

Functional Materials for Flexible Electronics and Smart Wearables: Advances and Applications

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Abstract: Flexible electronics and intelligent wearable technology are one of the core driving forces for future intelligent living, and their combination is reshaping the hardware form of industries such as consumer electronics, medical health, and industrial testing. Flexible electronics breaks through the physical limitations of traditional rigid devices by integrating electronic components on flexible substrates, endowing devices with excellent flexibility, extensibility, and biocompatibility, thereby promoting the development of wearable devices towards thinner, more comfortable, and multifunctional directions. This article is based on various research findings in flexible electronics and smart wearables, and introduces the characteristics, preparation methods, and processing techniques of functional materials applied in this technology. At the same time, research on practical industrial production applications is collected. In the future development, flexible electronics still need considerable improvement in mechanical and electrical properties, and the preparation process needs to be developed towards low-cost, large-scale manufacturing, etc. Based on the current research status, flexible electronics will continue to expand its application scenarios and intelligent trends, becoming an important development direction and application tool in multiple disciplines and fields.

Keywords: functional materials, flexible electronics, intelligent wearables

1. Introduction

Flexible electronic materials and intelligent wearable technology are a new transformative technology that has emerged in recent years. They deposit electronic materials and devices on flexible substrates, integrate corresponding circuits, and produce wearable products. The research on this technology is a typical new frontier interdisciplinary field, involving collaborative research of multiple fundamental disciplines such as physics, materials, biology, microelectronics, etc., and has brought revolutionary changes to multiple emerging fields.

Functional materials are a type of material that exhibits specific functions through optical, electrical, magnetic, thermal, chemical, or biological interactions, with the core being to meet non-structural functional requirements. Researchers are committed to finding and developing functional materials that meet the needs of flexible electronic materials and smart wearable technology. For the functional requirements of flexible electronic materials, they need to have novel features such as printability, foldability, and stretchability that traditional electronic materials do not have, while also maintaining good electrical and biological properties. For example, in terms of medical health, by attaching flexible sensors to human skin or implanting them into the body, real-time monitoring of

physiological data such as heart rate and blood pressure can be achieved, providing precise support for chronic disease management and postoperative rehabilitation; At the same time, data is collected through smart wearable devices to achieve early disease warning and personalized health advice.

At present, there are still urgent issues to be addressed regarding the stability and lifespan of flexible electronic materials in some extreme environments. Flexible materials are prone to deformation and fatigue when subjected to external interference, and due to the influence of deformation, signal interference can occur. In addition, the high power consumption of wearable devices during use also brings about power supply issues. Therefore, promoting interdisciplinary collaboration and innovation, optimizing performance and preparation processes are the future directions for the development of materials. This article provides a detailed introduction to the properties, preparation, and applications of functional materials in flexible electronics and smart wearables technology, and discusses the challenges and future development directions faced by this technology.

2. Material type and characteristics

2.1. Conductive materials

In flexible electronic fabrics, the materials in the circuit are quite important, as they need to have good conductivity to meet the collection of electrical signals. Traditional conductive materials such as copper and aluminum have poor flexibility, and fabrics composed of them are prone to breakage and damage, making them unsuitable for use in flexible fabrics. Considering the aesthetic appeal of fabrics, it is also necessary to use transparent conductive materials. At present, commonly used electrode conductive materials can be mainly divided into metal nanowires, conductive polymers, and carbon nanomaterials according to their material characteristics.

Metal nanowire materials refer to a type of metal material with a diameter ranging from tens of nanometers to hundreds of nanometers and an aspect ratio greater than 10, including gold nanowires (AuNWs) Silver nanowires (AgNWs), copper nanowires (CuNWs), etc., due to their high electrical and thermal conductivity, high mechanical strength, and good flexibility, are suitable for making flexible dry electrodes [1]. Meanwhile, silver nanowires (AgNWs) have good transparency and are widely used in the preparation of flexible sensors [2].

Conductive polymers refer to polymer materials with conductive properties, including various types such as polypyrrole (PPy), polythiophene (PT), polyaniline (PANI), etc. Poly (3,4-ethylenedioxythiophene): Polystyrene sulfonate (PEDOT: PSS) is an excellent organic coating that can adapt to various complex PCB design shapes and bending requirements due to its good conductivity, thermal stability, and processability. It can also be made into highly transparent conductive films and applied to components such as touch screens and display panels [3].

