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From Material Properties to Device Design and Clinical Transformation of Graphene-Based Flexible Wearable Devices

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Abstract. Rigid electronic devices suffer from poor adaptability and low comfort, limiting real-time physiological monitoring. Owing to its outstanding electrical, mechanical, and biocompatible properties, graphene has emerged as an ideal core material. This paper reviews the research progress of graphene-based flexible wearable devices. At the level of device innovation, it covers not only research on optimizing device performance through hetero structure design, but also the development of laser-induced graphene batch preparation processes to lay a solid foundation for the large-scale production of devices. In terms of system integration technology, in-depth exploration of multimodal sensing synergy mechanisms to achieve precise collection of multiple physiological signals, as well as research on hybrid energy supply schemes to ensure long-term stable operation of the equipment. In the field of clinical applications, a detailed analysis of its practical cases of real-time capture of cardiac electrical activity in dynamic electrocardiogram monitoring, facilitating early warning of cardiovascular diseases, and real-time monitoring of wound microenvironment in diabetic wound management, to promote wound healing. At the same time, it clearly points out the key challenges currently faced in this field: the high cost of large-scale preparation restricts the popularization of the technology; The lack of long-term stability affects the reliability of equipment use. Finally, looking forward to the future development direction, propose the core path of combining artificial intelligence and edge computing to improve data processing efficiency and building a closed-loop diagnosis and treatment system to achieve precise disease intervention.

Keywords: Graphene, Flexible wearable devices, Heterostructure sensors, Biocompatibility, Medical transformation

1. Introduction

Driven by the deepening of global health concepts and the iterative upgrading of smart technologies, flexible wearable devices are gradually expanding from consumer electronics to precision medicine. Personal health monitoring, telemedicine, human-computer interaction, and other application scenarios impose strict requirements on the flexibility, lightness, and biocompatibility of devices [1].

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Although traditional rigid electronic devices can detect signals, due to the mismatch between their mechanical stiffness and human skin, various interference situations are prone to occur during limb movement, resulting in signal distortion, and long-term wearing is prone to cause skin discomfort, which cannot meet the needs of 24-hour dynamic physiological monitoring.

The key to achieving a core breakthrough in flexible wearable devices lies in the innovation of high-performance sensing materials, and the discovery of graphene has brought about a breakthrough in this field. The unique single-atom layer structure of graphene gives it excellent overall performance, laying a solid material foundation for the improvement of device performance. Guo et al.confirmed through comparative experiments that graphene-based devices significantly outperform traditional metal or polymer materials in terms of strain sensing and energy storage synergy [2].

Despite the outstanding achievements of current research, graphene-based flexible wearable devices still face three core challenges. Firstly, there is an inherent contradiction in device design between high sensitivity and a wide detection range, which limits the device's applicability in multiple scenarios. Secondly, there is a lack of standardized solutions for multimodal sensor unit integration, resulting in insufficient system compatibility. Finally, long-term stability issues in health monitoring scenarios, such as device performance degradation in fluid environments, have not been completely resolved.

Based on this, this paper reviews the performance of graphene materials, device design innovation, system integration technology, and clinical application practice, analyzes existing problems in combination with the latest research results, such as heterostructure devices and artificial intelligence-assisted signal processing, and looks forward to the key paths for the industrialization and clinical transformation of this technology.

2. Properties of graphene materials

The unique structure of graphene gives it an irreplaceable advantage in flexible wearable devices. Its core properties can be developed in three dimensions: electrical, mechanical, and biocompatibility. The synergy of these properties provides a solid foundation for the device to work stably in complex physiological environments.

