Advanced Plastic Electronics in Smart Wearable Devices

Jiaqi Zhang *

Faculty of Material Science and Engineering, Northwestern Polytechnical University, Xi'an, 710072, China

* Corresponding Author Email: 15114587602@mail.nwpu.edu.cn

Abstract. The swift advancement of Internet technology has catalyzed the proliferation of wearable intelligent devices. These devices seamlessly integrate technology into everyday life, facilitating instantaneous health surveillance. These devices, leveraging plastic electronics, offer unprecedented flexibility and user interface accessibility, marking a significant shift from traditional mobile technologies. This paper explores the advancements in wearable electronics, focusing on plastic substrates' role in enhancing device functionality and user comfort. It highlights key materials like spray-on metallic plastic and polyethylene terephthalate (PET), which contribute to the development of lightweight, flexible electronic components for health monitoring applications. Technological progress in smart wearables, including dual strain-temperature sensors and self-compensating temperature sensors, demonstrates their potential in the health and rehabilitation sectors. The paper examines wearable applications in continuous body temperature monitoring, crucial for early disease detection and managing cardiovascular health. It concludes by addressing the challenges in wearable technology, emphasizing the integration of devices into daily life and the exploration of new applications to improve health and convenience.

Keywords: Health monitoring; early disease detection; temperature monitoring.

1. Introduction

The advent of the Internet of Everything, propelled by the rapid development of the Internet and the launch of 5G networks, necessitates that electronic devices transmit information swiftly and reliably, ensuring efficient connectivity and interoperability [1]. This has led to a surge in interest and development of wearable smart devices, which are designed to meet the specific needs of users and are distinct from traditional mobile devices in both appearance and functionality. For optimal utility, these devices must be worn on the body, often requiring a constantly available user interface for real-time monitoring and smart functionalities.

Smart wearable electronic devices are tailored to meet the unique needs of specific user groups, distinguishing themselves from traditional mobile devices through their design to be worn on the body, thereby ensuring functionality. These devices often feature a user interface that must remain accessible, enhancing visibility for monitoring systems with advanced functionalities [2]. Their applications span enhancing human comfort, convenience, and safety, notably in health monitoring—ranging from early disease detection to real-time monitoring of treatment effectiveness and overall health. The escalating adoption of wearable devices can be ascribed to their harmonious interfacing with human physiology, which empowers the real-time tracking of diverse health metrics encompassing blood pressure, heartbeat, and physical activity [3].

The aim of this research paper is to concentrate on the evolution and utilization of wearable electronic devices for monitoring human health and the enhancement of life quality for individuals with disabilities, which can be realized through the fabrication of appropriate flexible plastic substrates [4]. It improves processing and encapsulation with an emphasis on flexible electronic systems on plastic substrates and creates alternative electronic devices that mimic human organs [5]. It also optimises the overall design, battery life, and other issues. This paper provides valuable insights into the aspect of wearable plastic electronics.

2. Plastic Electronics in the Evolution of Wearable Technology

2.1. Materials and Mechanisms of Plastic Electronics

2.1.1 Spray-On Metallic Plastic

The plastic material, which can be sprayed on and has a 'metallic' appearance, is a novel innovation with potential applications in wearable electronics. Its versatility makes it a valuable material, as it can be used in various scenarios due to its robust electrical conductivity and flexibility. Its versatility makes it a valuable material, as it can be used in various scenarios due to its robust electrical conductivity and flexibility. Although specific applications are not yet well-documented, this material shows promise for future developments. This ability to spray metallic plastic onto surfaces opens up possibilities for creating wearable devices with improved conductivity and adaptability. The researchers are exploring the use of spray-on 'metallic' plastic to enhance the electrical conductivity of wearable electronics, making them more reliable and efficient. The material's spray application also allows for easier integration into different wearable forms, ensuring it can conform to various shapes and sizes [6].

2.1.2 Polyethylene Terephthalate (PET)

PET is a versatile material that plays a pivotal role in wearable electronics. It functions as a flexible substrate, enabling the development of lightweight and flexible electronic components, and contributing to the design and comfort of wearable devices [7]. PET also functions as an exceedingly flexible transparent electrode in organic electronic apparatuses, rendering it particularly apt for applications necessitating transparent and pliable elements, such as wearable visual interfaces. PET is a versatile material that can be used as a flexible substrate in electronic devices. It has excellent dielectric, structural, and mechanical properties, which can be further enhanced when combined with materials like graphene to improve electrical conductivity. PET is also a stable and reliable foundation for bioelectronic devices, making it ideal for applications such as controlled drug delivery. Its utility in bioelectronic technologies is expanding [8].

