WEP Warwick Evans Publishing

Transactions on Materials, Biotechnology and Life Sciences
ISSN: 2960-1932, eISSN: 2960-2319 | Volume 4
NSCBM 2024

Application of Flexible Wearable Sensors for Revolution of Personalized Medicine in the Age of Digital Health

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Abstract. With the advent of the digital health era, flexible wearable sensors show great potential in personalized medicine and health monitoring. This research discusses recent advances in polymer-based flexible sensors that enable real-time, non-invasive monitoring of vital signs and physiological parameters, which are essential for early diagnosis and timely intervention in health conditions. Researchers are developing new flexible materials to adapt to the shape and dynamics of the human body while maintaining comfort and performance. By integrating advanced nanotechnology and environmentally friendly biomimetic materials such as MXene quantum dots (MQDs) and molybdenum disulfide (MoS_2), researchers have developed sensors with high sensitivity and excellent biocompatibility. These sensors can not only provide continuous health data, but also realize remote transmission and encryption of data through wireless modules, ensuring user privacy and data security. In addition, new signal processing modules and multimodal sensors offer a wide range of application possibilities for intelligent perception, interactive devices and health motion monitoring. The research also discusses the revolutionary role of flexible wearable sensors in the future of health management, and how to process and analyze the large amounts of data generated by sensors. These studies not only promote the progress of health monitoring technology, but also provide new solutions for personalized medicine and smart medicine.

Keywords: Flexible wearable sensors; Personalized medicine; Health monitoring.

1. Introduction

With the advancement of technology, the demand for wearable electronic devices is increasing, providing people with convenient access to information exchange, health monitoring, and entertainment media. However, traditional inorganic materials often fail to meet the requirements of flexibility, lightness, and comfort for wearable electronic devices, making the development of new flexible materials an important research direction. In the era of digital health, integrating polymer-based flexible wearable sensors into health monitoring systems has become a transformative method for personalized medicine. These sensors offer real-time, non-invasive monitoring of vital signs and physiological parameters, which are crucial for the early diagnosis and timely intervention of various health conditions. The commercial implications of these developments are profound. As healthcare costs continue to rise, the ability to monitor health conditions in real-time and provide early interventions can significantly reduce the need for expensive medical procedures and hospital stays. Moreover, the data collected by these sensors can be analyzed using advanced algorithms to predict potential health issues before they become critical, offering a proactive approach to health management.

Research on flexible wearable sensors is rapidly evolving, especially in the fields of materials science, nanotechnology, and bioengineering. Researchers are uncovering how to adapt highly flexible electronic devices to the human body to achieve more accurate and personalized health monitoring. Yan et al. have highlighted advancements in developing flexible sensors capable of detecting strain, pressure, chemical composition, and gases using conductive polymers and elastomer substrates. The ability of these sensors to monitor physiological parameters in real-time heralds a new era in personalized medicine and proactive health management [1]. Visualizable flexible wearable sensors reveals sensor types that use visual cues, such as color changes or luminescence, to convey information [2]. The attributes of lightness, adaptability, and biocompatibility make these sensors suitable for a wide range of applications, from military to healthcare to sports.

Despite progress, current flexible wearable sensors still face challenges that impede their accuracy, real-time performance, and stability. These limitations hinder their widespread adoption and effectiveness in capturing and monitoring motion-related signals. To address these shortcomings, Zhang and colleagues have created a flexible sensor system designed for tracking movement. This system's efficacy was evaluated by synthesizing and examining novel functional polymer conjugated materials [3]. Their study underscores the influence of these innovative materials on enhancing flexible wearable sensors, which contributes to overcoming current limitations in athletic performance tracking and fosters their improved evolution. Li et al. have delved into the sensing mechanisms, exploring the active layer materials and microstructure designs that underpin flexible piezoresistive pressure sensors [4]. Their work discusses the emergence of new sensing mechanisms, the integration of novel functionalized nanomaterials, and cutting-edge fabrication processes that are set to redefine the landscape of flexible devices. The researchers also foresee the prospective applications of flexible piezoresistive pressure sensors, particularly highlighting their promising capabilities in health monitoring and human-machine interfaces. The exploration of the most suitable polymer materials for flexible sensor wearables, which can match the dynamism of human activities without compromising comfort or performance, is ongoing. At the same time, the combination of nanotechnology and polymer science has opened up new possibilities, enabling the creation of sensors that are not only flexible but also possess self-healing properties, stretch ability, and enhanced electrical conductivity. The convergence of these technologies promises to bridge the gap between electronic devices and the human body, creating a symbiotic relationship where each informs and enhances the other.