2.1. Electrical performance

Electrical properties are the core basis for graphene to play a role in physiological signal monitoring. The remarkable advantage of graphene over traditional metals lies in its ability to exhibit the quantum Hall effect at room temperature, a property that enables a qualitative leap in its sensitivity to capture weak electrical signals. Physiological signals such as electromyography and electroencephalogram are mostly microvolt-level weak signals, and traditional electromyography is highly susceptible to environmental interference, resulting in signal loss or distortion. Graphene, with its highly efficient electron transport channels formed by conjugated electron systems, can precisely capture such weak signals [2]. Guo et al. experimentally confirmed that graphene-based sensing units can not only stably capture microvolt-level physiological electrical signals, but also have a significantly better signal-to-noise ratio than traditional metal electrodes, providing a feasible solution for high-precision physiological monitoring [2]. Further research shows that graphene has an electron mobility of up to 15,000 cm2/(V · s), and this efficient electron conduction ability effectively reduces signal loss during transmission, ensures the integrity of weak physiological

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signals, and provides a reliable data source for subsequent signal analysis and diagnosis [2]. To sum up, graphene has excellent electrical properties that are in line with flexible wearable devices.

2.2. Mechanical properties

Flexible wearable devices need to adapt to the dynamic deformation caused by human movement for a long time. Therefore, the mechanical properties of the materials directly determine the practical value of the devices. Graphene itself has excellent mechanical properties, and conventional graphene films can withstand repeated bending without failure. The graphene material, which has been optimized through structural design, has broken through the tensile limitations of traditional two-dimensional materials. Zu et al. constructed a three-dimensional porous network structure in graphene-based composites by uniaxial hot pressing, which is a typical case of mechanical property optimization in the field of flexible electronics. The structure relies on the fold-concave synergistic elastic deformation of the pores to efficiently disperse local stress concentration during stretching. The results showed that the unidirectional tensile rate of the material exceeded 1200% and a negative Poisson's ratio characteristic of -0.174 was achieved, further expanding the application scenarios of graphene-based materials in flexible sensors [3, 4]. This combination of high strength and high toughness enables it to closely adhere to moving parts such as joints and muscles, and still achieve a stable sensing function even when the human body is in motion.

2.3. Biocompatibility

Wearable devices come into long-term direct contact with the skin and impose strict requirements on the biosafety of materials, while the biocompatibility of graphene provides a safety guarantee for long-term wearing. The system biocompatibility assessment experiments conducted by Pelin et al. are representative. They used fest-layer graphene (FLG) and three types of graphene oxide (GO) as research subjects and conducted 72-hour continuous contact experiments using skin keratinocytes (HaCaT) as models. The skin biosafety of graphene materials was systematically evaluated by combining mitochondrial activity detection (WST-8 method) with cell membrane integrity analysis (propidium iodide uptake test) [5]. The results showed that within the practical application concentration range, exposure to feiler-layer graphene did not cause significant cytotoxicity - the median effective concentration of mitochondrial damage (EC_{50}) was 62.8 μg/mL, and the EC_{50} of cell membrane damage was 45.5 μg/mL. The mitochondrial damage $EC5_0$ of GO3 was significantly higher than that of high-oxidation graphene (only 5.4 μg/mL), confirming the biosafety [5] of low-oxidation graphene.

This safety is closely related to graphene's unique material properties, atomically smooth surfaces characterized by atomic force microscopy, which reduce physical irritation to cells. The low hydroxyl content verified by X-ray photoelectron spectroscopy (60% lower than high oxidation GO) demonstrates good chemical inertness and reduces the risk of adverse reactions with skin secretions. The study also found that cell damage was only observed under high concentrations (>100 μg/mL)and prolonged exposure [5]. This sets clear safety application thresholds for graphene-based wearable devices, enabling them to meet safety requirements in long-term physiological monitoring scenarios such as 24-hour dynamic electrocardiogram monitoring and laying the foundation for clinical-grade applications. In summary, the good biocompatibility of graphene provides more possible scenarios for the safe application of wearable devices.

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3. Innovations in device design and fabrication

Innovation in device design and fabrication processes is a key link in moving graphene-based flexible wearable devices from the laboratory to industrialization. Achieving performance synergy through structural optimization and reducing production costs through process breakthroughs have become the focus of research in this field.

