

Application of Nanomaterials in Wearable Electronic Materials

Tianxiang Cai^{1,a,*}

¹*College of Materials and Energy, Guangdong University of Technology, Guangzhou, Guangdong, 511436, China*

a. 13622292267@163.com

**corresponding author*

Abstract: In recent years, with the rapid development of wearable devices, nanomaterials have played an important role in the field because of their unique physical and chemical properties. Although nanomaterials exhibit great potential in the field of wearable electronics, they still face many challenges related to technology, safety, environmental impact and industrial applications. This paper reviews the latest applications of nanomaterials in the field of wearable electronics, focusing on specific examples such as flexible displays, biomedical sensors, nanogenerators and nanobatteries. Additionally, it also discusses the challenges associated with nanomaterials in this field, including issues of production scale, signal stability and biocompatibility. Lastly, this paper explores potential solutions to these challenges and proposes future research directions and application prospects. The findings indicate that due to their unique physical and chemical properties, nanomaterials can significantly improve the electronic, mechanical and stability performance of wearable devices, making them pivotal for future innovations in this area.

Keywords: Nanomaterials, wearable electronics, flexible display screens, biomedical sensors, nanogenerators

1. Introduction

In the tide of scientific and technological progress, nanomaterials have become the focus of research because of their unique physical and chemical properties. From the end of the 20th century to the beginning of the 21st century, the rapid development of nanotechnology has spawned many breakthroughs in frontier fields, especially in the field of materials science. Nanomaterials have been widely used in many fields due to their significant surface area, high chemical activity and controllable photoelectric properties. With the continuous development of science and technology, the application of nanomaterials in the field of wearable electronics is not limited to the existing sensors and display devices, but also extends to many aspects such as energy collection and storage, medical health monitoring and virtual reality technology. With their excellent properties and application potential, nanomaterials are gradually becoming the primary driving force behind the development of future smart wearable devices. Overall, the expansion of the nanomaterials market and the expansion of application fields not only reflect its strategic position in scientific and technological innovation but also mark its great potential in the process of industrialization.

This paper discusses the application potential and research progress of nanomaterials in the field of wearable electronics and discusses the current challenges. This study provides a new idea for the research and development of a new generation of wearable electronic devices.

2. An Overview of Nanomaterials

Nanomaterials are materials that are in the range of 1 to 100 nanometers in at least one dimension, and the reduction of this dimension makes nanomaterials exhibit significantly different physical and chemical properties from bulk materials [1]. Nanoscale effect is an important concept of its properties. Due to the reduction of size, the specific surface area of the material increases significantly, which leads to the increase in the proportion of the number of surface atoms to the total number of atoms, thus affecting chemical reactivity, thermal conductivity, mechanical properties of the materials.

Based on their structure and composition, nanomaterials can be divided into many types, including but not limited to nanoparticles, nanowires, nanotubes, nanosheets and nanocomposites. Zero-dimensional nanomaterials, also known as quantum dots, are materials that are at the nanoscale in all three dimensions [2]. Han et al. have developed a novel quantum dot-polymer composite ink that exhibits excellent water dispersion [3]. With this ink, it is possible to achieve the display of patterns through inkjet printing technology, which do not emit light under ordinary light but only appear under ultraviolet light, so it has potential applications, especially in the field of anti-counterfeiting and identification. One-dimensional nanomaterials refer to materials that have a nanoscale in one dimension and can be macroscopic in the other two dimensions [2]. Such materials include nanowires, nanorods, and nanotubes, among others, which exhibit excellent properties in terms of electron transport, heat conduction, and mechanical strength. Zou Xintao has successfully developed two flexible capacitive sensors, one based on the black phosphorus-gold /Ecoflex composite dielectric layer, with a sensitivity of 0.0984 kPa⁻¹ and a response time of 45 ms; the other one is based on the titanium-gold/sponge composite dielectric layer, with 0.4177 kPa⁻¹ sensitivity and a 32 ms response time, both of which demonstrate high application potential in monitoring human physiological signals and tactile perception in wearable electronic devices [4].

Due to their unique microscopic scale and large specific surface area, nanomaterials exhibit many unique physical, chemical, biological and other properties, which make them show a wide range of application potential in various fields. First of all, nanomaterials have excellent optical properties due to the quantum size effect. For example, metal nanoparticles can significantly enhance their optical activity through surface plasmon resonance, making them widely used in sensors, photocatalysis, and biological detection. In addition, nanomaterials have excellent mechanical and thermal properties. Thanks to the strong atomic bonding force, some nanomaterials exhibit higher strength and toughness than steel. In terms of chemical reactivity, nanoparticles have high catalytic activity due to the high specific surface area of nanomaterials. Finally, nanomaterials also exhibit unique biocompatibility and bioactivity. Because their structures are close to the scale of biomolecules, they have found innovative applications in the fields of biosensing, bioimaging and drug delivery. In the future, with the continuous development of materials science and technology, the properties and application potential of nanomaterials will be further explored and expanded.

