molecule materials. Nevertheless, n-type materials and corresponding devices are indispensable components in fields including biological detection, enzyme-coupled reactions, and complementary logic circuits. Accordingly, researchers have adopted molecular design strategies that integrate backbone engineering (including all-acceptor fusion, conjugation extension, conformation regulation, and molecular conformation locking) with side-chain engineering, and developed novel device processing techniques. These efforts have achieved breakthroughs in the performance of small-molecule-based organic electrochemical transistors in the research fields of perylene diimide-based small-molecule materials, naphthalene diisatin-based small molecules/oligomers, and multiple fused naphthalene diisatin-based small molecules [8].

2.3. Research on materials for polymeric organic electrochemical transistors

Conjugated polymers are commonly used active-layer materials in the field of organic optoelectronics. Through rational selection of polymerization building blocks, controllable modulation of their chemical structure, energy level and crystallinity can be achieved. Meanwhile, polymeric materials exhibit excellent film-forming capability, mechanical properties and stretchability. Although device performance is of great significance, highly stable organic electrochemical transistors are the fundamental prerequisite for realizing their biological applications. The stability of organic electrochemical transistors encompasses the chemical stability of materials in aqueous electrolytes, the operational stability of devices, and air stability. Accordingly, the design and synthesis of high-efficiency and stable organic ion-electron materials applicable to organic electrochemical transistors and synaptic transistors remains one of the key scientific challenges in organic bioelectronics. Starting from the perspectives of low cost, excellent stability and facile modification, researchers have conducted relevant studies on conjugated polymer

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materials, including lactam-based conjugated polymers, naphthalimide-based conjugated polymers, and p-type polythiophene conjugated polymers [9].

3. Application directions

The unique ionic doping process of OECT devices endows them with relatively high transconductance, which generally exceeds ~10 mS. This indicates that OECT devices feature strong signal amplification capability, enabling them to collect and amplify weak physiological signals of organisms including electrocardiogram, electroencephalogram and electromyography signals, thereby realizing health monitoring and medical diagnosis for organisms.

3.1. Physiological signal detection

Measuring the electrical activity of biological organs, tissues and even individual cells is a commonly used method to examine their functional integrity. The accuracy of the acquired biological physiological signals directly determines whether the pathological location can be identified rapidly and precisely [10]. Therefore, biological physiological signal monitoring is of great significance, as it can provide real-time feedback on the health status of individual organisms.

Owing to their excellent properties, including simple fabrication process, high signal-to-noise ratio and good compatibility with flexible substrates, organic electrochemical transistors (OECT) have enormous application potential in the field of physiological signal monitoring. Compared with commercial physiological signal monitoring equipment, OECT-based physiological signal monitoring devices eliminate the limitation of rigid substrates. Meanwhile, they require smaller electrode dimensions while maintaining a high signal-to-noise ratio within the physiological frequency band, thus exhibiting superior biocompatibility and skin conformal ability. They can greatly improve user comfort while ensuring signal accuracy [11]. OECT technology has achieved extensive application progress in the monitoring of various physiological signals, including electrocardiogram (ECG), electrooculogram (EOG), electroencephalogram (EEG), electrocorticography (ECoG) and electromyogram (EMG) [12].

3.2. Biochemical sensing

Conventional biochemical sensors mainly consist of two core components: a sensing unit and a signal transduction unit. The sensing unit is primarily responsible for recognizing target analytes, including chemical ions, biological metabolites, antigens, antibodies, etc., while the signal transduction unit converts the intermolecular interactions generated during target recognition into electrical signals. The stable and efficient working capability of organic electrochemical transistors (OECTs) in liquid media renders them a hotspot research technology in the field of next-generation biochemical sensors, capable of providing data support for health assessment at the molecular level.

The application of OECT technology in biochemical sensing mainly involves four working mechanisms: (1) The target analyte directly undergoes a chemical reaction with the channel layer material, leading to a change in the conductivity of the channel layer and thus altering the output signal; (2) The interaction between the target analyte and the electrolyte changes the ionic conductivity , which in turn affects the output signal of the OECT; (3) The binding of the channel layer material to the target analyte induces a conformational change in the channel layer material; (4) The presence of the target analyte triggers a cascade reaction that alters the chemical state of the channel layer material [13]. The concentration of the target analyte can be obtained through analysis

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based on changes in the source-drain current or the effective gate voltage. OECT technology has been extensively applied in the quantitative detection of ions, glucose, other common metabolites and biomarkers [14].

3.3. Bio-inspired neuromorphics

The von Neumann architecture is primarily composed of four core components: the central processing unit, memory, input devices and output devices. Due to the physical separation of memory and the processor, the performance of traditional computers based on von Neumann architecture is inherently constrained. By collaboratively integrating various sensors with synaptic devices, bio-inspired interactive neuromorphic devices can directly perceive, store and process diverse stimulus information from the external environment, and implement functions including perception, learning, memory and computation [15].

The functional realization of bio-inspired interactive neuromorphic devices mainly relies on the synergistic interaction of the input layer, hidden layer and output layer. The input layer is responsible for converting signals such as tactile and olfactory signals into processable signals within the neural network. The hidden layer converts input signals into higher-level representations, and the output layer is responsible for outputting the processed high-level signals. Adjacent layers are connected via bio-inspired synapses that mediate signal transmission. This architecture, which resembles the human brain, enables interactive perception with the environment and efficient information processing while consuming extremely low energy. The three-terminal electrode structure of OECTs and their inherent ionic-electronic mixed transport property endow them with excellent bio-inspired compatibility for interactive neuromorphic devices, enabling their application as artificial synapses and neurons, bio-inspired perception systems, or for simulating neural network computation.

4. Conclusion

At present, research on organic electrochemical transistors (OECT) mainly focuses on improving ion-electron coupling performance via conjugated molecular design, interface regulation and device structure optimization, while promoting its advancement in the fields of physiological signal detection, biochemical sensing, bionic neuromorphology and other related domains. This paper provides a detailed overview of recent research progress on OECT in terms of molecular materials and functional applications.

In terms of molecular materials, high-performance ion-electron coupling capability and mechanical properties matching with living organisms remain the core orientation of future molecular design. However, limited by slow ion dynamics, the transient response speed of current OECT is still relatively low, thus the development of novel organic ion-electron mixed conductors is urgently needed.

To promote the practicalization and large-scale application of OECT devices, it is necessary to construct OECT array devices with high resolution and high integration density, while conventional preparation technologies can hardly meet the requirements for fabricating high-integration OECT arrays. With the development of emerging manufacturing technologies such as printing and roll-to-roll automated production, large-area, high-performance OECT devices will gradually achieve wide application. It is believed that in the near future, bioelectronic devices based on OECT technology will be truly implemented in industrial production and daily life.

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