3.1. Novel device structures

Sandwich composite structures show unique advantages in the field of sensing performance optimization. The sandwich composite structure is a typical function-enhanced configuration in the field of flexible sensing, typically with a flexible polymer substrate as the upper and lower support layers, and the middle layer integrates two or more functionally complementary sensing materials, breaking through the performance limitations of a single material through interlayer functional partitioning and synergy. The laser-induced graphene/silver nanowire (LIG/Ag NWs) sandwich sensor designed by Li et al. achieves efficient synergy of material performance [6]. Graphene as the conductive skeleton provides a stable electrical path with a conductivity of up to 850 S/m; Silver nanowires, as high-strain sensitive materials, produce a significant resistance response to small deformations [6]. When subjected to external force, the stress concentration effect at the sandwich interface (caused by the difference in modulus between the PI-PDMS substrate and the conductive layer) amplifies the resistance change, making the sensor sensitivity (GF=778.468) more than five times that of a single graphene sensor [6]. This high sensitivity enables it to precisely capture tiny limb movements such as finger tremors and maintain stable performance after 2000 cycles of testing, providing core device support for quantitative assessment of tremors in Parkinson's disease [6].

In addition to the sandwich structure for focusing sensing sensitivity, the heterogeneous design achieves a leap in device performance through complementary advantages of different materials. In the field of energy storage, the single-layer MoS_2 / graphene heterojunction zinc-ion microbattery developed by Chen et al. is a typical case, which ingeniously combines the high conductivity of graphene with the high zinc storage capacity of MoS_2 [7]. Graphene provides an efficient channel for electron transport, while the layered structure of MoS_2 offers ample space for reversible deposition/exfoliation of zinc ions. The interinterface contact is optimized through interinterface charge transfer effects, significantly enhancing ion transport efficiency and ultimately achieving a substantial increase in energy density. This single-layer heterojunction design, on a flexible substrate, not only strikes a balance between high energy density and fast charging performance, but also ADAPTS to on-chip integration requirements and is better compatible with the miniaturization and integration design of wearable devices, effectively alleviating the battery life anxiety of wearable devices.

3.2. Fabrication process

Breakthroughs in laser-induced graphene (LIG) technology offer a new path for the efficient batch production of devices. As a new type of graphene preparation technology, the core of laser-induced graphene (LIG) technology is to irradiate carbon-containing precursor materials (such as flexible polymers, paper, resins, etc.) with lasers of specific wavelengths (typically infrared, ultraviolet, etc.), and utilize the energy effects such as high temperature and high pressure generated instantaneously by the laser to reorganize and graphitize the carbon elements in the precursor in situ. It directly

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generates graphene structures with high electrical conductivity and high specific surface area without the need for traditional steps such as complex chemical synthesis, high-temperature annealing, and graphene transfer. The roll-to-roll LIG production system developed by Zhang et al. revolutionizes the traditional preparation mode [8]. The technology induces graphene generation in situ on a flexible polymer substrate using a 10.6 μm infrared laser without the need for complex precursor pretreatment or subsequent transfer steps [8]. The high energy of the laser can instantly reorganize the carbon in the polymer into a three-dimensional porous graphene structure, enabling the direct preparation of patternized graphene with a batch production efficiency of up to 10 m/min, which is two orders of magnitude higher than the traditional chemical vapor deposition (CVD) process [8]. The process is fully automated through modular design, which not only significantly reduces the time cost of equipment preparation but also is compatible with a variety of flexible substrates such as polyimide and PET, laying the foundation for industrial production.

Inkjet printing integration technology has driven the development of the precise assembly of multiple materials. The core of inkjet printing integration technology is to spray ink containing functional materials(such as conductive ink, semiconductor ink, graphene-based ink, etc.) onto the surface of the target substrate (such as flexible polymer, glass, metal, etc.) in the form of tiny droplets on demand through the precision nozzles of inkjet printing equipment. The pre-patterned functional layer or device structure is directly formed after curing (such as heating, UV irradiation, etc). The core advantage of this technology lies in the integrated manufacturing of "sensor-circuit-substrate", which enables seamless integration of multi-functional layers by precisely controlling the printing paths and curing conditions of different materials. In addition, the technology is compatible with a variety of flexible substrates such as fabrics and hydrogels, providing a viable path for high-density integration of multimodal sensing units, especially for the personalized customization requirements of wearable devices.