2.2. Evolution of Smart Wearable Devices

Contemporary scholarly investigations have centered on the progression of intelligent wearable apparatuses. Beyond the contributions of Matuska et al., enhancements in these smart wearable devices encompass the incorporation of biometric detectors for a multitude of applications. These sensors measure healthy characteristics such as pulse, blood pressure, and physical temperature [9]. They play a crucial role in health monitoring, allowing users to track their fitness levels, detect abnormalities, and manage chronic conditions. For example, wearable electrocardiogram (ECG) monitors provide continuous heart rate monitoring and can detect irregular heart rhythms, potentially preventing cardiac events [10]. Further, research trajectories focus on the engineering work involved in designing and developing wearable sensors and systems. Improving battery life and data accuracy in smart wearables. Longer battery life ensures uninterrupted use, especially in medical monitoring scenarios where continuous data collection is essential. In addition, improved data accuracy ensures that the information collected is reliable and actionable. Advanced signal processing algorithms and sensor fusion techniques help to minimise noise and improve the accuracy of measurements [11].

Smart wearables are increasingly being used for medical applications beyond fitness tracking. For example, wearable devices equipped with accelerometers and gyroscopes can detect falls in the elderly population and trigger automatic alerts for assistance [12]. Similarly, wearable glucose monitors provide non-invasive blood glucose monitoring for people with diabetes, reducing the need for frequent finger-stick tests and providing real-time data for better management. From early forms such as smartwatches to cutting-edge developments in flexible electrodes, wearable technologies continue to evolve, promising a future with innovative applications [13].

In the field of electronic materials, researchers have consistently pursued innovative substrates. For example, Tobjörk et al. (2011) delved into the realm of paper electronics, exploring the integration of plastic-coated paper substrates in electronic applications. Their study highlights the use of laminated plastic films to encapsulate electronic components, creating a hybrid platform that combines the tactile familiarity of paper with the operational capabilities of electronics [14].

Similarly, an article entitled 'Unveiling the Paradigm Shift in Organic Electronics' delves deep into the field of organic electronics, often associated with plastic electronics. It describes the use of organic semiconductor materials in various electronic applications, shedding light on the dynamic development of this field and its future implications.

3. Technological Advancements in Intelligent Wearable Technology

Simultaneous monitoring of motion and body and environmental temperatures in real-time during rehabilitative training can aid in safeguarding patients from secondary injuries and excessive exertion. Consequently, there is a pronounced emphasis on the fabrication of flexible dual-mode sensors capable of detecting both strain and temperature for applications in healthcare, rehabilitative training, human-computer interaction, soft robotics, and related domains [15]. The dual-mode sensor comprises a pair of electrodes and a tubular mechanical heterostructure. Its operational schematic and the real-time human physiological parameters it monitor are depicted in Figure 1. The sensor can concurrently detect strain and temperature without any cross-interference. The sensor's architecture includes a thermocouple encircling a flexible strain-magnetic induction transducer, which demonstrates a substantial magnetoelastic effect [16]. It also incorporates an amalgamated crystal filament. The thermoelement quantifies the heat, while its filament configuration measures the impedance change induced by the load imposed. The double-mode sensing element also provides interference-free thermal sensing performance.

