Low-power soft transistors triggering revolutionary electronics

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INTRODUCTION

Transistors have been reshaping our lives since their initial appearance in the 1940s. As the central element of logic gates and integrated circuits (chips), they undoubtedly play an incomparable role in promoting the development of computers, smartphones, flat panel displays, Internet of Things, and even all electronic or electrical systems. The past decades have witnessed dominant transistors usually made from inorganic semiconductors such as silicon materials and metal oxides, which are advantageous to achieve high mobility, fast switching speed, and excellent stability. Thus, silicon transistors and metal oxide semiconductor field-effect transistors have been broadly used for electronic applications. However, these transistors are rigid and nearly approaching the fundamental limits on speed and power consumption, despite being manufactured at a much smaller scale to meet the projection of Moore's law. As future transistors with mechanical flexibility/robustness and low-power consumption are demanded, innovation in functional materials, device configurations, and integrated processing techniques to facilitate the evolution from rigid devices to soft, durable, and biocompatible devices is imperative.[1]

Soft transistors, generally constructed from organic soft matter endowed with flexible, adaptable, stretchable, and transparent features, are emerging as the new-generation electronic devices. Organic semiconductor and dielectric materials are of great interest for uses in all types of soft transistors, benefiting from their molecule tailorability, inherent flexibility and even stretchability, as well as distinct electrical properties. Moreover, unlike traditional silicon- or oxide-based matter, organic materials can be produced and modulated by low-cost solution-processing methods, suiting for large-scale production and micro/nano-fabrication. Currently, the coupling of proper organic semiconductor/dielectric materials with suitable device operation mechanisms has been utilized to develop low-power soft transistors, their device array, and integrated electronic systems (Figure 1). They will provide transformative solutions for conventional rigid transistors and lead to revolutionary changes in device design and integration toward the next-generation electronic applications in flexible sensors, wearable e-skins, biomedical electronics, artificial synapses, neuromorphic computing, and much more.

ORGANIC SOFT TRANSISTORS AND LOW-POWER OPERATION

A three-terminal device architecture is mostly employed for organic soft transistors (Figure 1A). Briefly, an organic semiconductor channel layer contacts source and drain electrodes, while a dielectric layer electrically isolates the channel from a gate electrode on a thin soft substrate. When a voltage between the source and gate electrodes is adopted, an established electric field can stimulate the accumulation of charge carriers at the semiconductor/dielectric interface. Facile modulation of on/off-state currents by tuning the applied bias voltages enables organic soft transistors to afford attractive features in signal conduction, amplification, and switching for promising electronic devices.

The mobility, on/off current ratio, threshold voltage, subthreshold slope, and operating voltages are important parameters for assessing the performance of organic soft transistors. Particularly, low-operating voltages are crucial for achieving low-power soft transistors and their integrated devices, in which the dielectric material undoubtedly plays a paramount role. At present, three mainstream approaches of dielectrics design have been employed to achieve high-capacitance and thus low-power operation for soft transistors (Figure 1B). First, utilizing insulator materials with a high dielectric constant (κ) enhances the charge storage capacity of a dielectric layer (Figure 1B-I). As a consequence, it amplifies the electrostatic control exerted over the channel of soft transistors, enabling the target current modulation at low-voltage operation. Recently, Bao and coworkers unraveled the unique properties of nitrile-butadiene rubber, boasting an impressively high κ value of ~28 due to the polarization of nitrile groups from its molecular structure.[2] Nevertheless, this polarization effect induced energy disorder at the semiconductor/dielectric interface, leading to a decline in the electrical performance. Subsequently, by modifying such a high-κ dielectric with successively deposited an ultra-thin nonpolar elastomer layer and a hydrophobic monolayer, the exceptional performance in soft transistors was achieved with a low-operating voltage of 3 V. Notably, both the dynamic (1.7 pJ) and static (0.25 pW) power dissipations for the low-power organic field-effect transistors were reduced by ~100 times compared to those of the existing stretchable transistors.

