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Organic Electrochemical Transistors: Principle, Characteristics, and Application Frontiers

Leyao Zhong

Department of Chemical Engineering, University College London, London, United Kingdom
zcechon@ucl.ac.uk

Abstract. Organic electrochemical transistors (OECTs) are operated at the intersection between ionic and electronic conduction and are a fast-advancing and highly promising platform for bioelectronic integration. Recent research progress revealed how their mixed ion-electron coupling mechanism leads to high-device performance: their transconductance is high, their operation voltage is low and they are outstanding biocompatible. OECTs could be especially attractive for physiological conditions because they possess these aforementioned characteristics. In this survey, the breakthroughs of operation principles, material and structure design has been summarized from the typical planar structures to novel three-dimensional and non-semiconductor structures. The key results concerning operation robustness, n-material growth and fabrication of devices and systems have been discussed for various functional applications. The paper concludes with the efforts on how performance optimization efforts and remain challenges can be overcome regarding device design, modeling and low cost fabrication in order to predict further significant applications of OECTs in wearable health monitoring, neural interface, and neuromorphic computing devices, thus exploiting the interface between the living and the digital world.

Keywords: Organic electrochemical transistor (OECT), Ion-electron coupling, Bioelectronics, Biosensor, Neuromorphic computing, Flexible electronics

1. Introduction

Organic electrochemical transistors (OECTs), leveraging the unique mixed ionic-electronic conduction, have emerged as a pivotal technology in bioelectronics [1]. These devices function through electrochemical doping and dedoping processes in organic semiconductor channels, modulated by ion migration from an electrolyte under gate voltage [2]. This mechanism enables efficient transduction of ionic biological signals into amplified electronic outputs, making OECTs exceptionally suitable for bridging biological systems and electronic interfaces [3]. Key advantages—such as operation under 1 V, high transconductance, and intrinsic flexibility—allow their use in implantable and wearable applications, from real-time metabolite sensing (e.g., glucose, cortisol, ions in biofluids) to neural interfacing and neuromorphic computing [4].

Although there has been considerable promising developments towards the materials, devices architectures (e.g., planar, vertical, solid-state) etc. [5], there are still some challenges to be tackled. Nowadays, there are considerable efforts involved in these directions, such as for the operational

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stability, enhanced n-type semiconductor's quality and the integration towards the level of system for the purpose of facilitating scalable application [6]. Ongoing research using electrochemical measurements, multimodal characterization and device modelling is currently engaged with these challenges, yet longevity for biocompatibility and steady signal response under physiological conditions, need confirmation [7].

In this paper, a comprehensive review on the basic working principle, structural development, and high performance, performance enhancement on the functioning of OECT has been presented along with the status and prospects for further applications. Further, summarizing the recent research work and laying out the future challenges would promote structured studies on OECTs in the future.As the research about personalized healthcare and brain-inspired computing has gained interest, the upcoming use cases in the field of OECTs shall become bigger in next generation of the bioelectronic devices [8]. It not only advances the scientific knowledge about organic mixed conductors but also facilitates the commercialization of the world of flexible, low power and high sensing capability of biomedical sensors [9], for which the global health care solutions as well as intelligence human machine interface are becoming a reality.

2. Operational mechanism and key characteristics of OECTs

2.1. Fundamentals of ion-electron coupling

The operational principle of OECTs is rooted in bulk modulation of the organic semiconductor channels by the ion injection from the electrolyte under gate voltage [2], where the positive gate bias in p-type OECTs (e.g. PEDOT: PSS based device) increases conductance in the channel by anions dedoping hole carriers [10], whereas in n-type OECTs the negative gate bias leads to cation injection into the channel which will promote additional electrons in the channel and so increase current at the drain contact [11]. This phenomenon of volumetric doping — in contrast to surface–limited phenomena in conventional transistors [2] — allows for extraordinarily high capacitance and transconductance for a high signal amplification under the physiological conditions [3].

