The Intersection of Plastic Electronics and Medical Innovation

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Abstract. The aging global population has catalyzed a paradigm shift in healthcare, emphasizing disease prevention over treatment and underscoring the need for large-scale, long-term monitoring of physiological parameters. Wearable health monitoring devices have emerged as a pivotal solution, offering real-time physiological data collection across prevention, treatment, and rehabilitation phases, thus revolutionizing traditional health monitoring approaches. This paper explores the integration of advanced materials—conductive polymers, flexible carbon nanomaterial electrodes, and metal foil substrates—into wearable health technologies. These materials enhance device flexibility, biocompatibility, and non-intrusive monitoring capabilities, providing medical-grade data crucial for early diagnosis and treatment guidance. With the wearable device market projected to expand significantly, fueled by the Internet of Things (IoT) and device miniaturization, this study delves into the technological advancements in detection technologies for electrophysiological, physical, biochemical, and photoelectric signals. It also examines the challenges and future directions in wearable health devices, focusing on material innovation, device miniaturization, and the integration of plastic electronics to improve wearability, sustainability, and interactivity. Through systematic analysis, this paper aims to highlight the transformative impact of wearable health technologies on enhancing patient care, facilitating early disease detection, and offering personalized health management solutions.

Keywords: Flexible electronics; wearable devices; Healthcare application.

1. Introduction

The current situation of the population aging society has led to a shift in people's demands for elderly disease prevention and treatment, transitioning from "treating diseases once they occur" to "preventing diseases before they manifest". To meet this requirement, the initial challenge lies in addressing the issue of large-scale and long-term monitoring of human physiological parameters. To meet this requirement, the initial challenge lies in addressing the issue of large-scale and long-term monitoring of human physiological parameters. The wearable health monitoring equipment excels in real-time physiological monitoring and other fields, enabling it to offer integrated services for real-time diagnosis, monitoring, and intervention. These services span from the prevention period through the entire treatment and rehabilitation periods, providing the wearer with convenient and practical mobile health benefits. This technology has a transformative impact on traditional wearable health devices.

The emerging technology of wearable health devices offers the advantage of non-interference with normal human activities during usage. The device not only excels in sports activities and fitness but also enhances individuals' ability to monitor their health status and engage in self-health tracking due to its exceptional flexibility and biocompatibility. It provides clinicians with a wealth of medical-grade data for early diagnosis facilitation and treatment guidance. The current state of wearable health devices has witnessed significant advancements in various human health information, especially in detection technologies, encompassing electrophysiological signals, physical signals, biochemical signals, photoelectric signals, and diverse biomedical applications [1-3]. According to research, the wearable device market is currently worth about $61.30 billion in global revenue in 2022. The increasing popularity of the Internet of Things (IoT) and connected devices, along with the miniaturization of wearable health devices, will drive a rapid development stage in the future for wearable devices aimed at tracking and detecting vital signs.

2. Plastic Electronics for Wearable Health Devices

2.1. Development of Wearable Health Devices

In the 1960s, the Apollo program conducted research on utilizing Holter for continuous health monitoring of astronauts, and Dr. Gilson authored the initial clinical report on Holter. Subsequently, this technology was gradually integrated into clinical practice, and further research was conducted on portable physiological parameter monitoring devices, including blood oxygen saturation, blood pressure, respiration, body movement, and other physiological parameters. The first commercialized glucose analyzer, which utilized Leland C. Clark's electrochemical biosensor, was introduced in 1975 [4]. In 2017, Apple Watch introduced the KardiaBand, an ECG band equipped with an intelligent ECG system that demonstrates a predictive accuracy of 90-94% for hyperkalemia and has received FDA approval. The emergence of integrated wearable health devices has been facilitated by the gradual miniaturization of electronic products, as well as the continuous advancements in micro and nanoelectronics and materials science. Wearable health devices consist of electronic devices that gather, analyze, and transmit data. The traditional hard semiconductor processes, such as printed circuit boards (PCB), are unsuitable for the manufacturing of wearable health devices due to their rigidity and bulkiness, which make them difficult to adhere to the human body surface. Additionally, the data obtained from these processes may not meet the required level of accuracy. Therefore, in recent years, with the continuous innovation of electronic devices in materials, manufacturing technology, processing circuits and sensors, wearable health devices developed using the characteristics of plastic electronic materials have exhibited easy operation, wearability, mobility, sustainability, interactivity and other desirable features. This has provided convenient conditions for subsequent medical research and treatment programs.