Secondly, solid-state polyelectrolytes as promising dielectrics have emerged as another viable option for low-power soft transistors. Under a gate voltage, ions of opposite charges within the solid-state polyelectrolyte dielectric layer migrate in distinct directions, ultimately stabilizing at different interfaces to create an electric double layer (Figure 1B-II). This unique character endows it with the remarkable dielectric capacitance at the microfarad (μF) scale, surpassing that of high-κ dielectrics. As such, it significantly enhances the charge carrier transport ability, affording high-performance organic thin-film soft transistors with impressive low-voltage operation (<1 V).[3] However, the ion migration induces a more intricate interfacial energy disorder, posing challenges to ensure stable transistor operation with ultralow-power consumption.

Lastly, liquid or gel electrolyte materials have been developed to further enhance the effectiveness of ion action within the electrolyte dielectric layer. Diverging from the mechanisms of the above two approaches, these materials enable volumetric ion injection into the active layer of organic semiconductors upon an applied gate voltage (Figure 1B-III). This direct integration of ions into the channel increases the conductivity and significantly reduces the operating voltages for organic soft transistors.[4] However, it is worth noting that the dynamics of ion migration and reaction may engender the sluggish response time and increase hysteresis effects in this type of organic electrochemical soft transistors.

Indeed, each of these methodologies exhibits unique advantages and also suffers from inherent shortcomings in the fabrication of low-power soft transistor devices. The selection of an optimal approach is contingent upon the specific requirements of low-power soft transistors while maintaining a delicate equilibrium among several important factors such as the κ, capacitance, leakage current, mobility, working voltage, switching rate, device flexibility, stability, and durability. Additionally, the choice and customization of organic semiconductors are also critical to high-performance soft transistors for targeted electronic applications.

FLEXIBLE WEARABLE ELECTRONICS

In the realm of flexible wearable electronics, it is essential to ensure the exceptional stress stability and rapid response of soft devices. Consequently, organic dielectric materials featuring high-κ properties and solid-state polyelectrolytes emerge as compelling alternatives to conventional inorganic dielectrics for constructing mechanically flexible, stretchable, stable, and soft transistors.[2,3] These soft devices not only adhere to the voltage standards for human safety but also boast energy-efficient and eco-friendly characteristics. Employing them as a low-power wearable sensor array for monitoring human movements, or integrating them as soft sensory units within prostheses, soft robotics, and artificial e-skins, can afford comprehensive detection of different physical or chemical signals encompassing touch, pressure, temperature, humidity, salinity, light irradiation, and even acoustic stimuli, etc. This remarkable versatility of low-power organic soft transistors endows them with immense potential for diverse emerging applications in flexible wearable electronics (Figure 1C). Compared to inorganic transistors, low-power organic soft transistors are more advantageously adapted to the deformation caused by human activities due to the intrinsic flexibility and bending durability of organic materials.

BIOMEDICAL ELECTRONICS

Organic soft transistors possess biocompatible, conformable, and even biodegradable properties that lend themselves to advanced biomedical applications in