3. Application of Nanomaterials in the Field of Wearable Electronics

Breakthrough advances in nanomaterials, with their superior physical, chemical and electrical properties, are reshaping the future development of wearable electronics, allowing them to show unprecedented potential and innovative applications in flexible displays, biomedical sensors, nanogenerators and nanobatteries.

3.1. Flexible Displays

A flexible display, also known as a crimp display, is a flexible and deformable display device made of ultra-thin glass, plastic or metal foil [5]. The materials for making flexible displays require not only relatively good electrical properties but also excellent flexibility and light transmission, and the application of nanomaterials makes flexible displays a reality.

Molybdenum disulfide (MoS_2), as a two-dimensional semiconductor material, has the characteristics of atomic thickness and outstanding flexibility, and has great application prospects in flexible organic light-emitting diode (OLED) displays. In 2018, Jong-Hyun Ahn's research group manufactured an OLED driven by a MoS_2 topgate thin film transistor on a flexible polyethylene terephthalate (PET) substrate [6]. The maximum driving current of this driving circuit is about 1.3 mA, and the brightness of the OLED can be adjusted by gate voltage and drain voltage, and the maximum brightness reaches 408 cd/m^2 . In 2020, the team further implemented a full-color OLED driven by a MoS_2 thin film transistor on a flexible PET substrate [7]. Huang Biying et al. Successfully prepared a MoS_2 2T1C (two transistors and one capacitor) pixel array for flexible display active matrix driver circuits using different insulating layer technologies [8]. In particular, the 2T1C flexible active matrix driver circuit based on 45-nanometer-thick alumina (Al_2O_3) insulation has a single pixel size of 500 microns by 500 microns. This innovative design ensures that the drive current remains stable under the action of AC voltage V_{scan} and V_{data} ; At the same time, the size of the drive current can be effectively modulated by V_{data} and V_{dd} . It is worth noting that the circuit shows excellent stability and negligible current drift under different frequency V_{scan} and V_{data} conditions, which provides a reliable performance guarantee for its application in flexible display technology.

3.2. Biomedical Sensors

The use of biosensors in wearable electronic devices is receiving increasing attention. In recent years, the unique properties of nanomaterials have made them a key material in biosensor design.

Carbon Nanotubes (CNTs) are hollow cylindrical structures that are curled up from layers of graphene. They are mainly in single-walled (SWCNTs) and multi-walled (MWCNTs) forms. Carbon nanotubes are widely used in wearable electronic devices because of their high electrical conductivity and biocompatibility, which can enhance the sensitivity and stability of sensors. Nie et al. proposed a flexible, transparent strain sensor with embedded multi-wall carbon nanotube mesh [9]. The sensor shows excellent light transmittance of up to 87% and high sensitivity, which makes it have potential application value in the field of transparent electronic devices. Especially in monitoring human movement, the sensor has achieved satisfactory results, proving its great potential in the field of wearable devices and health monitoring. Tian Guanghao et al. showed that carbon nanotubes and Ecoflex silicone composites showed excellent tensile properties, greatly improved the flexibility and functionality of the material, and could be applied to ECG monitoring equipment to significantly improve the accuracy of signal acquisition [10].

In addition, carbon-based nanocomposites are also crucial for the construction of high-performance electrochemical sensors due to their unique electronic structure, large specific surface area and excellent compatibility. He Wenya et al. successfully prepared carbon-based nickel metal nanocomposites (Ni/C) and carbon-based nickel-copper bimetallic nanocomposites (NiCu/C) [11]. The former achieved simultaneous detection of three small health-related molecules (ascorbic acid, dopamine, uric acid), showing good selectivity and sensitivity. The latter is an electrochemical sensor constructed with NiCu/C material, which can simultaneously detect five kinds of small biological molecules (ascorbic acid, dopamine, uric acid, adenine, guanine) and has high sensitivity and low detection limits.

3.3. Nanogenerators

At present, traditional lithium and lead-acid batteries are still the main energy source for most electronic devices, but they have limitations such as short life, frequent charging, environmental pollution, and lack of flexible dyeing. Therefore, the search for a green, flexible and sustainable power supply scheme has become the focus of current research.

A triboelectric nanogenerator (TENG) is a kind of power supply device that uses nanomaterials to collect mechanical energy and convert it into electrical energy. It is widely used in wearable devices to realize real-time energy conversion. In 2012, Wang et al. stacked two kinds of polymer sheets with different triboelectric properties to form a sandwich structure covered by a metal film. When mechanical deformation occurred, due to the surface roughness at the nanoscale, friction was generated between the two films, resulting in the same amount of charges but opposite symbols, forming a tribopotential layer in the interface region [12].

A piezoelectric nanogenerator (PENG) is a power supply device that realizes energy conversion through the positive piezoelectric effect. When a piezoelectric material is deformed, polarized charges are generated inside it, and these charges create an electric field inside the material. This electric field exerts an attractive or repelling effect on electrons on the upper and lower surfaces of the piezoelectric material. Once the externally applied stress is removed, the polarized electric field dissipates, causing previously accumulated electrons to flow in the opposite direction through the connected external circuit, creating an electric current. This process effectively converts mechanical energy into electrical energy.