Carbon nanomaterials refer to materials with at least one dimension smaller than 100 nm in particle size, such as carbon nanotubes (CNTs), graphene, and its derivatives. The unique surface effect, small size effect, quantum size effect, macroscopic quantum tunneling effect, etc. have brought it huge specific surface area, high conductivity, good biocompatibility and other characteristics. The structure of carbon nanotubes is mainly composed of carbon atoms arranged in a hexagonal pattern, forming coaxial circular tubes with several to dozens of layers. The p-electrons of carbon atoms form delocalized π bonds over a large range, resulting in significant conjugation effects and endowing carbon nanotubes with excellent conductivity. In addition, carbon nanotubes exhibit excellent mechanical properties, with elastic modulus and tensile strength reaching up to 1 TPa and 100 GPa, respectively, and a fracture elongation of 15%~30%, making them an ideal material for preparing flexible sensors [4].

2.2. Semiconductor material

Some semiconductor materials have controllable band structures and good carrier mobility, which have important applications in flexible devices, including some organic semiconductors, two-dimensional materials, and perovskites. Pentacene, as an organic semiconductor material, is widely used in the preparation of organic thin film transistors (OTFT) due to its excellent hole transport properties. In addition, two-dimensional nanomaterials including graphene, hexagonal boron nitride, molybdenum disulfide, and black phosphorus provide new development ideas for flexible semiconductor design with excellent electrical and thermal properties. Molybdenum disulfide, similar to graphene, is a two-dimensional layered structure that is bonded between layers through van der Waals forces, exhibiting excellent optical, electrical, and mechanical properties. The thickness of molybdenum disulfide is only at the atomic layer level, with a single layer thickness of around 7 Å. It has good flexibility and can be used to integrate large-area flexible storage devices [5]. Compared with traditional optoelectronic materials, perovskite can adjust its bandgap width by replacing halide anions in the perovskite structure, while changes in cations such as MA^+ , FA^+ , and Cs^+ can expand the emission spectrum of perovskite to the near-infrared or ultraviolet regions, which is beneficial for achieving full-color display of PeLEDs. However, traditional rigid substrate PeLEDs cannot meet the development needs of modern society for flexible displays and wearable electronic devices. Therefore, flexible perovskite light-emitting diodes (FPeLEDs) based on flexible electronics will shine brightly in flexible lighting [6].

2.3. Dielectric material

Flexible dielectric materials refer to flexible materials with insulating properties, including substrate materials for flexible displays, polymer capacitor dielectrics, and dielectric materials for pressure electronic skin sensors [7]. Polymer dielectric materials have become one of the ideal dielectric layer materials for flexible capacitive pressure sensors due to their excellent flexibility, good environmental stability, and low cost. At present, flexible capacitive pressure sensors based on polymer dielectric materials such as polydimethylsiloxane (PDMS), polymethyl methacrylate (Ecoflex), polyvinylidene fluoride (PVDF), and thermoplastic polyurethane (TPU) have shown great development prospects in the fields of motion detection and human-computer interaction [8].

2.4. Stretchable and self-healing materials

Flexible electronic fabrics with high stretchability, self-healing ability, and environmental compatibility have more convenient and practical competitiveness in practical use. Conductive nanomaterials, such as carbon nanotubes and conductive polymers, can be added to hydrogels as fillers due to their high conductivity and large specific surface area, and the conductivity of conductive hydrogels can be significantly improved by optimizing the interaction between the dispersion of conductive nanomaterials and the hydrogel network [9]. The substrate material is the key to determining the performance of sensors. Traditional flexible electronic devices are usually composed of bulky metals and sturdy composite materials, which cannot meet the requirements of flexibility and softness. Gallium based liquid metal (Ga LM), as a new generation of advanced electronic materials, has become one of the ideal candidate materials for flexible sensor manufacturing due to its inherent high conductivity ($3.4 \times 10^6 \text{ S/m}$), good environmental stability, almost negligible toxicity, and unique fluidity [10].