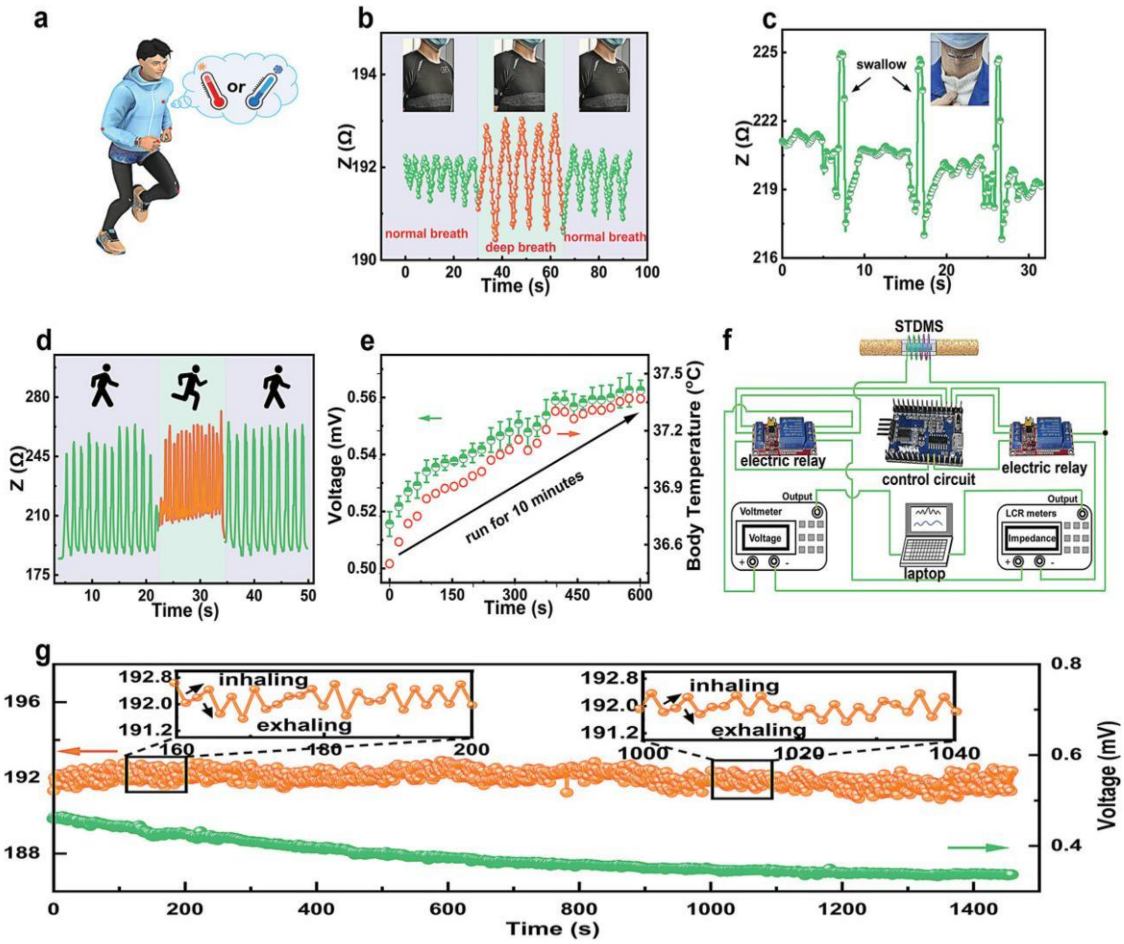

Fig. 1 In-site measurement of environmental temperature and body characteristics using device [16]

This sensor has a dual mode and is characterized by its elasticity. It incorporates a mechanical heterogeneity structure in the form of a tube and a dual-mode sensor with a hybrid recognition system. The sensor is designed to measure strain and temperature stimuli in real time without any interference. The detection component of the sensor consists of a triple part: a module that transforms the elongation into magnetic flux and exhibits a significant magnetoelastic effect, a substrate made of amorphous cobalt known for its high magnetic transmittance, and a thermoelement wrapped around the sensing structure to access the sensor. This design ensures accurate and efficient monitoring [17].

4. Application Areas of Plastic Electronics in Wearables

The persistent monitoring of body temperature is vital for health surveillance. The early symptoms of diseases such as influenza virus are an increase in body temperature, and fever is an important symptom of the immune response to the invasion of the disease. Early detection of a rise in body temperature can help identify the disease and be the first element in stopping the spread of the virus. This effectively prevents the spread of the virus between people.

Moreover, the measurement of temperature can aid in the monitoring of intricate cardiovascular diseases. At present, existing commercially available thermometers do not possess the characteristics required for portable devices. Optimal wearable devices need to be lightweight, smooth, physiologically compatible, and, crucially, able to conform to large, non-planar skin surfaces for accurate sensing. In the last few years, there has been a significant focus on the creation of bendable and extensible temperature sensors for a broad spectrum of applications, encompassing health monitoring, robotics, and artificial electronic skin. These flexible temperature sensors hold an advantage over traditional silicon-based sensors, as they are able to adapt to bent or uneven surfaces and provide accurate and stable measurements over extended periods.