4. Health monitoring applications

The application of graphene-based flexible wearable devices in the health field has moved from basic signal detection to clinical-level diagnosis and treatment practice, and their precise and intelligent characteristics provide new approaches for disease management and rehabilitation treatment.

4.1. Detection of physiological signals

Dynamic electrocardiogram monitoring is a core means of cardiovascular disease prevention and management, and the application of flexible electrodes has significantly improved the quality of monitoring. Traditional Ag/AgCl electrodes are highly susceptible to movement interference and can cause skin irritation when worn for a long time; The flexible electrode based on laser-induced graphene (LIG) technology optimizes the interface contact design through fractal structure, stably controls the contact impedance within 100 Ω, and enables 24-hour continuous dynamic electrocardiogram monitoring [9]. Fabricated using a one-step laser direct writing process, the electrode demonstrates excellent motion phantom suppression ability in daily activities, with a signal-to-noise ratio improvement of more than 30% compared to traditional wet electrodes. It can stably capture weak waveforms such as P waves and T waves, providing reliable electrophysiological data for the early screening of arrhythmias [9]. This gel-free design fundamentally addresses the skin discomfort caused by long-term wearing, and its 22g lightweight integrated system is more suitable for portable health monitoring scenarios [9].

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The synchronous decoding of electroencephalogram (EEG) and electromyogram (EMG) has opened up a new path for neurorehabilitation and human-computer interaction. The graphene array sensor developed by the research team, through a multi-channel signal fusion algorithm, builds a collaborative acquisition system for electroencephalogram (EEG) and electromyogram (EMG) to achieve precise decoding of motion intentions [9]. The system, based on a low-impedance LIG electrode array (impedance < 100Ω) and a 3D-printed flexible package structure, achieved over 94% accuracy in recognizing motor intent in prosthetic limb control experiments for patients with spinal cord injury, successfully converting neural signals into control instructions for mechanical limbs to help patients complete basic grasping movements [9]. This multimodal sensing technology is self-powered by a triboelectric-photoelectric hybrid power supply module, providing an integrated solution for the rehabilitation treatment of patients with neurodegenerative diseases.

4.2. Disease management

The precision of chronic disease management is highly dependent on real-time monitoring of the physiological microenvironment, and the application of graphene-based sensors in diabetic wound management shows a prominent advantage. Researchers integrated graphene oxide (GO) pH sensors into medical dressing matrices for real-time tracking of acid-base changes in wound exudate [10]. Fabricated using screen printing, the sensor has a response time of less than 5 seconds to pH changes and can precisely capture dynamic shifts in the wound environment from neutral (7.0) to alkaline (8.5). Experimental data established a quantitative correlation model of pH with infection risk: when the pH of the exudate rose to 8.5, the probability of Staphylococcus aureus infection increased sixfold compared to the neutral environment. Sensors transmit early warning signals in real time via wireless modules, providing an objective basis for clinical dressing change decisions [10].

In the field of neurodegenerative disease assessment, graphene strain sensors provide a quantitative means for tremor assessment in Parkinson's disease. Traditional tremor assessment relies on subjective scores by doctors and is susceptible to differences in experience. Flexible strain sensors based on graphene-glycerol systems can directly capture tremor signals in patients' limbs through patch design. The sensor has 1000% super tensile performance and a high gauge factor of 45.13, which can accurately record multi-dimensional parameters such as tremor frequency, amplitude, and duration, with quantitative analysis error maintained within 7% [11]. In clinical trials, the system successfully distinguishes the spectral characteristics of resting tremors from those of motor tremors, providing objective quantitative indicators for dose adjustment and efficacy evaluation of levodopa drugs and significantly improving the accuracy of diagnosis and treatment.