2.2. Materials and Properties of Plastic Electronic Products

The plastic electronics utilized in wearable devices frequently encompass flexible components, sensors, energy storage, and other functionalities. The future wearable devices must transcend the confines of traditional rigid semiconductor technology and hard circuit processes, in order to embody the characteristics of being lightweight, flexible, cost-effective, and long-lasting. The aforementioned devices will come into direct contact with the skin, exhibiting excellent flexibility, stretchability, and bendability while maintaining superior sensing performance even when subjected to deformation.

The flexible components of wearable health devices encompass flexible circuit boards, adaptable screens, and other related elements. Recent advancements have incorporated small molecules or organic polymer materials that exhibit excellent biocompatibility. For example, polyethylene naphthalate, polyethylene terephthalate, Ecoflex and polydimethylsiloxane (PDMS), silicon-based materials and polymers thin film [5-6]. The aforementioned materials exhibit exceptional flexibility and stretchability, in addition to their remarkable chemical stability, rendering them ideal substrates for wearable health devices. The elongation limits of Ecoflex and PDMS are 900% and 400% respectively, with the Young's modulus of Ecoflex closely resembling that of human skin [6]. The flexible electronic devices, in comparison to conventional counterparts, not only exhibit cost-effectiveness but also demonstrate low power consumption that enables uninterrupted data acquisition over extended durations.

The rise of the IoT and Artificial Intelligence (AI) has led to increased demands for the performance of sensors in wearable health devices, including high sensitivity, wearability, intelligence, visualization, and multimodal operation. The smart sensors based on plastic electronics technology are classified into three categories according to the material structure: organic small molecules, organic polymers, and conductive polymers. For example, poly (3-hexylthiophene) (P3HT) and pyrrole pyrrodione (DPP) polymer systems, polypyrrole (PPy) and so on. The unique structural characteristics of these materials confer on them with flexibility, a high specific surface area, and an abundance of contact sites, thereby enabling them to exhibit exceptionally high sensitivity even to minuscule pressures. The demonstrated potential for monitoring biological signals in wearable health devices is excellent.

The prerequisites for wearable health devices to achieve optimal performance are energy storage and uninterrupted power supply. The majority of wearable health devices are currently powered by lithium batteries. However, the exploration of harnessing solar energy, mechanical energy, and thermal energy from the environment is an essential area of research. This field will undoubtedly emerge as a crucial avenue for sustaining power supply to wearable medical devices in the future. The Swiss Center for Electronics and Microtechnology (CSEM) Brazil recently announced a significant breakthrough in the research of "plastic" solar cells, marking the transition of organic polymer-based solar cell manufacturing technology from the experimental to commercial development stage. It is anticipated that plastic solar cells will soon find applications in wearable health devices.

2.3. Application of Plastic Electronics in Wearable Health Devices

The primary advantage of plastic electronics in wearable medical devices lies in their capacity to adapt to deformation. The characteristics of flexible electronic components allow it to be easily manufacturable, cost-effective, and resistant to bending. Therefore, an increasing number of plastic electronic technologies with intricate structures and functionalities based on diverse mechanisms are being applied to wearable health devices [7-8]. For instance, the rigid circuit board substrate can be substituted with a flexible substrate, and the fragile LCD display can be replaced with a stretchable composite material possessing some degree of flexibility. This can reduce the risk of damage by finely adjusting the arrangement of electronic components while integrating monitoring sensors on the surface of the skin-to-skin substrate film to minimize solid parts. On one hand, this is to enhance the comfort of the human body. On the other hand, incorporating materials with a certain level of flexibility can significantly enhance the durability of wearable health devices, thereby greatly reducing their susceptibility to pressure or impact-induced cracking damage. The advancements in flexible batteries, catalog and storage systems, and photovoltaics have also significantly influenced the field of health science. As a result, there is a proliferation of wearable health devices that are being developed to enhance the collection of health data and improve disease detection capabilities.