One commonly used type of temperature sensor is the resistive temperature detector (RTD) [18]. The development of RTDs on flexible substrates poses a significant challenge due to the resistance variation induced not only by temperature changes but also by the automatic distortion of the surface. This can result in significant thermal readings inaccuracies. A novel flexible temperature sensor is proposed to address this issue. This sensor can compensate for the resistance change caused by deformation, thereby enabling temperature measurement with minimal error. The sensor comprises two RTDs, which are fabricated by stencil printing in reverse order on a polydimethylsiloxane substrate. The twin RTD arrangement is designed to compensate for mechanical deformation caused by flexure and extension. When the sensor is flexed on a convex surface, the resistivity of the two changes differently due to the tension experienced by one RTD and the compression experienced by the other. This phenomenon can be visualized in Figure 2 [19]. Consequently, the sum of the resistances of the two RTDs remains constant.

Similarly, the difference in resistance between the two Resistance Transducers can be used to accommodate the straight-line change in the resistance as the probe is stretched. When the sensor is flexed, the resistance of the two RTDs changes differently, producing a constant sum of resistances. When the sensor is stretched, the resistance of the two RTDs changes linearly, resulting in almost zero resistance subtraction. For simplicity, R1 is assumed to be approximately equal to R2.

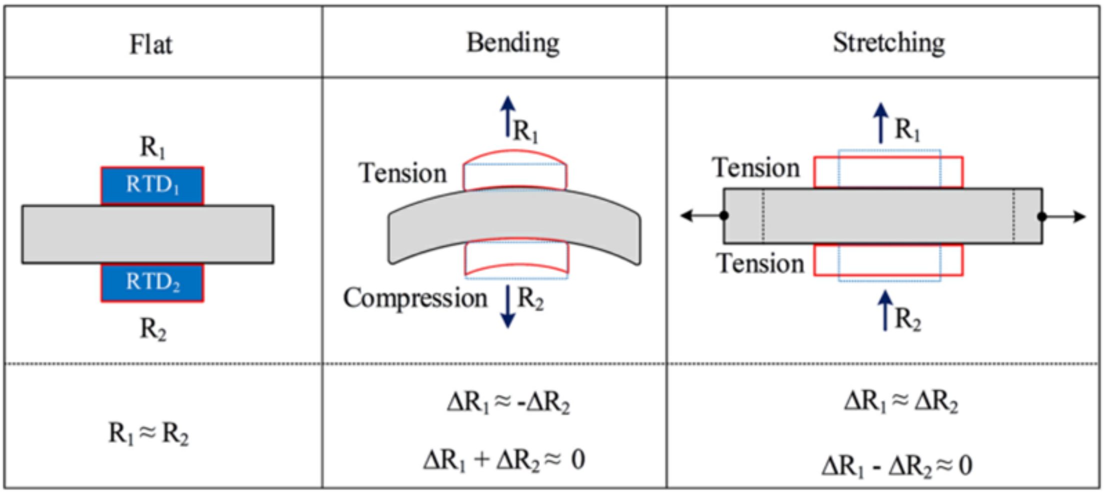

Fig. 2 A schematic representation of the compensation method [19].

Figure 3 illustrates the fabrication procedure of Resistance Temperature Detector (RTD) sensors. The front-side RTDs were imprinted using silver paste and subsequently deposited on a Polydimethylsiloxane (PDMS) substrate utilizing a stencil mask. The wires were then affixed to the substrate using an identical silver adhesive. The same type of RTD has been produced on the reverse side of the substrate.

The self-compensating flexible temperature sensors, equipped with a calibration algorithm for quantifying the change in the resistance value of the double-sided RTDs, can reduce the flexural strain change from 30% (observed in a unique RTD) to 10%. After calibration, the deflection bias is further reduced to 3.2%. As well as being effective and innovative, this method is simple to employ. It can easily be incorporated into other bending element designs to ensure accurate thermal measurements [20].