5. Challenges and prospects

5.1. Challenges

Although significant progress has been made in graphene-based flexible wearable devices, there are still multiple challenges for large-scale industrialization and clinical application, and key breakthroughs need to be achieved through technological innovation in the future. The cost constraint of large-scale production is the core obstacle to the development of the industry at present. A study of the roll-to-roll chemical vapor deposition (CVD) process published by the MIT team in 2019 shows that in the cost composition of graphene prepared by traditional CVD technology, the cost of copper-based materials is as high as $40 per square meter, and the equipment

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depreciation cost is about $1 per square meter. The combined cost of energy and gas is only $2.85 per square meter [12]. This cost structure has led to large-scale production of high-quality graphene films that are difficult to meet the cost expectations of civilian wearable devices [12]. Further cost breakdown analysis shows that the CVD process requires maintaining a high vacuum environment of $10^{-}5$ Pa, with a single-batch growth cycle of up to 8 hours, and equipment depreciation and energy consumption costs account for 62% [12]. Although the subsequent development of Joule heating can convert carbon waste to graphene and reduce the cost to $0.5 per kilogram, the turbostratic structure of the product results in a carrier mobility of only 2000 cm2/(V · s), which is still difficult to meet the electrical performance requirements of high-precision sensing [12].

At the same time, long-term stability in a physiological environment is another major challenge. In a 2021 study published in the ACS series, a team from Northwestern University systematically evaluated the stability of laser-etched graphene sensors in simulated humoral environments (37 °C, pH 7.4 phosphate buffer). The results showed that the surface resistance of the unsurface-modified device rose from 180 Ω/ m 2 to 225 Ω/ m 2 after 30 days of continuous testing, and the conductivity declined by 25% [13]. X-ray photoelectron spectroscopy analysis confirmed that the performance degradation was mainly due to two aspects: water molecule penetration, causing hydroxylation of graphene edges (O/C atom ratio rising from 0.06 to 0.14); Na+ and Cl^{-} ions in the buffer form charge scattering centers on the graphene surface. Especially in a sweat environment containing lactic acid, the interfacial peeling phenomenon is more pronounced, reducing the device's lifespan to less than 21 days and severely restricting long-term applications such as diabetes monitoring [13].

5.2. Prospects

In the face of these challenges, future development should focus on intelligent and closed-loop technological innovation. Artificial intelligence edge computing will significantly enhance signal processing efficiency. Traditional wearable devices rely on cloud servers to process physiological signals and have problems with an average latency of 150ms and a standby power consumption of 5mW. A 2024 systematic review of 171 studies shows that edge computing algorithms based on convolutional neural networks (CNNS) and long short-term memory networks (LSTMS), when integrated into graphene sensing systems, can keep power consumption under 1 milliwatt [14]. These algorithms can filter out motion artifacts and baseline drift in real time, increase signal recognition accuracy to over 96% in cardiovascular monitoring, and reduce transmission energy consumption through a 10:1 data compression ratio to extend device battery life to 14 days, providing lightweight computing power support for portable health monitoring [14].

6. Conclusions

Graphene-based flexible wearable devices are expected to become core bridging carriers for advanced materials and precision medicine in the future. The high electron mobility, super stretchability, and atomically smooth surface derived from the single-atom layer structure of graphene have overcome the limitations of traditional rigid devices in capturing weak physiological signals, human dynamic adaptation, and long-term wearing safety, laying a material foundation for clinical-grade applications.

However, the high cost of CVD preparation and the degradation of electrical conductivity within 30 days in a body fluid environment remain the main bottlenecks for large-scale application. These limitations may be broken through in the future through material modification and process optimization, while deepening the integration of AI edge computing with closed-loop diagnosis and

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treatment systems. Overall, the evolution of this technology will drive the upgrade of the wearable industry, provide solutions for personalized medicine and remote health management, and help the medical system transform towards "prevention first, precise intervention".

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