This research analyzes the construction principle and materials used for flexible wearable sensors. On this basis, this research further analyzed the application performance of flexible wearable sensors in personal health monitoring and remote medical practice. Polymer-based flexible wearable sensors are not just an academic pursuit but a necessary evolution to meet the demands of modern society. If it continues to explore the capabilities of these materials, it is not only redefining what is possible in the realm of wearable electronics but also taking significant strides towards a future where technology and health are inextricably linked, offering a more informed, healthy, and connected way of living.

2. Application of flexible wearable sensors

2.1. Materials

Flexible wearable sensors are usually composed of two parts, namely a flexible substrate and a signal processing module. The flexible substrate is the part that comes into contact with the skin and is usually made of a soft, flexible material. The flexible substrate can be a film, fiber, sponge or other flexible material. It allows the sensor to adapt to the shape and movement of the human body. The signal processing module is responsible for converting the signal collected by the sensor into readable data. Signal processing modules can include circuits, chips and wireless communication modules. It converts the physical quantity measured by the sensor (such as pressure, temperature and humidity) into a digital signal for further analysis or display. In order to make these sensors wearable and flexible, materials with unique mechanical, physicochemical, and biological properties of each element need to be considered [5].

2.1.1. Substrate materials

Many researchers have been exploring new materials for flexible wearable sensors. Environmentally friendly biomimetic materials are very attractive in the field of health monitoring due to their good deformability, high pressure sensitivity, and excellent biocompatibility. Sun and the team have developed a biocompatible aerogel composed of MXene quantum dots (MQDs) and watermelon peel (WMP). They achieved this by submerging freeze-dried watermelon peel in a dispersion of quantum dots (Fig. 1) [6]. The aerogel formed possesses a three-dimensional porous network, characterized by its low elastic modulus of 0.03 MPa and a minimal detection limit of 0.4 Pa. The aerogel exhibits high sensitivity under a pressure of 323 kPa^{-1}, making it an ideal choice for monitoring subtle physiological changes in the human body. In cytotoxicity tests, the aerogel showed excellent biocompatibility, reducing the safety risk when applied to human skin. Moreover, through a Bluetooth module, the sensor signal can be displayed on a mobile phone, allowing real-time monitoring of human movement (pulse, voice, and walking). More importantly, the MQD/WMP aerogel demonstrated excellent biocompatibility in cytotoxicity tests, thereby reducing the safety risks when applied to human skin. This new type of environmentally friendly sensing material, derived from sustainable natural resources, also reduces potential impacts on the human body through its biocompatibility.

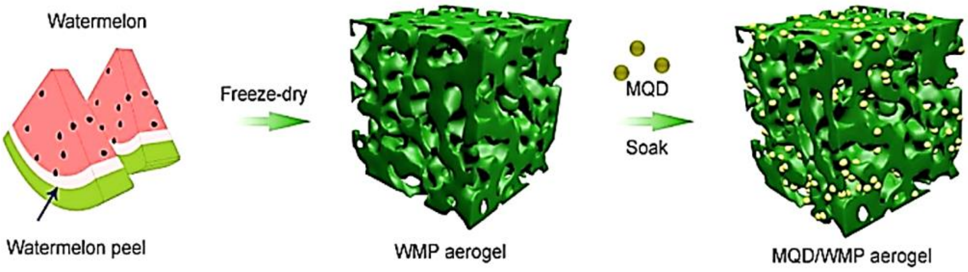

Fig. 1 The process of creating MQD/WMP aerogels [6].