3. Preparation and processing technology of materials

3.1. Printed electronics

Printing is the replication process of transferring pigments onto a substrate using analog or digital image carriers [11]. Chen et al. [12] developed a silver nanowire conductive ink for screen printing by printing silver grids using screen printing technology to improve electrode conductivity.

Inkjet printing technology is a non-contact, non-plate digital control material direct graphic technology, which uses electrical signals to control ink containing functional materials to deposit directly on the substrate surface through micrometer level nozzles to form high-quality patterns [13]. Mahmoud et al. [14] inkjet printed AgNP conductive patterns on tattoo films, and then coated a thin layer of EGaIn on the ink layer for sintering. The resulting circuits have good conductivity and stretchability.

3.2. Thin film deposition technology

Flexible electronic materials for wearable fabrics can be prepared using thin film deposition techniques based on flexible substrates, such as CVD and ALD. Chemical vapor deposition is the process of bringing reactive gases in atomic or molecular form onto the surface of a substrate to undergo a chemical reaction, forming the desired coating. OCVD can control the conductivity of conductive polymers by controlling the reaction rate, and directly affect the polymerization reaction rate by controlling the substrate temperature, making it a good method for preparing conductive polymers [15]. Tsai [16] obtained a novel nanolaminated structure by alternately depositing HfO₂ and PA-2,3 on a PET substrate, in which the PA-2,3 layers provided the tensile and bending properties of the flexible film, The HfO₂ layer can reduce the permeation of water vapor through aluminum and prevent the substrate from expanding due to moisture. This solution is a major breakthrough in wearable flexible electronic devices.

3.3. Micro nano processing technology

Micro nano processing technology is a technique that utilizes physical and chemical methods to visualize, structurally process, and functionally integrate materials at the micrometer to nanometer scale. The graphic technology includes photolithography, laser processing, and NIL. Martinez et al. proposed a photolithography process suitable for flexible and rigid substrates, which can manufacture complex three-dimensional interconnected silver nanowire grids [17]. However, the mechanism of laser action on polymers is relatively complex. In addition to the nonlinear absorption of laser energy caused by the properties of the polymer itself, the ablation process is also accompanied by photo induced chemical reactions and photothermal changes [18]. Hu et al. [16] proposed a laser ablation method at room temperature, using a 355 nanometer wavelength ultraviolet laser to ablate copper coatings on PET surfaces. By adjusting parameters such as laser power, copper based flexible electrodes with different accuracies and sizes were prepared.

NIL is a key nanofabrication method based on the principles of hot stamping and photolithography stamping, which stamps micro nanostructures on a template onto a substrate coated with imprinting adhesive. The pattern is fixed and demolded by heating or UV curing, achieving high-precision pattern transfer. Bao et al. [19] conducted research on the fabrication method of ultrafine flexible transparent conductive circuits based on NIL, and proposed the use of electric field driven filling of network grooves, providing a technical process foundation for the development of higher demand flexible printed electronics.

4. The application of materials in flexible electronics and intelligent wearables

4.1. Flexible sensor

A flexible sensor is a device that can sense changes in external physical quantities such as pressure, strain, temperature, humidity, bending, etc., and convert them into electrical signals. Its core characteristics are flexibility, stretchability, lightweight, and good environmental adaptability. Zhang [20] used a three-dimensional fabric structure and a novel two-dimensional $\text{Ti}_3\text{C}_2\text{Tx}$ MXene material to construct a complete pulse signal monitoring system, which can accurately extract and analyze normal pulse and cardiovascular disease patients' pulse. At the same time, based on the piezoresistive and thermoelectric properties of SWCNTs and PEDOT: PSS, a pressure temperature dual parameter sensor was designed and prepared to accurately collect pulse and temperature signals from different parts of the human body. Abudu Waili Mijiti [21] developed a flexible motion sensor capable of detecting human motion using AgNWs and PDMS. The PDMS substrate demonstrated superior cyclic stability and mechanical properties compared to PVA substrate, making it an ideal choice for preparing high-performance flexible strain sensors. By adjusting the concentration of AgNWs, the sensor's responsiveness to dynamic changes was enhanced, and multiple monitoring functions including electromyographic signals, joint deformation, and skin deformation monitoring were successfully integrated, demonstrating the application prospects of flexible sensors in real-time health monitoring and human-computer interaction. Luo [22] achieved suicide bacteria and degradability in mask fabric by modifying PLA non-woven fabric with ionic salt, and successfully prepared a high-performance PLA/DDAC/SMS multifunctional flexible sensor. The sensor has excellent humidity response performance, with response and recovery times of 0.12 s and 0.16 s, respectively, and good stability and repeatability. Based on humidity response, it can monitor human respiration.

