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Flexible Electronic Skin Based on Graphene and Its Composites

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Abstract:

Flexible electronic skin, as an important part of bionic technology, has a wide range of applications in the fields of wearable devices, intelligent robots, and bionic prostheses. Graphene, as a two-dimensional material with excellent electrical conductivity, mechanical flexibility and chemical stability, shows great potential in flexible electronic skin. This paper reviews recent advances in flexible electronic skin based on graphene and its composites, presenting the unique physicochemical properties of graphene and its advantages in flexible sensor materials. This paper discusses in detail the application of graphene and its composites in flexible sensors, including pressure sensors, humidity sensors, and flexible supercapacitors. This paper summarizes the challenges faced in current research, such as the cost and process complexity of material preparation, increased sensor integration, and issues of long-term stability. In addition, this paper proposes future directions, including the large-scale preparation of low-cost and high-performance graphene materials, the improvement of sensor sensitivity and durability, the optimization of graphene composites, and the realization of multifunctional and integrated flexible e-skin systems. Valuable references are provided to further promote the practical applications of graphene-based flexible electronic skin in the fields of medical monitoring, bionic technology and smart wearable.

Keywords: Graphene; flexible electronic skin; composite material; wearable sensors.

1. Introduction

Flexible electronic skin is a class of electronic devices that mimic the function of human skin and can sensitively sense external tiny stimulation signals, which are widely used in wearable devices, soft robots and smart prostheses. Because of its skin-friendly and easy-to-integrate advantages, it has attracted much attention in the research of the new generation of bionic electronic skin. Flexible sensors as emerging advanced electronic components, its research needs to start from the use of demand, its device assembly methods and adaptive circuit design, is a set of materials, devices, and circuit systems in one of the comprehensive research areas. In the material research of flexible sensors, among many conductive materials, graphene has attracted much attention due to its good physicochemical properties and is widely used in the preparation of sensitive materials for tactile sensors because of its high conductivity, light weight, flexibility and easy modification and processing. However, at this stage, flexible tactile sensors based on graphene materials have failed to realize large-scale applications, because on the one hand, such sensors are still in the early stage of research, and the existing research results are difficult to use in complex and harsh environments due to performance limitations. On the other hand, the problems inherent in tactile sensors, such as susceptibility to interference and complexity of peripheral circuits, have not been effectively solved.

In 2014, James M. Tour's team discovered laser-induced graphene (LIG), which exhibits advantages such as high electrical conductivity, high thermal conductivity, and high specific surface area, providing a single-step processing solution for the preparation of graphene-based devices [1]. Compared with the traditional graphene preparation process, this process has the advantages of a wide range of substrate choices, simple processing steps, and ease of graphical design, which provides a feasible strategy for multifunctional integration, and has widely attracted the interest of researchers in related fields.

The objective of this study is to explore the potential of graphene and its composites for applications in flexible electronic skin. It aims to promote the practical application of graphene-based flexible electronic skin in medical monitoring, intelligent robotics and environmental monitoring by optimizing the material preparation method and enhancing the device's performance. It is committed to solving the current technical challenges, such as long-term stability of the device as well as the integration problems in practical applications, in order to promote the wide application of this technology in the next-generation smart devices.

2. Preparation Methods of Graphene Composites

2.1 Physical Doping

The physical doping method is applicable to a wide range of substrate materials, such as polymers, metals, ceramics with high flexibility. Graphene is mixed with the matrix material by mechanical mixing, ball milling, high-speed shearing, or ultrasonic treatment. Graphene is physically embedded in the matrix during the mixing process, forming a composite material.

Graphene nanosheets, consisting of 10 to 30 layers of graphene layers, are easy to prepare and low cost and are often used in electrochemistry and are generally prepared by physical doping[2].

2.2 Chemical Compound

Through the polymer/graphene composites prepared by methods such as in-situ polymerization, graphene and polymer monomers or oligomers are linked by covalent bonding, and graphene and polymers are connected by chemical bonding that occurs between the layers of polymers and the lamellae, which forms a more stable chemical bond that is not easily broken, and has a stronger force, and the dispersion of graphene in the polymer is better [3].

2.3 Covalent Bond Modification

The negatively charged oxygen-containing functional groups on the surface of GO bind with positively charged substances through electrostatic interactions. Inorganics or polymers can also be inserted into the GO interlayers by interlayer hydrogen bonding, ionic bonding and covalent bonding. These methods can increase their interlayer spacing to facilitate GO exfoliation and dispersion to form GO composites [4]. The covalent bond modification enhances the dispersion of graphene and the bonding strength with the matrix, which contributes to the physical and chemical properties of the composites.

