Wearable Electronic Devices Driven by Flexible OFETs

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Abstract. This paper discusses flexible organic field-effect transistors (OFETs) in wearable medical, health and sports monitoring electronic applications including polariton organic light-emitting diodes (POLEDs), flexible sensors as well as self-powered and highly sensitive sensors. It reviews the structural features of flexible OFETs and emphasizes their dual function in energy harvesting and smart sensing. With energy harvesting, triboelectric nanogenerators (TENGs) and piezoelectric harvesters work together with OFETs to generate electricity from mechanical energy and store energy. For example, in smart sensing, they sense pressures, temperatures, glucose, and tumor markers through modulating the channel conductance. The review reports progress in material innovation and structural integration, and also ultra-fabric-like devices of OFET-TENG. It further discusses the remaining issues such as the stability of materials, energy conversion efficiencies and large-scale production, and proposes the prospects of commercialization of the technology through the modification of materials, 3D printing technology and the application of machine learning.

Keywords: Flexible organic thin-film transistors (OFETs); Wearable electronic devices; Energy harvesting; Intelligent sensing.

1. Introduction

At present, wearable electronic devices have evolved from concept to commercialization, displaying considerable potential in areas such as healthcare and sports monitoring. By 2023, the global shipment of wearable devices had surpassed 600 million units, with more than 45% of them incorporating physiological monitoring capabilities. The desire for an "all-day, high-precision, and unobtrusive" experience has emerged as the main driving force for the industry. However, traditional devices encounter three major obstacles: their inflexible structures lack adaptability to the human body’s curved surfaces, are prone to deformation, and cause discomfort during prolonged wear; their reliance on lithium batteries results in short battery life, limiting the use of implantable or skin-contact medical devices; and the separation of sensing and driving circuits leads to increased device size, high power consumption, and challenges in meeting the requirements of "lightweight and low power consumption".

Flexible organic thin-film transistors (OFETs) have emerged as a key element to break through these limitations. Compared with silicon-based transistors, they use flexible substrates such as polyimide (PI) and polydimethylsiloxane (PDMS), and integrate solution processing techniques such as inkjet printing, achieving ultra-thinness (thickness < 10 micrometers) and large-scale production, with excellent mechanical flexibility. After 1,000 bends (bending radius < 5 mm), the carrier mobility decreases by only 10%. In addition, the molecular structure of organic semiconductors can be designed to enhance electrical performance through chemical modification (carrier mobility of conjugated polymers exceeds 10 square centimeters per volt-second), while ensuring biocompatibility, creating conditions for skin-contact or implantable applications. They can also integrate energy harvesting and sensing functions, providing an integrated approach for "self-powered - precise sensing" [1-4].

The advantages of organic flexible field-effect transistors (OFETs) lie in two aspects: "functional integration" and "performance breakthrough". In terms of functional integration, traditional devices have separate energy modules and sensing modules, which require complex connection and management circuits. This leads to increased volume, power consumption, and reduced stability. In contrast, flexible OFETs can simultaneously act as "energy converters" and "signal processors". They can convert human mechanical energy into electrical energy for the sensing module through

triboelectric and piezoelectric technologies. Moreover, due to their electrical properties, they can directly serve as sensing units, reducing signal loss, and improving accuracy.

In terms of performance breakthroughs, they offer new solutions for optimizing device performance indicators. In the self-powered field, traditional triboelectric and piezoelectric collectors have energy utilization efficiencies < 20%, while flexible OFETs can achieve dynamic impedance matching through gate voltage regulation, increasing efficiency to over 45%. In the intelligent sensing field, functionalized OFET sensors exhibit outstanding performance, such as including microstructure array pressure sensors with a sensitivity of 10^4 Pa^{-1} (far exceeding traditional capacitive < 10^3 Pa^{-1}), and antibody-modified biosensors with a detection limit for tumor markers as low as 10^{-9} mol/L.

In addition, they also have significant industrial and social significance: the solution processing technology is compatible with roll-to-roll large-scale production, with a cost of less than 0.1 US dollars per square centimeter, which helps to popularize the equipment; self-powered medical devices can achieve long-term non-invasive monitoring of patients with chronic diseases, reducing medical expenses.