Molybdenum disulfide (MoS_2), in both single and multilayer forms, stands out as a prime candidate for future flexible optoelectronic devices. This is attributed to its high intrinsic mobility, tunable energy bandgap that is comparable to silicon, and excellent mechanical flexibility [7]. Li et al. proposed a new method for directly synthesizing large area MoS_2 patterns on polymer substrates that are critical to enabling high-performance MoS_2-based flexible electronic devices [8]. Li et al. employed a method that integrates inkjet printing with thermal annealing to develop an optimal precursor ink. This ink is specifically formulated for creating various patterns on polyimide films. By introducing an argon/hydrogen (Ar/H_2) atmosphere, heat treatment at 350 °C causes the patternization precursor to decompose and crystallize in situ, resulting in the formation of MoS_2 patterns (Fig. 2). This technique allows for the direct acquisition of patterned MoS_2 on polymer substrates, bypassing intricate procedures. It showcases remarkable mechanical flexibility and endurance, with only about a 2% change in resistance after 10,000 bending cycles, and also boasts superior chemical stability. This is due to the resulting continuous and thin microstructures, as well as their strong adhesion to the substrate. In addition, they used this approach to create a variety of flexible sensing devices that are insensitive to body movement and humidity, including temperature sensors and biometric potential sensing systems for real-time, continuous monitoring of skin temperature, electrocardiogram and electromyogram signals. This research provides a new strategy for the manufacture of flexible sensing electronics, which is expected to play an important role in the field of health monitoring and wearable technology.

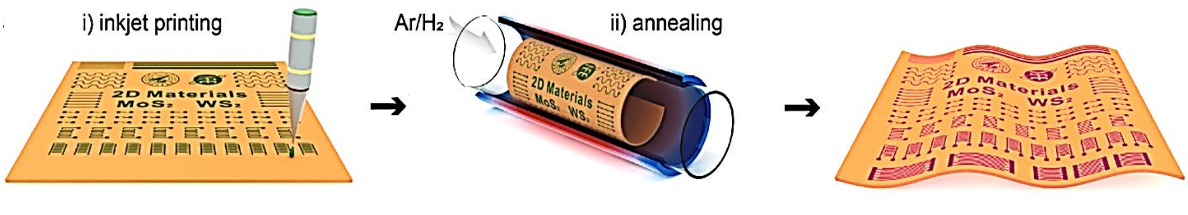

Fig. 2 3D schematics of the patterning of large-scale MoS_2 on flexible PI substrates by a combined approach comprising [8].

2.1.2. Signal processing module

The material of the signal sensing element varies according to the working principle. Wu et al. investigated a low-cost, flexible pressure sensor based on laser-etched graphene with a positive resistance-pressure response [9]. This means that the sensor can adjust its resistance in response to changes in external pressure, enabling ultra-high sensitivity and a wide detection range. Unlike traditional pressure sensors, which are based on changes in negative resistance, the resistance of this sensor increases as the pressure increases, thus achieving a better balance of maintaining high sensitivity while having a wide detection range. They prepared the sensor using laser etching technology, giving it excellent mechanical flexibility and durability. Based on this positive resistance graphene pressure sensor, they implemented an integrated gait monitoring system that provides a wide range of applications in intelligent perception, interactive devices, and real-time health and motion monitoring. For example, multi-mode sensors, which integrate capacitance and piezoresistive mechanisms, can measure multiple forces simultaneously. Peng et al. designed a sensor using a three-layer sandwich design, with two panels serving as both piezoresistive sensors and capacitive sensors as electrodes, while the core in the middle is a porous structure prepared using a simple sugar particle template technology, giving it a high degree of scalability [10]. The two panels are composed of a conductive network featuring distinct silver nanowires (AgNWs) and carbon nanofibers (CNFs). By assessing variations in the resistance of the panels and the capacitance across them, it’s possible to identify three separate mechanical stimuli: positive pressure, planar tension, and lateral shear force. This innovative multi-directional sensor heralds a substantial advancement for future wearable sensors, which hold promise for human health monitoring and the development of robotic synthetic skin.