3. Graphene and Its Composites in Flexible Electronic Skins

3.1 Applications in Sensors

3.1.1 rGO Film

The multilayer structure of self-supported rGO films is a piezoresistive effect structure that can realize good performance results, so rGO films based on multilayer structure can be used as sensitive materials for flexible pressure sensors. The multilayer structure can effectively respond to external pressure changes, thus realizing high sensitivity detection performance.At the same time, rGO films can be modified by appropriate modifications to prepare optimized sensitive materials that meet the performance requirements of applications. In the application of wearable devices, pressure sensors usually need to be non-toxic and environmentally friendly, so it is necessary to design a mild and non-toxic rGO film preparation method [5]. At the same time, pressure sensors, as the most basic tactile

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sensors, are often used in wearable devices in large quantities and intensively, while wearable devices also need to take into account the need for portability and ease of use, so it is also necessary to design small, multi-channel, high-precision data acquisition systems adapted to the corresponding pressure sensors.

Compared with traditional flexible pressure sensors, rGO thin films not only have significant advantages in sensitivity and tunability, but also their preparation methods can be customized according to specific needs, making them suitable for a wide range of application environments. Meanwhile, considering the requirements of wearable devices for portability and ease of use, rGO thin films also have unique advantages in designing miniaturized, multi-channel high-precision data acquisition systems.

3.1.2 Mxene/Graphene Composites

Mxene/graphene composites combine the excellent properties of both and show outstanding performance in flexible supercapacitors. Flexible supercapacitors, as energy storage devices, require electrode materials that are not only highly electrochemically active but also need to remain lightweight, flexible, and wear-resistant. Therefore effective design of electrodes with high capacitance and flexibility is essential [6]. Mxene material is integrated into the electrodes in fiber form due to its high electrochemical activity, which effectively enhances the capacitance and flexibility of supercapacitors. This composite material offers significant advantages in terms of fast charging and discharging as well as long cycle life to meet the demand for high power density and long-lasting stability in modern wearable electronics.

MXene has high electrical conductivity while GO is a dielectric material with tunable electronic properties [7]. The flexible LC wireless humidity sensor integrating GO/Mxene composites is based on polyimide as a substrate and the prepared composite as a humidity-sensitive material. Tests show that the sensor can work in the range of 20%-95%RH and has high sensitivity, the sensitivity of the sensor reaches 90.51kHz/%RH at humidity 20%-70%RH, and 651.86kHz/%RH at humidity 70%-95%RHjf. Meanwhile, the response time of the sensor is 6s and has good stability [8].

Compared to conventional flexible sensors, Mxene/graphene composites not only enhance the performance of the sensors, but also provide superior electrochemical stability and structural flexibility, making them suitable for applications in a wide range of complex environments.

3.1.3 Graphene/Polydimethylsiloxane (PDMS) Composites

Flexible pressure sensors prepared from graphene/polydimethylsiloxane (PDMS) composites can detect changes in small pressure aspects of the human body in real-time. Reduced graphene oxide/iron nanowire flexible pressure sensors are well laid out through the overall structural design, transmission electrode configuration and composite pressure-sensitive material composition for the design of flexible pressure sensors. Ultrasonic treatment, self-assembly method and vacuum filtration technique were used to deposit reduced graphene oxide and iron nanowires onto the fabric carrier to construct the composite sensitive layer, respectively. This can effectively improve the deformation of the composite sensitive layer to the pressure applied, which in turn improves the sensitivity of the flexible pressure sensor, so that it can have good flexibility, mechanical properties and sensing properties on the basis of having a composite sensitive layer and modified microstructural layer [9].

3.2 Application in Flexible Electrodes

3.2.1 Graphene/gold Nanoparticle Composites

Graphene/gold nanoparticle composites are widely used in the field of transparent electrodes due to their excellent conductivity and biocompatibility. It is suitable for flexible sensors and displays.

Utilizing the characteristics of carbon nanotubes (CNTs) and graphene such as extremely high specific surface area and good electrical conductivity, the CNTs-rGO materials were mixed, and then the Au nanoparticles were modified on the surface of the CNTs-rGO By electrochemical deposition, the researchers constructed an electrochemical immunosensor based on Au/CNTs-rGO composite nanomaterials for detecting the performance of HBsAg. The results showed that the Au/CNTs-rGO composite nanomaterials have high electrical conductivity, large active specific surface area, and good biocompatibility, which not only can promote the electron transfer ability but also can effectively immobilize more biomolecules, thus improving the performance of the immunosensor [10].

Compared with conventional flexible sensors, graphene/gold nanoparticle composites show higher sensitivity and stability, which is particularly suitable for biomedical applications requiring high accuracy and reliability.

3.2.2 Graphene/polypyrrole (PPy) Composites

Graphene has demonstrated great potential for application in the field of sensors due to its excellent electrochemical properties. However, the application of graphene is limited by its own problems such as curling, agglomeration, interlayer stacking, and poor dispersion. To solve these problems, researchers have significantly improved the electrochemical properties of graphene by compounding it with functional materials such as polypyrrole (PPy). It has been shown that the use of different dopants during the synthesis of polypyrrole changes its surface morphology, physical properties, and charge characteristics, thus improving its electrochemical sensing ability [11]. The conductivity and biocompatibility of polypyrrole make this composite material widely applicable in medical monitoring and bio-signal electrodes. This composite material not only provides enhanced electrochemical responsiveness, but also better biocompatibility, and thus has greater potential for development in the medical field.