Nanogenerator technology, with its environmental protection, flexibility and sustainability, shows broad application prospects in the field of future energy management and wearable devices, providing an innovative solution to the problem of traditional power supply.

3.4. Nanobatteries

As a core energy storage solution in modern wearable devices, nano-batteries are receiving more and more attention.

In the current study, carbon nanotubes became ideal as electrode materials due to their inherent high electrical conductivity and large specific surface area. The electrochemical performance of lithium-ion batteries can be significantly improved through a reasonable carbon nanotube construction strategy. Chen et al. successfully prepared a nitrogen-sulfur co-doped porous carbon microsphere (N, S-PCS) synthesized by a simple hydrothermal, carbonization and etching process as a negative electrode material for lithium/sodium ion batteries [13]. N, S-PCS electrode not only showed excellent electrochemical performance in lithium-ion batteries, but also showed good cyclic stability in sodium-ion batteries. The experimental and theoretical results confirm that the N, S co-doping strategy can improve the structural stability, shorten the ion diffusion path and promote the reaction kinetics, so as to achieve excellent electrochemical performance. This study provides guidance for the practical application of nonmetallic doped functionalized porous carbon structures in metal ion batteries.

In the field of energy storage, the application of flexible batteries is also particularly important. In view of the limitations of traditional indium tin oxide (ITO) transparent electrodes, Gauss proposed two new flexible transparent electrode solutions [14]. The first solution is to prepare a wavy silver mesh-stretched transparent electrode by inkjet printing technology. The electrode material optimizes the photoelectric properties (square resistance R_s 29.85 Ω sq⁻¹, transmittance T 81.94%) and exhibits excellent mechanical tensile properties (tensile strain 100%). This electrode is embedded in the PDMS elastic substrate by a one-step transfer process, and has excellent oxidation resistance. It can replace ITO transparent electrodes and be used in flexible stretchable electronics. Another option is

to prepare Ag NWs/MXene/PEDOT: PSS flexible, transparent electrodes by a multi-layer spinning coating full solution processing process. The electrode combined with high-elastic PDMS substrate, showing good bending resistance, is expected to replace the ITO transparent electrode and has a wide application prospect in the field of flexible electronics.

4. Challenges and Prospects of Nanomaterials in Wearable Electronics

In the field of wearable electronic materials, the preparation of nanomaterials requires precision process control to ensure uniformity of particle size, shape and surface properties. However, even subtle changes at the microscopic scale can significantly affect material properties, which are especially difficult to control in mass production. In order to reduce costs and improve production efficiency, low-cost and efficient production methods need to be developed. The research results show that graphite derivatives play a stable dispersion role in the preparation of graphene, and the combination of RPB and RSM provides a green and efficient technology for the preparation of graphene [15]. In addition, due to its paper-based sustainability, biocompatibility, and inherently porous structure, this sensor also has excellent sensing capabilities and large-scale manufacturing potential, paving the way for the next generation of wearable electronics.

In wearable electronic devices, nanomaterials can be affected by environmental factors, leading to signal drift and performance degradation. At present, optimizing the signal stability of nanomaterials can reduce the impact of environmental factors on nanomaterials and improve signal stability through encapsulation and protective layer technology. In addition, nanocomposites with high mechanical strength can be developed to resist mechanical stress and maintain signal stability. Finally, materials with high environmental stability can also be selected as an effective way to improve the signal stability of the sensor.

In the field of biomedicine, nanomaterials may cause different levels of compatibility after contact with organisms, especially possible negative effects on patients and people who suffer occupational exposure during manufacturing. Therefore, in terms of surface modification technology, the direct contact between nanoparticles and cells can be effectively reduced by coating biocompatible polymers on the surface of nanoparticles, thus reducing the potential damage to cells. In terms of material characteristics, the selection of materials with high biodegradability can effectively improve the biocompatibility of materials. In addition, the use of inorganic nanocomposite materials is also a new solution. The implementation of these strategies not only improves the performance and safety of nanomaterials in practical applications but also provides a new direction for future biomedical research and clinical applications.

5. Conclusion

This paper reviews the application and research progress of nanomaterials in the field of wearable electronics, focusing on the specific examples of flexible displays, biomedical sensors, nanogenerators and batteries. It is found that nanomaterials significantly improve the performance of wearable devices due to their excellent physical and chemical properties. These findings suggest that nanomaterials are significant in driving the development of wearable electronic technology. Although this paper provides a wealth of research information, there are still some shortcomings. This is mainly reflected in the brief description of emerging nanomaterials in some contexts, and the lack of more in-depth case analysis. Future research methods can consider the combination of experimental and theoretical models to enhance the depth and reliability of the research.

Looking ahead, further research can focus on the following aspects. The first step is to explore the synthesis and functionalization of new nanomaterials to improve their application performance in wearable devices. Secondly, the biocompatibility of nanomaterials can be enhanced to meet the needs

of the medical field. By solving these challenges, nanomaterials will have a broader application prospect in the field of wearable electronics, providing a solid foundation for the popularization and development of smart devices.

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