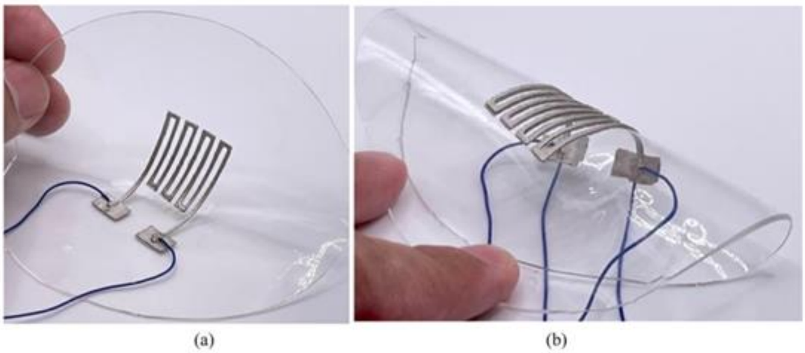

Fig. 3 Fabrication process of RTDs [20].

5. Outlook and Challenges

5.1. Challenges

Intelligent wearable devices and electronics epitomize novel convergence of technology and human elements, engendering unique complexities. These challenges require consideration of both technological and human elements. The operation of wearables is influenced not only by technological advancements but also significantly by human behaviour. To address the challenges in the field of wearables, it is necessary to take various aspects into account.

The aim is to minimize the burden on the user and integrate wearable devices with everyday items. Depictions of wearable devices frequently portray individuals adorned with sensors at all conceivable bodily locations, encompassing the arms, legs, and torso. However, this scenario is impractical and places an unrealistically high burden on the user.

The practicality, utility, and convenience provided by wearables have driven their evolution throughout history [21]. Contemporary wearable electronics grapple with the task of identifying pervasive applications, given that their prospective expansion is contingent upon the emergence of applications in health, wellness, and other personal necessities.

5.2. Emerging Trends and Future Directions

Wearable electronic apparatuses have the potential to significantly improve the lives of individuals with physical disabilities. One such device, the artificial larynx, is a conductive plastic electronic chip integrated with graphene [22].

Strategically situated on the neck, adjacent to the throat, this device provides a mechanism for individuals suffering from dysphonia to produce audible sounds. This wearable synthetic larynx possesses the ability to discern signals associated with laryngeal vocalizations. Utilizing an artificial intelligence model, it has the capacity to recognize and transmute these signals into speech, attaining a remarkable reduction accuracy that surpasses 90% [23].

The proposed design paradigm leverages the capabilities of artificial intelligence algorithms to transcribe and transfigure the signals captured by the synthetic larynx into audible speech. This process facilitates the meticulous discernment of essential phonological elements, including phonemes, intonations, and lexemes. Furthermore, it empowers the system to recognize and replicate indistinct speech patterns exhibited by laryngeal cancer patients. Consequently, this novel methodology offers a transformative solution for communication and interaction for individuals afflicted with vocal impairments.

Despite these advancements, there remains room for further optimisation and expansion of the artificial larynx. Potential improvements include enhancing the quality and volume of the voice, diversifying the range of voices and expressions, and integrating other physiological signals and environmental data to facilitate more natural and intelligent voice interaction.

6. Conclusion

In summary, the requirements for creating an optimal polymer-plastic wearable electronic strain sensor are a conductive network for signal generation and an elastic polymer for flexibility and protection of the conductive network. In addition, it is important to select appropriate packaging techniques, such as vacuum packaging, to ensure that electronic devices can be used normally under appropriate body temperature and sweat conditions.

The integration of IoT-based smart sensors has led to advancements in temperature sensing technology, particularly in health applications. Intelligent devices, such as smartwatches, utilize temperature sensors to monitor sleep quality in Ambient Assisted Living (AAL) environments. This technology enhances healthcare by providing real-time temperature-related insights. Wearable smart sensors play a crucial role in disease prevention and the early detection of high-risk disabilities. Physical sensor networks are used for health monitoring, activity recognition, and disease prediction. AI-enhanced sensors can improve the capabilities of health monitoring systems, making them more intelligent and convenient.

Technology can also provide intelligent assistance for individuals with disabilities. Wireless health monitoring systems that leverage IoT and mobile networks provide support for patients' healthcare needs anytime and anywhere. This includes monitoring and managing health conditions and providing personalized assistance to individuals with disabilities. The integration of temperature sensing, disease monitoring, and intelligent assistance for the disabled showcases the transformative impact of smart plastic wearable sensors and IoT technologies in healthcare. These innovations contribute to proactive healthcare management, early disease detection, and personalised support for individuals with disabilities, ushering in a new era of intelligent and accessible healthcare solutions.

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