3. Technologies advancements in Flexible Devices

The advancement of plastic electronics technology has led to the gradual integration of wearable medical devices with plastic electronic components, including flexible substrates, displays, transistors, and integrated circuits. These components are utilized for processing sensor-acquired data and transmitting it wirelessly to communication systems.

Bao's group has successfully developed a highly luminous and flexible color display. By incorporating SuperYellow (SY), a yellow light-emitting polymer, with polyurethane (PU), SY forms intricate nanostructures that interconnect like a fishnet, resulting in enhanced softness, flexibility, and superior light emission capabilities (Figure 1) [9-12]. The light-emitting polymer is incorporated as a light-emitting layer in the middle of the display structure. When an electric current flows through the display, charges interact and transition to an excited energy state, resulting in photon emission that ultimately converges into luminous output. The red, green, and blue stretchable polymer LEDs have been successfully fabricated with exceptional brightness (7450 cd/m2), high current efficiency (5.3 cd/A), and remarkable stretchability (approximately 100%). An all-polymer light-emitting diode is affixed onto the skin using a wireless energy harvesting system and powered by radio waves for real-time pulse signal visualization.

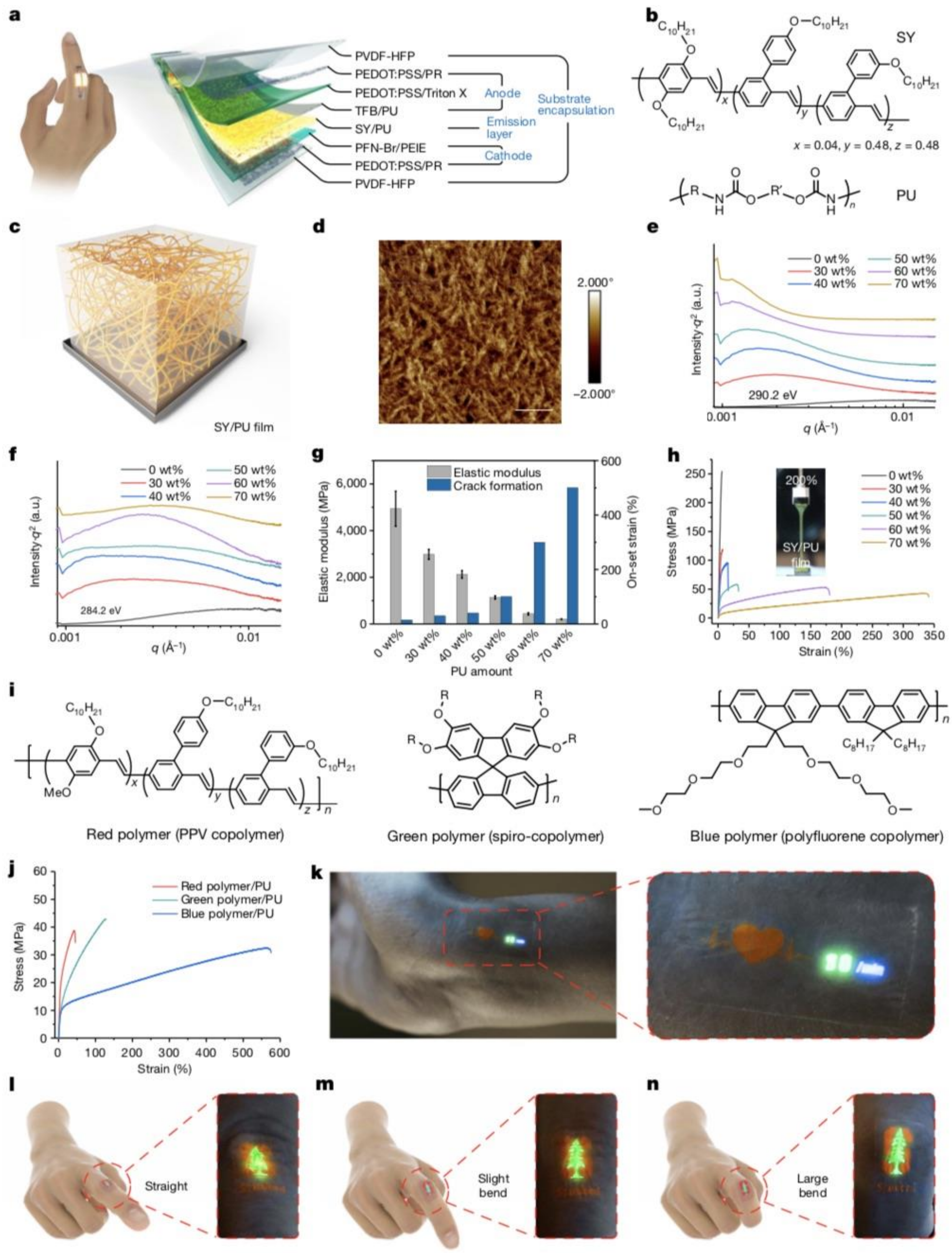

Fig. 1 Spontaneously formed nanofibre light-emitting structures of various colors for enhanced stretchability of light-emitting conjugated polymer films [9].

Johanneum Research has developed an ultra-thin sensor capable of measuring various vital signs and harvesting energy [13, 14]. The sensor utilizes a material known as Poly VDF-TrFE (vinylidene difluoroethylene trifluoride) as an ultra-thin film for electronic modules. This material is deposited between two ultra-thin electrode surfaces on a micrometer-thick carrier film composed of propylene. Due to its permanent electrical polarization, it exhibits exceptional sensitivity to mechanical motion, thereby demonstrating a robust piezoelectric effect. It can detect changes in the propagation rate of human pulse waves while simultaneously generating electrical energy from biomechanical movements.

4. Human Machine Interface

4.1. Enhanced Patient Care and Health Monitoring

Human health can be characterized by a range of physiological parameters, and when evaluating and diagnosing diseases, it is crucial to consider their respective roles and interactions. Wearable health devices have the ability to detect these biological signals, providing valuable references for early disease prediction and diagnosis.