2.2. Performance metrics and modes of operation

The quality of the OECT performance is measured by a few parameters describing their performance collectively [12]. The transconductance (g_m), representing signal amplification capability, reaches values surpassing 180 mS in state-of-the-art devices, enabling detection of subtle biological signals [4]. Switching performance demonstrates sub-microsecond response times in vertical architectures while maintaining on/off ratios typically above 10^6 [5]. Operating stability has been advanced considerably via material and encapsulation optimization and we have shown up to a 180 day continuous operation period, a particular advantage for implantable devices [7]. Most of them functions in the depletion mode (p-type) and enhancement mode (n-type) regimes. Moreover, enhancement mode of operation provides low quiescent power consumption and is thus preferred for long-term monitoring applications with low power-consumption constraints [13].

2.3. Theoretical modeling and device physics

The Bernards–Malliaras model captures the steady-state behavior of OECTs, describing a linear relationship between drain current and gate voltage [14]:

$$I_d = \frac{q\mu p_0 t W}{L}(1 - \frac{C^*}{p_0 q} V_g) V_d \tag{1}$$

This model highlights the roles of volumetric capacitance (C*) and ionic-electronic coupling, distinguishing OECTs from conventional field-effect transistors [14].

3. Device architectures and fabrication strategies

3.1. Planar vs. vertical configurations

Planar OECTs usually involve coplanar electrodes with micron-scale long channels from the lithography, where the production is easy but the switching speed is relatively slow and the integration density is not high [12].On the other hand, the vertical OECTs (vOECTs), which exploit channels with nanometer scale in length by means of spacer layers [5], and which offer sub-microsecond response times and much higher integration density in comparison to horizontal OECTs, are ideally suited to applications in neuro- morphic computing and high-frequency sensing [5].

3.2. Solid-state and flexible device integration

In response to the leakage and stability problems of the liquid electrolytes, the ion gel and solid state electrolyte have been increasingly used for the advantages of OECT, which help create mechanically tough, flexible fully-solid-state OECTs, with superior compatibility for wearable system [8]. Further ion injection efficiency and device stability are achieved by using multilayer structuring and interface engineering [7].

3.3. Material selection and functionalization

Material selection and functionlization are key for selecting the OECT performance. Even though p-type semiconductors, like PEDOT: PSS, are mature materials, tremendous effort has been devoted to n-type materials, such as doping-engineered polymers, reaching record μC* values over 54.8 F $cm^{-1}V^{-1}s^{-1}$, which has resulted in creation of complementary logic circuits and superior sensing capabilities [6].Parallelly, the electrolyte employed, from aqueous electrolyte to ion gel, substantially determines the working medium and the long-term stability [13].

3.4. Fabrication techniques

Lithography offers high-resolution patterning, while printing technologies (e.g., inkjet, aerosol jet, and screen printing) enable scalable fabrication of flexible devices [15]. For instance, research teams have successfully fabricated stretchable OECT arrays using high-resolution inkjet printing, achieving feature sizes as small as 100 micrometers with production yields exceeding 95%, and demonstrating sensor-in-computing modules compatible with smartwatches [16]. Laser-induced graphene (LIG) and chemical modification strategies, such as side-chain engineering—are expanding possibilities for porous electrodes and stretchable electronics [4]. Recent work has demonstrated fully gel based OECTs integrating hydrogel electrodes and electrolytes, exhibiting high stretchability (up to 50% strain) and transconductance (86.4 mS) while maintaining stable operation after 10,000 stretching cycles, providing new avenues for electronic skin and wearable sensors [17].

4. Performance challenges and optimization pathways

4.1. Material-level limitations and advances

The development of stable n-type and ambipolar semiconductors remains a central challenge [6]. Innovations in molecular design, including hydrophilic backbone integration and cross-linking groups, are improving operational stability in aqueous environments [2]. Doping-state tuning has emerged as a promising strategy for enhancing charge carrier stability and mobility [11].

