

Advanced Plastic Electronics in Wearable Devices

Xiao Han *

Beijing Number 80 High School, Beijing, 100020, China

* Corresponding Author Email: 1801010322@stu.hrbust.edu.cn

Abstract. The rapid evolution of wearable technology, characterized by its integration into devices such as smartwatches, medical instruments, and smart clothing, has significantly expanded the functionalities of these devices, enabling sensing, energy harvesting, luminescence, and thermoelectricity generation. Central to this technological revolution is the development of plastic electronics, which combines the electrical properties of semiconductors with the flexibility and lightness of plastics, offering unprecedented opportunities for wearable applications. This article explores the pivotal role of conductive polymers, such as polypyrrole (PPy), polyaniline (PANI), and polythiophene (PT), in advancing wearable devices, focusing on health monitoring and environmental sensing. It first discusses the fundamentals of conductive polymers, their applications in wearable health monitoring devices for tracking body signals and fluids, and their use in environmental sensing devices for detecting gases and humidity. The integration of conductive materials with wearable devices, through methods like textile structure incorporation and tattoo-based sensors, is discussed, highlighting the challenges and future expectations in the field. The paper emphasizes the need for balancing aesthetic appeal with functionality, the pursuit of miniaturization, and the importance of addressing environmental concerns associated with the sustainability of conductive polymers. Through this comprehensive review, the transformative impact of plastic electronics on wearable technology and its potential to significantly advance the sensing industry is underscored, marking a promising direction for future research and development in wearable applications.

Keywords: Conductive polymer; wearable sensor; integration technique.

1. Introduction

The burgeoning field of wearable technology is witnessing a surge in interest aimed at augmenting the functionalities of devices such as smartwatches, medical instruments, smart glasses, and smart clothing. These advancements equip wearables with capabilities for sensing, energy harvesting, luminescence, and thermoelectricity generation, underscoring their vast potential across various sectors including healthcare, environmental sensing, safety, fashion, fitness, and data collection.

Plastic electronics, often referred to as organic or flexible electronics, are fundamental to the advancement and widespread adoption of wearable devices. This innovative technology merges the electrical characteristics of semiconductors with the versatility and lightness of plastics, thereby broadening the horizons for wearable technology. At the core of the wearable technology revolution, plastic electronics provide unparalleled flexibility, comfort, and design opportunities. Plastic electronics primarily consist of conductive polymers featuring a conjugated carbon chain with alternating single and double bonds, where π bonds facilitate electrical conductivity. These polymers offer several advantages, including tunable electrical properties, environmental stability, and ease of processing, making them favorable over traditional metal conductors. Common conductive polymers such as PPy, PANI, PT, and PT derivatives like poly(3,4-ethylenedioxythiophene) (PEDOT) have been effectively utilized as electrode materials.

In light of the recent advances in plastic electronics as wearable devices, this article explores the role of plastic electronics in wearable devices, particularly focusing on health monitoring and environmental sensing, and the transformative impact these technologies have on specific products. The integration of wearable sensors with real-time monitoring and diagnostic systems is poised to significantly advance the sensing industry.

2. Fundamentals of Plastic Electronics

2.1. Liquid Crystalline Polymers

Liquid crystalline polymers (LCPs) are categorized into two main types based on their ordering: lyotropic main chain LCPs and thermotropic LCPs, both exhibiting liquid crystal properties. Lyotropic LCPs manifest liquid crystallinity when a polymer is dissolved in a solvent, whereas thermotropic LCPs do so upon heating above their glass or melting transition temperatures. The presence of hydrophilic side chain ends in LCPs leads to the formation of micelles through hydrophobic interactions when dissolved in water. Upon exceeding critical volume fractions, these micelles arrange into a liquid crystal structure, which varies with concentration changes above this threshold. Consequently, LCPs can respond to body signals such as temperature, electrical signals, chemical composition, and pressure, making them effective in wearable sensors [1].

2.2. Composite Conductive Polymer Gels

Composite conductive polymer gels, commonly utilized in wearable sensors, are networks of long macromolecular chains cross-linked to swell with a solvent. These gels, characterized by their strong, irreversible cross-links, exhibit a unique non-viscoelastic state and are insoluble in solvents, yet capable of absorbing significant amounts of solvent. In 1978, T. Tanaka discovered that these polymer gels could undergo discontinuous volume changes in response to external stimuli such as temperature, contracting within the temperature range of the soluble sol and swelling within the range of the insoluble gel [2]. Additionally, factors like pH and solvent composition can also trigger these changes, making stimuli-responsive gels widely applicable in sensing technologies. They can mimic autonomous biological oscillations, including heartbeats, brain waves, and cell cycles, serving as matrices when mixed with other conductive polymers. Composite conductive polymer gels are typically formed through self-assembly or by adding crosslinking agents to a mixture of conductive and hydrophilic polymers/monomers, with their conductivity often enhanced by increasing the concentration of conductive polymers.