3.3 Energy Collection and Storage

3.3.1 Graphene/calcite Composites

Graphene and chalcogenide composites are used to prepare flexible photovoltaic cells to power electronic skin devices by efficiently converting light energy into electricity. With its excellent light absorption ability and flexible tunability, the chalcogenide material can significantly improve the energy conversion efficiency of photovoltaic cells. Graphene, as a transparent conductive electrode, not only improves the electron transport performance of the cell, but also enhances the mechanical flexibility and stability of the device. Compared to conventional materials, photovoltaic cells made of graphene/calcite composites are able to maintain high efficiency under bending and stretching, making them suitable for use in wearable electronics and flexible sensors.

3.3.2 Graphene/Polyvinylidene Fluoride (PVDF) Composites

Graphene and polyvinylidene fluoride (PVDF) composites can be used in flexible friction nanogenerators (TENGs) to generate electricity through friction between skin and clothing.PVDF is a piezoelectric material capable of generating an electrical charge when subjected to mechanical stress, and the addition of graphene enhances its conductivity and mechanical flexibility. Such composites can not only effectively harvest energy from human movement, but also utilize mechanical energy from the environment to provide a continuous power supply for low-power electronic skin devices. This technology is particularly suitable for the field of wearable devices to realize self-powered systems with no or few batteries.

4. Field of Application

4.1 Medical Monitoring

Electronic skins integrated with graphene and its composites can be used for physiological parameter detection, such as real-time detection of heart rate, blood pressure, respiratory rate and other physiological parameters. These sensors are highly sensitive and accurate and can be applied for continuous health monitoring and clinical diagnosis.

Due to the high conductivity and biocompatibility of graphene, the flexible electronic skin can be used for non-invasive diagnostics and health monitoring, such as non-invasive blood glucose monitoring, skin conductivity analysis, and other health monitoring, which can help in early disease detection and personal health management.

4.2 Human-computer Interaction (HCI)

Flexible sensors made of graphene material can be attached to the human skin to sense external pressure signals, and they are widely used in the field of human-computer interaction because of their wide sensing range, short response time, high sensitivity and durability [12]. Shi et al[13] developed a soft robot with ultrasonic localization and multimodal sensing capability, which simulates the sensing function of human skin through tactile sensing sensors The pneumatic robot has human vision (ultrasonic sensing) and tactile sensing (flexible sensing), and can recognize the shape, material, size and hardness of objects. It can recognize the shape, material, size and hardness of the object. It has good human simulation visualization and tactile cognition ability.

Flexible electronic skin made of graphene material can be integrated into wearable devices and smart clothing for motion monitoring, posture detection, and even emotion recognition to enhance user experience and interactive functions. The human-machine interface enables machines to serve humans more efficiently and accurately and is a key technology for realizing rehabilitation treatment for the disabled and better control of robots, prosthetics, surgical instruments, virtual reality, and other devices. Electronic skin enhances the interaction function of the human-machine interface, which can effectively convert human commands into machine-recognizable signals, and especially excels in the operation of close contact and expression of information. Vision-based recognition is currently a common method for human-machine interfaces. However, visual perception alone makes it difficult to handle operations involving close contact and some expression of information. The electronic skin enables a tight connection and ensures a good fit to the contact surface.The precise sensing and actuation capabilities of the e-skin allow for long-term, multi-point monitoring and manipulation. This technology provides a highly wearable and reliable solution to meet the demands of complex tasks.

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4.3 Other Applications

Graphene-based flexible electronic skins can be used as highly sensitive gas sensors for detecting harmful gases and pollutants in the environment, such as CO2, NOx, and NH3 , and thus be used for environmental monitoring and safety alerts[14].

The high conductivity and transparency of graphene materials make them suitable for the manufacture of flexible displays. These displays can be applied to devices such as bendable screens and e-paper, expanding the application scenarios of smart devices. These application areas demonstrate the versatility and cutting edge of graphene in flexible electronic skin, driving technological innovation and development in various fields.

5. Conclusion

Graphene is an ideal material for flexible electronic skin sensors due to its excellent conductivity, flexibility and lightweight properties.

Various preparation methods such as physical doping, chemical compounding, metal oxide modification and electron beam etching have been used to enhance the properties of graphene composites. These methods play a key role in the dispersion, stability and functionality of the material.

By compositing graphene with other materials (e.g., MXene, PDMS, ZnO), the performance of the sensors can be significantly improved, including sensitivity, responsiveness, and environmental adaptability. The application of these composites in flexible electronic skin demonstrates superior performance in humidity, pressure and gas detection. The graphene-based flexible electronic skin shows good adaptability under various environmental conditions (e.g., temperature, humidity, chemical corrosion, etc.). Its stability and reliability in extreme environments can be further enhanced by optimizing the material formulation and improving the preparation process.

Graphene and its composites not only show excellent performance in flexible sensors, but also play a role in flexible electrodes and other electronic devices. Especially in transparent conductive electrodes and high sensitivity sensors, the application of graphene composites provides more design possibilities and technological breakthroughs.

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