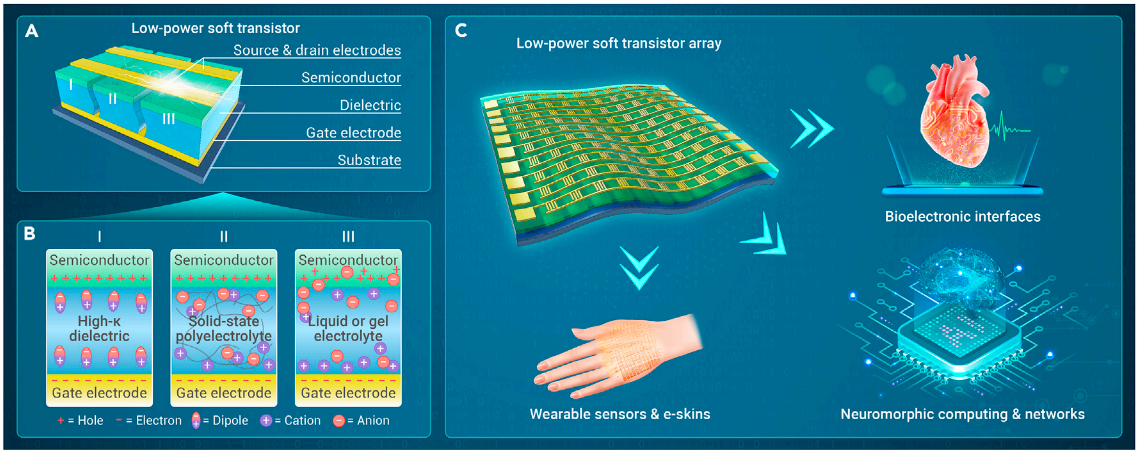

Figure 1. Comprehensive overview of low-power soft transistors (A) Schematic diagram of the device structure. (B) Illustration of the working principles based on three types of dielectric materials. (C) Promising prospects for applications in emerging electronics.

revolutionary bioelectronics (Figure 1C), such as soft bioelectronic interfaces, brain-machine interfaces, prosthetics, implantable medical devices, and so on. These applications require seamless integration between artificial devices and biological systems. In this context, the utilization of soft transistors with liquid electrolyte dielectrics presents an appealing choice to create a harmonious interface with tissue at low-operating voltages. By establishing intricate connections between soft electronic devices and both plant neurons as well as rodent brains, the acquisition, processing, and transmission of neurophysiological signals become more feasible.[4] This groundbreaking research has good potential to be extended into a broad range of clinical and societal domains, paving the way for future transformative applications.

NEUROMORPHIC ELECTRONICS

Hysteresis is undesirable in low-power organic soft transistors, but it has emerged as an intriguing prospect in the domain of neuromorphic electronics (Figure 1C). By deliberately and gradually tailoring the current variations under stimuli, it effectively emulates the sensing, memory, and processing functions exhibited by biological synapses. Remarkably, the power consumption per single stimulation of these soft transistor-based synapses has reached an astonishingly low magnitude on the order of attojoule (aJ).[5] The integration of low-power artificial synapses and device arrays in large-scale neural computing systems holds tremendous potential for significantly reducing overall energy consumption while enabling efficient information storage and processing. This capability empowers them to learn and discern various sensory signals, thereby opening up immense possibilities in artificial intelligence, deep learning, neuromorphic computing, and beyond.

CONCLUDING REMARKS AND PERSPECTIVES

In summary, the low-power operation of organic soft transistors, which has been realized by dielectric engineering *via* the effective design of organic high-κ materials, solid-state polyelectrolytes, and liquid or gel electrolytes, demonstrates a promising avenue for emerging applications in flexible, wearable, biomedical, and neuromorphic electronics. However, achieving excellent performance and reliable device operation with ultralow-power consumption remains a challenge for soft transistors, in particular for their integrated arrays and bio-inspired electronic systems (*i.e.*, e-skins, e-noses, e-eyes, e-ears, e-throats, bionic actuators, prostheses, and soft robots) with multifunctional signal detection, information memory/storage, and intelligent processing. Another challenge in realizing the multistability of soft transistors should be intensively explored in different aspects of soft electronics, such as novel materials synthesis, device construction, array integration, circuit design, interface engineering, and electronic packaging. In addition, high-reproducibility and scale-up fabrication of soft devices still require the identification of appropriate materials and compatible processing techniques. Future improvements in advanced manufacturing techniques, such as photolithography and high-resolution printing, are essential to enable large-scale production and deployment of low-power soft transistors as well as their integrated devices. With these limits, it is significant to establish clear material-structure-property-performance relationships, where a basic step is to develop robust and stretchable materials (*e.g.*, soft dielectrics, semiconductors, electrodes, and substrates) with tunable structures at the micro/nano-scale level. The finely designed materials and structures will afford good physical or chemical properties, which in turn determine the performance of soft devices and jointly shape the potential application scenarios. The coming decades still require continuous efforts on both theoretical and practical innovation in the interdisciplinary fields of advanced materials and device architectures with light, soft, portable, self-healing, and even smart response features as well as pioneering integration techniques, constantly promoting revolutionary progress toward future electronics such as soft circuits and intelligent chips.

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DECLARATION OF INTERESTS

The authors declare no competing interests.