In recent years, significant progress has been made in related fields. In the area of flexible OFETs, through material molecular design (pentacene, perylene imide semiconductors) and structural optimization (top-gate top-contact structure), the carrier mobility has increased from 10^{-3} to over 10 $cm^2/V \cdot s$. In 2022, *Advanced Materials* reported that the carrier mobility of polythiophene derivative OFETs remained stable with only a 5% performance decline after 10,000 bends.

In the field of energy harvesting integration, TENG-OFET has become a hot topic. In 2023, *Nano Energy* reported a fiber-shaped integrated device with an output voltage of 50V, capable of driving low-power sensors. In the piezoelectric field, low-resonance frequency films (dual-resonance PVDF) have expanded their working bandwidth to 10-30Hz, suitable for human low-frequency mechanical energy, and OFETs can increase the output power density to 0.35 $\mu W/cm^2$ @ 16Hz.

2. Structure and characteristics of flexible OFETs

Organic field-effect transistors (OFETs) utilize organic semiconductors as conductive channels, exhibiting advantages such as flexibility, low power consumption, and solution-processability. Their structural configurations include bottom-gate top-contact and top-gate bottom-contact architectures, where the charge carrier density in the conductive channel is modulated via gate voltage to achieve voltage-controlled characteristics.

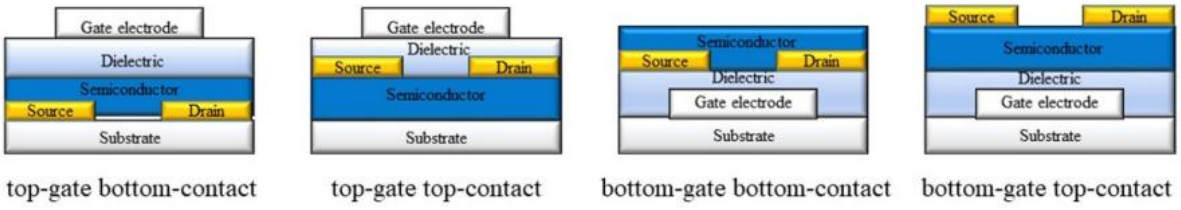


Fig. 1 The structure of OFET transistors [3]

Figure 1 shows the structure of OFET transistors. Within flexible electronics, organic field-effect transistors (OFETs) have solidified their position as cornerstone devices, thanks to a collection of properties—wide-ranging active material choices, seamless integration with rollable substrates, processing below 150 degrees Celsius, scalable batch routes, and economical fabrication costs. Current research converges on three interrelated priorities: mechanical bendability, low-voltage energy draw coupled with high sensor fidelity, and compatibility with human tissues. Collectively, these targets not only define the optimization frontier for mobility and on/off ratio values, but also chart a clear roadmap for engineering ultra-thin, skin-mountable gadgets and implantable diagnostics. Prolonging mechanical lifespan, however, necessitates a multi-faceted engineering framework that integrates materials science and device-circuit design principles. The choice of polymer substrate is

a key lever; for example, polyimide (PI) and polydimethylsiloxane (PDMS) can maintain device mobility while remaining pliable beyond 1000 bending cycles. Going a step further, the strategy evolves to coordinate nanoscale annealing of semiconductors and dielectrics to form 20-nanometre carrier channels, enhancing bending strength. Careful pre-straining of the substrate, combined with the evaporation of a low-surface-energy top layer, creates deterministic micrometer-scale wrinkles that act as stress-relief zones, dispersing tensile hotspots often responsible for early device failure. When miniaturizing polymer topologies, surface conversion techniques grow low-friction layers, suppressing crack propagation and ensuring uninterrupted device operation during daily movements [5,6].