Except for the above two typical types of polymers, there is a huge variety of other polymers that are used throughout the sensing industry including intrinsically conducting polymer, electrically conducting macromolecules consist double bonds and aromatic groups, and polymer composites, a combination of polymer and filler.

3. Application of Plastic Electronics in Wearable Health Monitoring Devices

Wearable sensors are crucial in regulating human health and monitoring vital signs such as temperature, heartbeat, breathing frequency, sweat, and other bodily signals. These devices are instrumental in advancing real-time health monitoring. Conductive polymers, known for their ease of production, high stability, excellent processability, and flexible electrical properties, have emerged as a favored option for wearable technology. In subsequent sections, the authors will present examples to delve into the benefits and future prospects of conductive polymers in the health monitoring sector.

3.1. Body Signals

Wearable temperature sensors are crucial in digital health, serving as effective indicators of metabolic or pathological states given that normal body temperature hovers around 37°C. Deviations beyond 42°C or below 33°C could potentially be fatal, underscoring the importance of developing advanced wearable temperature sensors. These sensors are designed for continuous, real-time monitoring of body temperature, alerting users to any abnormal changes, thereby facilitating personalized healthcare. Geng leveraged the electrical properties of conductive polymer composites (CPCs) to develop a body temperature sensor (BTS) [3]. The resistance of CPCs, which varies with temperature changes due to volume alterations, controls the electrical signal changes. This feature of CPCs offers high sensitivity, simplifying the readout circuit and minimizing the need for

amplification circuits. Similar to temperature sensors, other types of body signal sensors exhibit comparable characteristics, highlighting the versatility and potential of conductive polymers in health monitoring applications.

3.2. Body Signals

Analyzing body fluid composition offers a valuable direction for sensing, as metabolites diffusing in human sweat can reveal insights into the body's state. Essential ions like Na^+ , Cl^- , K^+ , and NH_4^+ , secreted by the endocrine glands in human perspiration, are critical for monitoring health. In Yoon's work, a textile basis with Bluetooth technology was integrated with an indication and a reference electrode to create a wearable sweat-sensing device [4]. The conductive polymer PEDOT: PSS was electrochemically deposited onto carbon nanotubes (CNTs), and ion-selective membranes (ISMs) specific to potassium (K^+) and sodium (Na^+) were placed on top of carbon fiber thread (CFT) electrodes. A CFT electrode was coated with Ag/AgCl ink and polyvinyl butyral (PVB) to create the reference electrode. With the help of these creative sensing threads, a flexible printed circuit board (PCB) and smart headband were able to wirelessly collect and transfer data, allowing for the real-time monitoring of ion composition while engaging in physical activity.

3.3. Special Detection Means (Optical Sensor)

Organic light-emitting diodes (OLEDs) represent a distinct category of conductive polymer LEDs, characterized by an emissive electroluminescent layer composed of organic compounds that emit light upon electrical stimulation. This technology finds application in wearable devices, particularly through optical sensors that monitor health indicators. By analyzing the light absorbed or reflected from the skin, as detected by a photodiode during illumination, it is possible to measure heart rate and blood oxygen concentration [5]. The exceptional flexibility and potential for miniaturization of conductive polymers are underscored by such advanced applications. Ochner et al. developed the inaugural SpO₂ sensor for quantitative oxygen saturation analysis, integrating a flexible PTB7:PC71BM polymer OPD with rigid red and green polymer OLEDs. This configuration demonstrated high accuracy, with errors of only 1% and 2% for pulse rate and oxygenation level, respectively, in PPG and SpO₂ measurements conducted on the fingertip in transmission mode [6].

4. Application of Plastic Electronics in Wearable Environment Sensing Device

In addition to the detection of human biological indicators, the monitoring of some environmental indicators is also an important application field of wearable sensors. Wearable sensors hold substantial value in both scientific research and daily life. The presence of heavy metals, toxic gases, and volatile compounds poses significant risks to human health and well-being, underscoring the critical importance of real-time environmental monitoring. Conductive polymers, with their special qualities including low cost, excellent electrical conductivity, and chemical and thermal resilience, are becoming more and more common.

4.1. Gas Sensor

The escalation of human activities has markedly increased the emission rates of harmful gases such as NH_3 and CH_4 , which not only irritate the respiratory system but can also be life-threatening at high concentrations. Additionally, the release of greenhouse gases contributing to global warming continues to grow due to industrial and daily human needs. This scenario underscores the growing importance of research into wearable gas sensors for public and occupational health protection. For example, Serafina and her team have developed a novel two-terminal gas sensor specifically for ammonia (NH_3) detection, utilizing a hydrogel interface for its detection mechanism via electrochemical gating, based on the potentiometric pH transducer IrO_x [7]. IrO_x particles, embedded in a thin organic semiconductor film, respond to pH changes within the hydrogel, altering the semiconductor's doping state and, consequently, the sensor's sensitivity to NH_3 .