A conceptual futuristic wearable health device, known as a "smart bandage"[15], integrates various sensors, circuits, and wireless systems on an ultra-thin and flexible substrate that can be applied to the skin inconspicuously. These medical sensors enable real-time monitoring and recording of data on memory devices. The device's display provides timely alerts to users to monitor their physical condition and track health trends by comparing the recorded results. Additionally, when health conditions deteriorate, the device can also notify the wearer regarding the necessity of administering injections to alleviate symptoms through the drug delivery system. In this device, the human-machine interface is facilitated as health conditions are monitored and stimulated by alarms or drug injections, resembling communication between the wearer and the device. Furthermore, the wireless system enables diagnostic results to be transmitted to doctors via mobile phones, allowing them to review data for medical assessment purposes. It also facilitates wireless drug administration or appointment scheduling with patients, thereby saving time for both doctors and patients while reducing medical costs and enhancing quality of life in terms of healthcare expenses.

4.2. Integration with Digital Health Platforms

The advantages of wearable health devices applied to the medical industry are evident. As long as our bodies remain functional, wearable devices can continuously record data through built-in sensors and perform transformative analysis. While we may be familiar with current wearable health devices such as smartwatches and smart bracelets, the future direction of wearable technology will inevitably involve seamless integration with the human body, rendering them undetectable. Examples include artificial skin, intelligent drug delivery equipment, and exoskeleton machine devices. Simultaneously, advancements in sensor technology and IoT, cloud storage, and big data analysis will continue to drive breakthroughs in wearable health devices, making them an optimal gateway for mobile healthcare. In the future, these devices will consistently monitor physiological indicators within the human body. The recorded data will then be analyzed and fed back through supporting infrastructures like the internet, cloud computing systems, and mobile health platforms to provide individuals with targeted health suggestions that aid in disease prevention or recommend appropriate medical resources for those requiring medical attention.