On the device level, low-power consumption, and high-sensitivity OFETs are correlated with overdetermination in physicochemical properties of core materials. The charge carrier mobility of the organic semiconductor material used has a direct impact on the responsiveness of the device and its signal transmission efficiency, while the capacitor characteristics of the dielectric layer (e.g., using a dielectric material with a high permittivity based on an organic/inorganic composite) can lead to a lower operating voltage and therefore to low power operation. With their low-cost and mass-producibility, such characteristics would even expand their application fields when merged with the advantages of OFETs.

When evaluating biocompatibility, the organic materials employed in organic field-effect transistors—such as polylactic acid or custom-modified organic semiconductors—must pass extensive biosafety validation, including both cytotoxicity assays and in vivo implantation studies. In parallel, applications of these transistors in wearable devices demand attention to practical attributes: the capacity to mold to the skin without discomfort and the resiliency to, or outright resistance against, bodily sweat, are critical to achieving the expected performance in flexible, skin-mounted biomedical systems.

3. Functional Mechanisms of Flexible OFETs in Energy Harvesting

3.1. Core Functions of OFETs in Energy Harvesting Systems

Among the sophisticated structure, flexible organic field-effect transistors (OFETs) are the first irreplaceable core devices, which possess superior electrical characteristics and structural merits and play the dual role of "converters" and "controllers". They can convert energy from the environment, and accurately control to realize stable electric output, that can drive kinds of low power electronic products for a long time.

Light, heat, and various forms of energy such as light, heat, and mechanical force are extensively prevalent in the environment and are renewable but are not readily available energy sources for practical use. OFET can serve as a “converter” of energy harvesting module, converting these underutilized and hard-to-directly-use environmental energy to electricity. Regarding light energy harvest, in organic optoelectronics, OFET cooperates with organic photosensitive materials. Electron-hole pairs will be created when photons hit photosensitive materials. OFET takes advantage of its own field effect to efficiently separate and deliver these carriers, which finally produces a current in the outer circuit and achieves the conversion from light energy to electric energy. Regarding the thermal energy harvesting, the organic thermoelectric devices using the Seebeck effect with the OFET produce the electric potential difference between the two ends of the material by the temperature difference. The weak thermoelectric signals generated are further processed via OFET, realizing effective conversion of heat into electricity. In the case of mechanical energy such as the mechanical energy of human motion OFET operates together with piezoelectric or triboelectric materials. By means of piezoelectric or triboelectric effect, mechanical energy is converted to the electric energy and the generated electric signals are well modulated.

Apart from energy conversion, OFET also plays the role of the controller in an energy harvesting system by stabilizing the output of electrical energy. Owing to the unstable and intermittent nature of environmental energy harvesting—for example, light intensity fluctuates over time, and the

magnitude and frequency of mechanical forces from human motion change continuously—the electrical energy generated by energy harvesting components (as mentioned earlier) is relatively erratic. OFET can control and steady these changing electrical energies by its own electrical properties, so that the output electrical power meets the requirement for operating the load devices. For example, OFET can function as a variable resistor, automatically correcting its resistance value based on the changes in output voltage of the energy harvesting component so as to stabilize output current; or, by controlling the gate voltage, OFET is able to accurately regulate output electrical energy and make the load device work under stable voltage and current states.

Matching of energy harvesting constituents and loads is important in improving the efficiency of energy utilization and OFETs are an invaluable player which can bridge the gap. Energy harvesting elements such as triboelectric and piezoelectric devices generally have large output impedance, and they are hard to match the load elements with low impedance directly, which causes a great transmission loss. OFETs have novel electrical characteristics, can be reasonably designed and optimized, and can fine-tune impedance so that it can be well matched with energy harvesting devices and loads. It has been demonstrated that the input and output impedances of OFETs can be tuned accurately by varying the channel length and width of OFETs and the properties of the organic semiconductor materials. When coupled with TENG, the OFETs can be optimized for electrical parameters corresponding to the output impedance of TENG, thereby improving the energy transmission efficiency and reducing energy loss. Power management is another way to improve energy utilization efficiency of OFETs. They have a proper adaptation modulation path of output power to the load, to avoid energy loss. When the load works under low power, the OFETs will automatically reduce the output power; once the load needs a high-power operation, the OFETs are able to adjust in time amount of electrical energy to the load.