Moreover, there has been a lot of scientific interest in the development of sensors for different gases. In order to create a flexible, fiber-shaped hydrogen gas sensor, Zhu and his colleagues used conductive polymer gel fiber and an electrochemically generated palladium detecting layer on a PEDOT: PSS fiber electrode [8]. This PEDOT: PSS/Pd fiber has remarkable H₂ sensing capabilities at room temperature and is ideal for a variety of applications due to its flexibility, light weight, knittability, and high mechanical strength.

4.2. Humidity Sensor

Another crucial environmental indicator that affects climate, agriculture, and forestry is humidity. A humidity sensor based on conductive polymers was created by Mahlkecht and his group. Solid-state synthesis was used to create PANI/SLS-X nanorods [9]. The paper-based humidity sensor, coated with PANI/SLS (polyaniline/sodium lauryl sulfate), demonstrated outstanding response capabilities coupled with rapid response and recovery characteristics. The presence of SLS facilitated the PANI nanorods, enhancing their electrical conductivity and augmenting their surface area. As a result, the nanorods interacted efficiently with water molecules, leading to a substantial increase in sensor sensitivity. PANI is a conductive polymer that possesses the qualities of an affordable monomer, simplicity in synthesis, high yield, and stability in the environment. PANI's drawbacks of low mechanical strength and solubility can be addressed by combining them with other ingredients.

5. Integration of Conductive Material with Wearable Devices

Compared with traditional rigid sensors, the flexibility and stretchability of organic electronics, exemplified in this paper by plastic electronics, reveals the significant potential of conducting polymers as a foundation for wearable sensing devices. This section introduces the typical integration method of conductive polymers in practical applications.

5.1. In Textile Structure

It is possible to create conductive fibers using conductive polymers and methods like melt and wet spinning. Unfortunately, these polymers usually have poor mechanical qualities since they are soluble and do not melt, which limits their processability. Thus, to overcome the expected deficiencies in mechanical and physical properties, it is required to include intrinsically conductive polymers with widely used polymers [10]. Direct integration of conductive polymer fibers into knitting, sewing, embroidery, and weaving techniques provides e-textile manufacturers with feasible production routes. Other techniques for producing e-textiles include coating, printing, or depositing electroconductive solutions onto the surfaces of knitted, woven, and nonwoven fabrics.

5.2. Tattoo-based sensor

A new development in wearable technology is tattoo-based sensors, which create gadgets that are practically undetectable on the skin but nonetheless functioning. A basic hydrogel transfer printing method was used in a work by Zhang et al. to create a tattoo-based sensor [11]. Specifically, tattoo paper is used in this study to facilitate the customisation of PEDOT: PSS on a stiff substrate prior to its transfer to a soft substrate. Strong adherence between hydrogel carrier (PVA) and PEDOT: PSS allows the polymer to lift off of the glass in a hydrogel-like way before being transferred to the tattoo paper.

The challenge can be resolved for certain basic sensors, including skin-attachable temperature sensors, by printing PEDOT/graphene ink using an inkjet onto commercial skin-formable bandage plaster. When using inkjet printing, it is compatible with inductive ink thanks to the commercial PEDOT: PSS, which is water-soluble.

6. Challenges and Future Expectations

The rapid advancement of wearable sensing devices has significantly enhanced convenience in daily life and industrial applications, yet it also presents several challenges. As living standards rise, there is an increasing demand for aesthetically pleasing wearable devices. Consumers prefer devices that are simple, portable, aesthetically appealing, or even invisible, over bulky and conspicuous ones. However, most current wearable sensors prioritize functionality over design, often resulting in increased size as more features are added. Balancing the miniaturization of the sensing unit while maintaining its high performance is a critical area for further research. Moreover, while conductive polymers offer numerous benefits, traditional conductive polymers are non-degradable, raising concerns about their sustainability [12]. These materials typically exhibit shorter lifespans, and their frequent replacement can lead to environmental pollution. Long-term strategies should focus on minimizing the loss of conductive polymers and developing wearable devices with greater commercial viability and environmental sustainability.

7. Conclusion

This paper is a review of the application of plastic electronics in wearable devices, mainly focusing on health monitoring sensors and environmental detecting sensors. Plastic electronics, also known as conductive polymers, are selected since they have tunable electrical properties and environmental stability, also easy to manufacture. Because of these advantages, several kinds of different polymers, such as liquid crystalline polymers and polymer gels, have been used to create wearable devices that are able to detect many aspects of humans. The polymer can be used in various wearable sensing devices such as body temperature, body fluid, and heartbeat sensors applied in the human health monitoring industry and gas and humidity sensors designed for environment sensing. This paper also focuses on several integration probabilities of conductive polymers with our daily objects such as clothes or our skin. Even conductive polymer-based wearable devices still have many problems with environmental and aesthetical aspects that should be overcome in the future, the author believes that this type of device will change the future of wearable sensors.

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