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Prospects of Research and Application Graphene-Based Flexible Pressure Sensors

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Abstract. As a new direction of electronic technology, flexible electronics has enormous possibilities of use in the areas of wearable devices, biomedical monitoring, human-machine interaction, robotic tactile sensing, and artificial intelligence. Graphene because of its outstanding physicochemical properties has set out to be a desirable material in the production of high-performance flexural pressure sensors. It has been reported in this paper that, in the recent past, the field of graphene-based flexible pressure sensors has made tremendous advancements in terms of high sensitivity, broad detection, and long-term stability. The paper has systematically reviewed these advances and offered a detailed discussion of how these advances have been done, the underlying sensing mechanism of these sensors, their performance features, and potential applications. Yet, there are still some problems, such as the complexity of fabrication, the rather high costs, and mass production issues. The future technological advancement will be aimed at the enhancement of mass production methods, development of multi-modal sensing, intelligent algorithms, and biocompatibility. The developments will thrust the grazable graphene-based flexible pressure sensors, which are currently in the laboratory research stage, into the industry.

Keywords: Graphene, flexible pressure sensor, fabrication process

1. Introduction

Several years back, the flexible electronics technology attracted huge interest among scholars and the industry due to its critical direction of development in the electronic information industry. Flexible electronics have better flexibility, extensibility, and biocompatibility than standard rigorous electronic systems, thus operating in challenging application environments. They portray tremendous usage capacity in various circumstances, including wearables, biomedical systems, human computer interaction, robot sensing, and the artificial intelligence.

Being the fundamental part of work of flexible electronic systems the work of flexible pressure sensors directly defines the perceptual accuracy and pragmatics of the system. A perfect flexible pressure sensor must have high sensitivity, wide range of detecting, fast response, high stability, low prices, and easy to manufacture.

Since its first time discovery in 2004 by Professors Geim and Novoselov at the University of Manchester [1], graphene has become a quick research center in materials science and nanotechnology owing to its honeycomb crystal structure of a two dimensional structure and

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outstanding physicochemical characteristics. With a high mechanical strength that is ultra-high, excellent electrical conductivity, stretchable characteristics alongside biocompatibility, graphene is a good material in construction of high-performance of flexible pressure sensor.

Graphene pressure sensors Flexible pressure sensors made of graphene have high sensitivity to detect very small changes in pressure, with detection limits of low as 0.11 kPa and response times of just a few milliseconds, and have great stability and reproducibility. These exceptional characteristics give graphene-based flexible pressure sensors a great potential of application in various advanced fields:

Graphene-based flexible pressure sensors, in wearable technology, can be fitted in the clothes of garments, wristbands, smartwatch etc. as this enables real time reading of the physiological signals like pulse, breathing and blood pressure, an important data source that aids personal health management.

In biomedical measurements, flexible pressure sensors are invented, and made to be perfectly conformed along the skin surfaces or organ surfaces to allow accurate tracking of physiological activity and provide new methods of diagnostic and treatment.

Graphene-based flexible pressure sensors can also allow more natural and traditional user experiences in human-machine interaction, including providing flexible touchscreen, electronic skin and virtual reality devices.

A recent market research shows that the world graphene market is projected to increase at a CAGR of 41.22 percent between 2025 and 2030 to USD 9.28 billion in 2030 [2]. Electronics and tele-communications market is estimated as the leading market with the rising demand of flexible displays, transistors and sensors. Such a fast development points to the great potential of the graphene-based technologies in the nearest future [3].

This paper methodically presents an overview of the existing research position of graphene-based flexible pressure sensor, its fabrication, principle of operation, the characteristics of its performance, and potential application of the sensors. The study does not only contribute to the progress of flexible electronics but also provides new technical possibilities to free hypersensitive needs in human health control, human-machine interface and intelligent production with great scientific and practical importance.

2. Preparation of graphene materials preparation of graphene materials

The following methods have been employed in preparing graphene materials.