The data processing between wearable health devices and digital health platforms generally relies on three layers: the perception layer, the transport layer, and the cloud layer. The perception layer encompasses various wearable health devices such as smartphones and wearable electrocardiograms for efficient data collection. The transport layer comprises computers, server gateways, and transport networks responsible for collecting, processing, storing, and transmitting data from these wearable health devices. Lastly, the cloud layer serves as a remote storage facility for high-performance computing tasks. The functions of the perception layer and the transport layer can be integrated in certain wearable health devices. Although there is a continuous need for improvement in data accuracy and convenience in these interactive human-computer wearable health monitoring systems, with ongoing technological innovation, a truly practical wearable health system will be realized in the future.

5. Challenges and Future Perspectives

5.1. Challenges and Limitations

The rapid advancement of plastic electronics has significantly stimulated the progress of wearable health devices. To meet the demands of the market, extensive advancements must be made through interdisciplinary collaboration in fields such as materials science, electronics, biology, and sensing signal acquisition and processing. While there is a certain amount of research being conducted on electronic components, sensors, energy storage, etc., wearable health devices need to continuously enhance their materials, devices, and data transmission capabilities to cater to the growing needs of wearers.

First, the inadequate materials and design. The proven factors of plastic electronics technology for wearable health devices, such as flexibility, stretchability, low cost, and lightweight, have established its potential. However, the development of breathable, flexible, and stretchable materials remains a significant challenge in meeting the stringent requirements of wearable applications like e-skins, smart patches, or textiles. The future focus should be on developing new materials that are breathable, flexible, and stretchable to ensure wearer comfort (such as adaptive e-skin, smart patches, or textiles). Additionally, addressing issues like biocompatibility and biodegradability is crucial along with considering the size, cost, and complexity of these devices.

Second, the deficiencies in electronic components. Apart from the integration of materials and electronics, wearable health devices also exhibit fundamental disparities in their sensing systems. The demand for highly responsive sensing materials has stimulated significant interest in the development of diverse sensing approaches while achieving sustainable and cost-effective mass production of wearable sensors necessitates instantaneous and recyclable substrate materials. With the increasing complexity and miniaturization of sensors, self-powered wearables have emerged, encompassing "green" power units (such as disposable solar cells or biofuel cells) or unpowered alternatives through near-field communication [16]. These advancements hold potential for the creation of autonomous, fully integrated wearable sensors or biosensing units that can be used alongside other ubiquitous personal devices. Furthermore, there remain numerous challenges pertaining to the accuracy, safety, reliability, and applicability of wearable health devices that require further optimization and enhancement by researchers.

Third, the deficiencies in data collection. The current challenges that are encountering include the accuracy of data acquisition methods for wearable health devices, as well as the processing and selection of the vast amount of collected data. Furthermore, with the gradual growth of the wearable health device market, integrating cloud computing, 5G Internet, Internet of Things (IoT), big data, and other technologies to seamlessly connect dynamic health management and telemedicine through collaboration with medical institutions and teams in a cloud service model poses our next challenge.

5.2. Fugure Trend

The integration of novel technologies in wearable health devices, particularly plastic electronic technology, is already a prevailing trend. It can be anticipated that an abundance of flexible smart devices will emerge shortly, leading to innovation and exerting an impact on existing wearable device products. The forthcoming technology employed in wearable health devices is expected to be lightweight, based on flexible substrates, intelligent through various composite sensors, energy-efficient to overcome prolonged usage requirements, and even transformed from a substantial entity into a delicate patch for wearing. Future wearable health devices will undoubtedly enable the augmentation of senses, body extension, and even mind expansion through technological advancements. Consequently, users will no longer be confined by human senses and physical limitations but rather experience genuine liberation.

6. Conclusion

Plastic electronic technology represents a revolutionary advancement in the field of electronics, owing to its exceptional attributes of being lightweight, thin, soft, and small. These characteristics render it highly suitable for utilization in wearable health devices. This article aims to present and discuss the various types and properties of plastics employed in electronic products, highlight the latest advancements made in wearable health devices, as well as explore human-machine interface interactions. With continuous enhancements in substrate materials, flexible sensors, energy storage devices, and other related technologies; wearable health devices hold great promise for personalized health management, early detection of chronic diseases, disease diagnosis and treatment facilitation, as well as rehabilitation tracking and monitoring.

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