3.2. Triboelectric Effect Coupled with Energy Harvesting Technology

3.2.1 Interfacing of Triboelectric Nanogenerators (TENG) and Organic Field-Effect Transistors (OFETs)

Triboelectric nanogenerators (TENGs) have been reported as a promising energy harvesting technology relying on the principle of contact electrification and electrostatic induction coupling, which opens a door to a variety of energy sources to harvest a variety of energy sources. When two dissimilar materials are in contact and are separated again, the electrons from one material remain on the other because of the different electron affinities of the materials, leaving the material surfaces with net static charges. Thereafter, he variation of these static charges under electrostatic induction induces currents in the external circuit, and therefore, the mechanical energy is transferred into the electric energy. It is featured by a simple structure, low cost, and working in multiple environments, which makes it suitable for converting mechanical energy of human motion, environmental vibration and the like.

The high performance of flexible TENGs is essential to improve the output performance of TENG. For example, the triboelectric output performance of modified polyvinylidene fluoride (PVDF) through chemical modification or composite with other substances can be remarkably improved. Adding nanoparticles (e.g., titanium dioxide (TiO_2) nanoparticles) into PVDF enables modification of the surface charge density and polarization property of the material, enhancing the triboelectric output. Graphene composite films are also a hot spot of research. The remarkable electrical and mechanical properties of graphene make it an ideal composite material. When TENG based on graphene composite films (T4) are coupled with other triboelectric materials, not only is the conductivity of the film increased, but the flexibility and mechanical strength of the film are also enhanced, thus broadening the application range of TENG.

The rational structure of OFET-TENG integrated devices is clearly the key for efficient energy conversion. Fiber-like and fabric-like integrated devices have the feature of high weavability and good flexibility, which are especially suitable to harvest human motion energy. The TENG-OFET glove that can be woven is a redox reaction structure that cleverly introduces TENG and OFET into

fabric. During human movement, such as walking and gesturing, the TENG unit can produce electricity on surface of the glove driven by the friction and stretching. The OFET controls and manipulates this electricity, enabling high-efficiency energy collection at an output voltage of 10 - 50V, which can be used to drive low-power sensors, such as acceleration sensors and pressure sensors, for monitoring hand movement states—providing a viable solution for wearable self-powered devices.

3.2.2 Application Scenarios

Self-powered wearable devices are one of the promising application fields of TENG-OFET integration technology. Consider smart bracelets and insoles, for instance. By integrating TENG-OFET devices into these devices, the mechanical energy from human motion can be converted into electrical energy and used to power the devices' built-in sensors, microprocessors, without the need for traditional batteries. During users' daily-life actions, a smart bracelet can realize the conversion of mechanical energy into electrical energy by the TENG on the bracelet surface caused by swinging and bending movements of the wrist. The OFET can egulate and supply electrical power, so the bracelet is always normally working and human physiology data such as walking steps, heart rate and sleeping quality can be monitored in real time. By contrast, smart insoles drive TENGs to collect the electric quantity of the pressure sensors and temperature sensors in insoles through the friction between the insole and the ground as well as the pressure applied to it, which makes the insole to monitor foot pressure distribution and foot temperature and to provide data support for sports health monitoring and disease prevention.

3.3. Energy harvesting technology with piezoelectric effect

3.3.1 Complementary Functions of the Piezoelectric Energy Harvesters and OFETs

Piezoelectric effect is the fact that some materials generate positive and negative charges at their ends when they are elastically deformed [7] and is used for converting mechanical energy into electric energy. Both poly (vinylidene fluoride) (PVDF) and zinc oxide (ZnO) nanowires have been reported to have good piezoelectric properties and are extensively investigated and used in energy harvesting.[8] Under the action of externally-induced mechanical stimulation, such as vibration, stress, etc., dipoles undergo a re-orientation of the internal electric dipoles, which in turn causes charge to separate, and an electrical potential difference is established on the surface of the piezoelectric particles.