4.2. Flexible display and lighting

A flexible display is a display device made of deformable and bendable soft materials, as thin as paper, that can retain its content even in the event of a power outage. Flexible display technology has broad prospects and rapid development, providing more diverse and diversified ways of presenting information. The main technologies currently being widely researched for implementing flexible displays include Liquid Crystal Display Organiclight emitting devices, Electrophoretic Display. Among them, OLED is considered the most ideal display technology so far [23]. Due to its excellent features such as self-luminescence, ultra-thin, low power consumption, and flexibility, OLED has significant advantages in flat panel displays, lighting, and other areas. Adachi et al. [24] separated the electron clouds of the highest occupied molecular orbital and the lowest unoccupied molecular orbital in the molecule, resulting in photons with extremely small single triplet state differences, achieving high reverse intersystem crossing at room temperature and achieving 100% internal quantum efficiency. This type of material is called thermally activated delayed fluorescence (TADF) luminescent material, which combines the advantages of low cost and high efficiency, and has sparked a new wave of research on novel OLEDs. Wu [25] prepared a high-performance binary sensitized superfluorescence device with a maximum external quantum efficiency of 32.2% and a brightness of $1000 \text{ cd} \cdot \text{m}^{-2}$ using a spatially resistive MR-TADF blue light material PhCzBN as the dye, based on the TADF material 5CzTrz with high intersystem crossing rate and bipolar transport. Bian [26] and others used SiCzCz: SiTrzCz2 as the main material for the light-emitting layer of the device, and introduced TADF molecule DMAC-DPS, phosphorescent material Ir(ppy)₂(acac), and RD071 to prepare TADF/phosphorescent hybrid WOLEDs devices. This design optimizes the balance of carrier transport and exciton utilization. The designed white light device exhibits ultra-low efficiency roll off and excellent spectral stability, with a maximum EQE, current efficiency, and

power efficiency of 23.0%, $45.9 \text{ cd} \cdot \text{A}^{-1}$, $33.9 \text{ lm} \cdot \text{W}^{-1}$ provide a simple and feasible approach for the preparation and research of efficient and stable hybrid white light devices.

4.3. Flexible energy devices

Flexible energy devices are the cornerstone of the new generation of wearable electronic products, with multiple functions such as photovoltaic energy conversion, frictional power generation, energy storage, etc. These functions can be achieved through solar cells, flexible batteries, and supercapacitors. Among numerous solar cells, organic solar cells (OSCs) occupy an important position in the field of solar cell technology due to their unique advantages of lightweight material properties, semi transparent properties, and excellent flexibility. Song et al. [27] significantly improved the conductivity and mechanical properties of PEDOT: PSS films through green acid treatment and doping with polyhydroxy compounds, achieving excellent mechanical properties that are well compatible with complex three-dimensional curved electronic device surfaces. This has significant implications for promoting the commercialization of OSCs.

Compared with batteries, flexible supercapacitors have advantages such as fast charging and discharging, long lifespan, etc. Their flexible design can adapt to various shapes and application scenarios, and have broad application prospects in the field of portable wearable smart devices. Wei et al. [28] developed an asymmetric all solid state supercapacitor, in which porous activated carbon was used as the negative electrode and graphene loaded CoMoS₄ (GN-CoMoS₄) was used as the positive electrode. The porous structure and good stability of GN-CoMoS₄ and activated carbon enable the supercapacitor to have an energy density of $42.85 \text{ W} \cdot \text{h/kg}$ at a power density of 900 W/kg , and maintain a capacity of 93.2% after 8000 cycles, demonstrating excellent cycling stability. Conductive polymers have diverse molecular structures and have attracted widespread attention as active electrodes for capacitors due to their excellent conductivity, electrochemical activity, and high theoretical capacitance. Thanks to its diverse molecular structure, conductive polymers have become a popular choice for active electrodes in capacitors due to their excellent conductivity, electrochemical activity, and high theoretical capacitance.