4.2. Device design and structural innovation

Vertical structure design has drastically reduced channel length and improved response speed [5]. Nanostructured gate electrodes—e.g., Au-nanocluster-decorated LIG—have demonstrated enhanced catalytic activity, enabling ultrasensitive metabolite detection (e.g., glucose monitoring at sub- μM levels) [4].

4.3. Integration and manufacturing hurdles

Despite progress in printing and patterning technologies, achieving high-resolution, reproducible large-scale fabrication remains a key challenge [9]. Although vertical OECTs (vOECTs) show significant advantages in switching speed and integration density, their fabrication processes remain relatively complex and technologically immature, representing a major challenge in current development stages. Integrating OECTs with CMOS electronics requires novel interfacing strategies to combine low-voltage OECT operation with silicon-based signal processing [8]. Recent strategies have focused on developing hybrid integration platforms that maintain OECT performance while ensuring compatibility with standard CMOS processes [18].

4.4. Critical research directions

A number of essential research thrusts need specific concentration to accelerate OECT technology, such as the fabrication of stable n-type materials having high electron charge carrier mobility and biocompatibility [11]. For example, recent research on high-spin conjugated polymers has demonstrated n-type performance with μC^* reaching 147.4 F $cm^{-1}V^{-1}s^{-1}$, showing less than 6% current variation after over 1000 switching cycles, significantly improving the performance and stability of n-type devices [19]. The development of encapsulation methodologies capable of ensuring long-term operational stability in biological environments calls for systematic research [7]. Research indicates that the degradation of OECT cycling stability results from the combined effects of repeated ion doping/dedoping, bias stress, and faradaic side reactions, necessitating targeted encapsulation designs [20]. The advancement of dynamic models capable of accurately simulating ion-electron interaction dynamics [14], and the realization of high-density array integration for spatial sensing and neural recording applications represent additional key challenges [9]. Emerging research explores embedding artificial intelligence and machine learning capabilities within OECTs to enable real-time on-device computing (edge computing), a capability critical for developing high-density, intelligent sensing systems [21]. Ongoing research efforts are concentrating on multi-physics modeling, innovative material engineering, and hybrid integration strategies to address these fundamental challenges [15].

5. Conclusion

Organic electrochemical transistors (OECTs) have developed as a versatile platform for bioelectronic applications, by virtue of their ion-electron coupling mechanism that renders them to be highly sensitive, to amplify the signals, and to have neuromorphic capabilities, all in a flexible and biocompatible configuration.Their low-voltage yet high transconductance operation make them very suitable for seamless integration with biological system, opening the way to revolutionary application in the field of health-monitoring, neural interfacing and low-energy computing.

However, despite such a step forward these limitations need to be overcome by a pursuit of progress in order to fully implement OECTs, namely poor stability of n-type semiconductor materials under biologically-relevant medium, lack of long-time scale encapsulation schemes for implantable devices, and scalability of fabrication of a high density array of such devices.Additional, the interfacing to traditional siliconbased electronics is non-trivial, requiring new interfacing as well as co-design strategies.

Future research should prioritize the development of high-performance ambipolar and n-type organic semiconductors with enhanced environmental stability. Advanced encapsulation techniques using biocompatible barrier layers are critical for extending device lifetime in vivo. From a systemic perspective, exploring heterogeneous integration pathways with CMOS backplanes and creating multi-parameter sensing platforms will be pivotal for practical implementations. Beyond healthcare, OECTs show significant potential in environmental sensing, soft robotics, and neuromorphic computing, if issues in reproducibility and large-area fabrication are systematically addressed.

With continued interdisciplinary collaboration focusing on material innovation, device engineering, and system-level optimization, OECTs are well-positioned to transition from laboratory prototypes to commercially viable technologies, ultimately bridging the divide between biological and electronic systems while enabling new paradigms in personalized medicine and adaptive bioelectronics.

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