The research of the bandwidth expansion of low resonance frequency piezoelectric films has attracted more attention in order to further match the human body motion frequency. With the help of special structural design and material optimization, the dual-resonance PVDF film is found to be capable of working in the effective frequency band from 10 to 30Hz, which corresponds to the frequency produced by human walking/running and other activities. This film, when working under mechanical vibration from human motion, could produce much more stable and stronger piezoelectric signals for more effective energy collection.

OFET is essential for signal amplification and rectification in piezoelectric energy harvesting, which contributes to excellent output power density. OFET amplifies the attendant weak electrical signal generated from piezoelectric material by its unique field effect to make the intensity of the electrical signal effectively enhanced. OFET may also rectify the alternating current electrical signal and convert into a direct current electrical signal, so as to enable storage and supply off to load devices. Driven by a frequency of 16Hz, the output power density can achieve 0.35μW/cm² by the rational modification of OFET and its synergic effects with piezoelectric materials, offering a solution for power supply of low-power electronic devices.

3.3.2 Application Scenarios

There is abundant mechanical energy available in human bodily activities [9], i.e., heartbeats and breathing. This mechanical energy can be converted into electrical energy using piezoelectric energy harvesters and organic field-effect transistors (OFETs), which can then power implantable or skin-attached medical sensors. Implantable heart monitoring sensors can be attached to the surface of or

onto the tissue around the heart. During each heartbeat, the piezoelectric material generates electrical energy in response to the mechanical force exerted on it. The OFET amplifies these electrical signals to ensure the sensor's continuous power supply, enabling long-term real-time monitoring of data such as cardiac electrophysiological signals and cardiac acrophase. This is crucial for the diagnosis and treatment of cardiovascular diseases. Skin-contact wearable respiratory devices use piezoelectric materials mounted on the skin to detect chest movements during respiration and generate electrical energy to power the sensor—thus monitoring respiratory rate and depth. These devices are commonly used for the screening and monitoring of respiratory diseases (e.g., sleep apnea syndrome).

4. Smart Sensing of Flexible OFETs: Form and Function

4.1. OFET Sensing: Fundamentals

In intelligent sensing, flexible OFETs have been proven uniquely beneficial. OFET-based sensing relies on the modulation of channel conductance by external signals, which occurs through charge transfer or molecular adsorption—and this modulation in turn affects carrier mobility. For chemical sensing, the adsorption of gas molecules modifies the charge distribution, which alters conductivity and the source-drain current. Sensitivity ($\Delta I/I_0$), response time, detection limit, and long-term stability are the key performance indicators for sensor applications [10].

4.2. Sensing of a physical quantity (Pressure, Temperature, Strain)

Flexible pressure sensors based on OFETs measure dielectric layer-thickness or contact area-dependent source-drain current. Highly sensitive (up to 10^4 Pa^{-1}) OFET pressure sensors with microstructure arrays sense weak pressure changes, for example, pulse and voice vibrations, offering potential health and voice recognition applications. The sensor response is temperature-sensitive, and this is used in a temperature sensor because the mobility of organic semiconductor decreases with increasing temperature. The strain sensor operates based on the fact that the semiconductor layer of the sensor undergoes changes induced by substrate strain (as for athletic training) [11].

4.3. Biological and Chemical Sensing

The detection of biomarkers involves functionalizing the OFET semiconductor layer with biological probes such as antibodies. For example, in diabetes diagnosis, an OFET sensor integrated with glucose oxidase monitors glucose levels in sweat by converting the enzymatic reaction into electrical signals. These novel flexible biosensors can achieve a detection limit of 10^{-9} mol/L for sweat components, making them suitable for diabetic healthcare applications.

OFETs are also highly sensitive to humidity, NO_2, and NH_3. The adsorption of chemical molecules alters the carrier concentration in the semiconductor, a property utilized for sensing purposes. They can even monitor real-time levels of poisonous gases, contributing to environmental protection and public health.