4.4. Human-computer interaction

Recent advancements in artificial intelligence and Internet of Things have pushed human-computer interaction towards intelligence, naturalness, and immersion, focusing on personalized needs and enhanced user experiences. Flexible electronics have improved interaction by conforming to body contours, enhancing comfort and efficiency. Brain Computer Interface (BCI) technology, which translates brain signals like electroencephalography (EEG) into control commands, shows promise in healthcare, smart homes, and VR/AR. ANG Xiao's team [29] has developed network-based electronic device (NeuE), a neuron-mimicking device that could aid in tissue repair and advance BCI and biomedical treatments.

5. Future development trends and challenges

In order to make wearable electronic materials and devices more in line with personalized needs such as human physiology and psychology, they need to have characteristics such as flexibility, signal stability, and long-term wearability. These requirements also pose further challenges to the mechanical and electrical properties of flexible electronic devices. For some conductive materials, their plasticity and toughness can be improved by optimizing nanostructure design and coating technology to meet complex morphological requirements. In the development of new organic materials, such as functionalized polymers, while improving oxidation resistance and wear resistance through molecular structure optimization, the synergistic effects of organic-inorganic composite

materials can also be explored. In terms of electrical performance, the development of flexible electronic materials will focus on designing low-power wearable devices that can maintain signal stability, minimize noise interference, and achieve accurate measurement functions during long-term wear [30]. Flexible materials are subjected to cyclic stress and environmental exposure for a long time. In addition to selecting materials with good electrical and mechanical properties, composite design and packaging treatment of materials are also effective ways to improve stability. The encapsulation process can effectively prevent materials from being affected by external environmental factors such as moisture and oxygen invasion, thereby extending the service life of materials. Tsai [16] obtained a novel nanolaminated structure by alternately depositing HfO₂ and PA-2,3 on a PET substrate, in which the PA-2,3 layers provided the tensile and bending properties of the flexible film, The HfO₂ layer can reduce the permeation of water vapor through aluminum and prevent the substrate from expanding due to moisture. This solution is a major breakthrough in wearable flexible electronic devices. Composite materials can significantly improve the mechanical properties and durability of materials by combining the characteristics of different materials.

To meet the needs of large-scale industrial production and enhance commercial competitiveness, it is also necessary to improve the preparation process. For example, promoting the continuous integration of printing electronics technology and computer digitization has brought revolutionary leaps to various electronic related enterprises such as intelligent packaging enterprises and electronic device manufacturing enterprises [14].

The development of flexible electronics and intelligent wearable technology in the future will focus on the expansion and intelligence of application scenarios. However, the application of flexible electronic technology in human-computer interaction still faces many challenges, such as signal interference, data processing speed, and system integration. Zhao et al. [31-36] used technologies such as RIS and vortex beam to achieve advanced artificial Doppler frequency shift in a space-time digital coding RIS system using a rotating vortex beam, improving spectral efficiency and anti-interference ability. Their performance in fast response space-time wavefront manipulation provides new ideas for the development of wireless communication technology. It can be seen that the solution to these problems will rely on the cross integration and innovation of multiple fields such as materials science, microelectronics technology, and information technology [37].

6. Conclusion

Flexible electronics and intelligent wearables overcome traditional rigid device limitations by combining innovative materials and flexible substrates, showing promise in healthcare, consumer electronics, energy, and human-computer interaction. Advances in conductive, stretchable materials and efficient processing technologies like printed electronics have driven lightweight, multifunctional wearable devices. However, challenges remain in material stability, cost, sensor sensitivity, and system integration. Future interdisciplinary innovation, integrating materials science, microelectronics, and AI, will accelerate applications in non-invasive medical monitoring, self-powered devices, and IoT, evolving toward low-cost, high-reliability, and eco-friendly solutions, ultimately becoming a core driver of intelligent society development.

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