2.2. Flexible wearable sensors for health monitoring

Wearable flexible sensors can continuously track physiological signals of the human body in real time. These sensors have excellent flexibility and scalability and can be fitted to the skin without causing significant discomfort and invasions. With these sensors, it is possible to monitor signals such as body movement, heart rate, breathing, skin temperature and metabolic parameters that are closely related to an individual’s health status. Currently, wearable flexible sensors show great potential in personal health monitoring and telemedicine practice.

For Internet of Things (IoT) connected healthcare applications, Wu et al. developed a rigid-flexible wearable health monitoring sensor patch [11]. Three sensors for tracking vital signs, a power board, and a center board make up the sensor patch. All components are designed with a rigid-flexible structure that can be easily attached to the human body for remote health monitoring applications. Integrated electrocardiogram (ECG), photoplethysmography (PPG) and temperature measurement. The sensor patch can continuously estimate blood pressure based on pulse arrival time (PAT) without the need for additional cables or equipment because the ECG and PPG sensors are integrated into the same device. Data on physiological measurements can be wirelessly transmitted from the sensor system to the gateway by integrating a tiny Bluetooth Low Energy (BLE) module. To ensure the confidentiality and security of data during transmission, it is crucial to implement encryption protocols on sensor patches and gateways. This measure encrypts the data being sent, preventing unauthorized access and maintaining the privacy of the information. The mobile gateway, which utilizes smartphones, and the fixed gateway, based on portable computers, serve as conduits linking the wearable sensor system to the cloud-based Internet. This connection facilitates the storage and subsequent analysis of health-related data. Tests were carried out to confirm the suggested sensor patch's functionality by contrasting it with a commercial reference device.

Abdollahi et al. studied a wearable pulse oxygen saturation sensor based on 3D printed rigid and flexible structure [12]. Conventional pulse oxygen saturation sensors are usually made of rigid materials, but are not suitable for prolonged wear, resulting in poor fit and mechanical mismatches. They created polydimethylsiloxane (PDMS) elastomer hand and foot cuffs using free-form reversible embedding (FRE) 3D printing technology in order to address this issue. The successful implementation of this technology demonstrates that wearable pulse oxygen saturation sensors for pressure sensing that are tailored to individual patients may be produced using FRE printed PDMS. The findings show that FRE printed PDMS can be comparable to commercial devices for manufacturing patient-specific wearable devices and measuring heart rate and blood oxygen saturation.

3. Conclusion

Flexible wearable sensors have great potential in personal health monitoring and telemedicine practice. The sensor is designed to be flexible and functional and can be tightly fitted to the human body to monitor various physiological signals in real time, such as heart rate, breathing, skin temperature and so on. By employing environmentally friendly biomimetic materials and advanced nanotechnology, such as MQDs and MoS_2, researchers have been able to develop novel sensors with high sensitivity and excellent biocompatibility. These sensors can not only provide continuous health data, but also enable remote transmission and encryption of data through wireless modules, ensuring user privacy and data security. In addition, novel signal processing modules, such as laser-etched graphene-based pressure sensors and multimodal sensors, offer a wide range of application possibilities for intelligent perception, cross-cloud interactive devices, and health and motion monitoring. The versatility and high customizability of these sensors make them an important development direction for future health monitoring and wearable technology. The development of flexible wearable sensors not only promotes the progress of health monitoring technology, but also provides new solutions for personalized medicine and smart medicine. As materials science and electronic engineering continue to advance, it can expect these sensors to become more widespread in the near future, revolutionizing people's health management. However, many studies focus on the development and testing of new materials, and it is important to consider that as the amount of data produced by sensors continues to increase, how to efficiently process and analyze these large amounts of data, as well as health information, becomes an important research question. This problem requires the collaboration of researchers from multiple disciplines, such as data science. From the user's perspective, the technology of flexible wearable sensors needs to establish a set of standardized manufacturing mode to ensure its quality and stable performance.

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