5. Frontier Technology Integration and Application Cases

5.1. Energy Harvesting - Integrated Sensor System Design

Energy efficiency, sensing efficiency, and self-sustainability are of great importance. The "self-powered sensing system" closed loop is developed by combining triboelectric nanogenerators (TENGs), piezoelectric modules, and flexible OFETs to convert mechanical energy from human movement into electrical energy. OFETs improve the measurement and processing of different signals with high accuracy.

For example, smart bandages are attached to wounds, and TENG or piezoelectric modules are used to power the OFETs, which then monitor temperature and humidity. Changes in these parameters

reflect the inflammatory state and healing progress of the wound, thus enabling real-time monitoring of wound conditions and supporting the effectiveness of medical treatment.

5.2. Typical Application Cases

Medical health wearable skin-contact devices are developed using flexible OFET technology to monitor physiological parameters such as heart rate and blood glucose. With the support of Energy Harvesting, they can operate continuously for up to 7 days without external power. These devices can monitor the health of people with heart conditions and diabetics, thereby helping prevent diseases and guide treatment.

There are smart insoles integrated with piezoelectric-OFET modules for motion monitoring. When the feet press down on the insoles during exercise, the modules generate electrical energy while analyzing pressure distribution to evaluate movement posture—supporting athletes' scientific training and reducing the risk of injuries.

In human-computer interaction, an adaptable gesture recognition glove based on triboelectric-OFET technology enables precise gesture recognition. It can identify over 96% of gestures and is applicable not only to virtual reality control but also to smart home control and other fields, providing convenient interaction for groups such as drivers.

6. Challenges and Prospects

6.1. Existing Challenges

Flexible OFETs face several challenges. First, organic materials are prone to environmental influences, resulting in poor performance stability over time. Their molecular structure and carrier mobility are sensitive to environmental temperature; additionally, high humidity induces more trap states in the materials, leading to rapid device aging. Thus, their long-term application in complex environments remains a problem to be addressed.

Second, integration and scaling issues persist. Dense integration of flexible OFETs and energy harvesting modules at a high level is constrained by material incompatibilities, size matching, and the need for balanced electrical performance—making electronic design far from simple. Moreover, while solution-based processing holds promise for low-cost, large-area material fabrication, limitations related to uniformity, production rate, and other factors have hindered large-scale commercialization.

Furthermore, energy conversion efficiency is another concern. Energy harvesting modules based on triboelectric and piezoelectric effects have efficiencies limited to several hundred nW/cm^2, which is insufficient to power high-power flexible devices.

6.2. Future Directions

To overcome these limitations, the further improvement of flexible OFETs can be pursued in several directions. First, the development of new materials is indispensable: new organic semiconductors—such as conjugated polymer/metal-organic framework composites—can further enhance carrier mobility and stability while reducing environmental sensitivity.

Second, structural optimization is necessary, which involves introducing advanced fabrication techniques such as 3D printing and transfer printing to flexibly integrate OFETs and energy harvesting elements. Specifically, 3D printing enables precise structure construction, while transfer printing facilitates efficient material transfer for device integration.

Additionally, the integration of machine learning may contribute to the fabrication of flexible OFETs. This can enhance anti-interference capabilities in signal sensing and assist in accurately obtaining and analyzing signals, thereby aiding in the development of intelligent health and smart wearable devices.

7. Conclusion

In this review, we focus on flexible OFETs in wearable devices and their important applications in energy harvesting and accurate sensing. In the field of energy harvesting, the integration of flexible OFET-based devices with triboelectric and piezoelectric technologies has enabled efficient conversion of environmental energy derived from human motion and physiological activities. This is essential for freeing these devices from heavy reliance on batteries. In terms of sensing applications, novel structural designs and material modifications have enabled flexible OFETs to achieve highly sensitive detection of physical quantities (e.g., pressure, temperature) and representative biomarkers—meeting the requirements of medical and sports monitoring.

To date, flexible OFETs still face some challenges, such as insufficient material stability, low integration levels, and low energy conversion efficiency. Future development should focus on material innovation, structural optimization, and intelligent integration to enhance their commercial application prospects—such as in portable healthcare and human-computer interaction—thus driving wearable devices towards lightweight, self-powered, and highly intelligent solutions.

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