2.1. Preparation of Graphene Oxide (GO)

Graphene oxide is a vital enabler of the graphene-based materials and so, it is important to note that, the creation of graphene oxide will directly affect the functionality of the end sensors. Today the modified Hummers method is the most used one when it comes to the synthesis of GO. This is a process, which involves the oxidation of natural graphite using powerful acids to form oxygen functional groups (hydroxyl, carboxyl and epoxy groups) to counteract this, increasing the distance between the interlayers and ensuring a reducing reaction will take place later.

Garcia Nunez et al. [4] used the modified Hummers technique to prepare GO, which was then vacuum filtered into transparent, flexible, graphene films. Studies show that the proper optimisation of oxidation time, temperature, and dosage of the oxidant is effective in regulating the level of oxidation and size of flakes of GO hence determining the operation of the end sensor.

The preparation of Reduced Graphene Oxide (rGO) will be performed as illustrated below.

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Graphene pressure sensors can be viewed as using reduced graphene oxide in the core of the sensor. Ordinary methods of reduction are chemical reduction, thermal reduction, photoreduction and electrochemical reduction. It is the chemical diminishing technique that is widely used because of its simplicity and the reduced cost.

2.2. Green preparation technique breakthrough: vitamin C reduction process

The research findings by Tang et al. [5]. can be used in the preparation technology of graphene-based pressure sensors. The work in 2024 is a significant advance in the principle of the green chemistry. Following the conventional harmful hydrazines agents, the team applied vitamin C as the reducing agent to effectively produce reduced grapehene oxide (rGO).

In practice, this technology was very impressive in performance. The sensitivity of sensor was 2297.47 kPa^{-1}, which is way beyond performance levels of traditional preparation methods. Additionally, biocompatibility is excellent due to the entire elimination of toxic reagents, and it remains a perfect solution to the use of biomedical and wearable devices. The sensor is also provided with high flexibility and stretchability, which provides it with an advantage in usage, as the structural design takes the form of fabric.

Most recently, a new design of smart material was published by employing graphene paraffin microspheres of composite [6]. It is an intelligent design to control the performance of sensors, offering a new approach that provides a different strategy to this subtle work.

Nonetheless, there are also some limitations portrayed by the technique. First, compared to other chemical reducing agents, vitamin C might have lower reduction efficiency as reducing agen, which in some degree affects the effectiveness of the process of preparation. Secondly, vitamin C is relatively expensive, which makes the production of the product prohibitive. Lastly, the intensive manufacturing of green reduction process is yet to be optimised further to fulfil industrial production needs.

2.3. Uses of laser micro/nanofabrication technology: ultraviolet laser-induced graphene

Another important integration of micro-nano fabrication technology to graphene sensors is the so-called ultraviolet laser-induced graphene (LIG) technology, which was developed by Tsinghua University in 2024, and is an innovation in the application of 3D carbide-structured graphene fabrication directly onto polymer substrates via a one-step manufacturing process. This solvent-free, template-free regime of making graphene makes life considerably easier in the usual processes of making graphene, providing a new route to quick sensor fabrication.

The real-life consequences of this technology are amazing. The sensor has sensitivity of 3.047 kPa -1, which, although not as high as the one obtained through green reduction techniques, is an excellent sensor in the lasser fabrication techniques. To a greater degree, the given method will allow controlling nanoscale 3D structures specifically, providing a new opportunity to optimize the operation of sensors. There is also significant improvement on production efficiency and minimization of fabrication cycles with the laser direct writing process which lays the foundation of mass production.

Nevertheless, the laser-produced graphene technology has limitations: the laser scanning distance restricts the size of a single fabrication cycle, making large-scale sensor fabrication challenging.

Very recently, scalable preparation was introduced via vapor-induced porosity on graphene/PDMS nanocomposites [7], achieving high compressibility and a super wide dynamic response range.

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The technology involved in the synthesis of monolayer graphene is coming into a critical threshold in the year 2025 and chemical vapor deposition (CVD) is the leading technology in the production of high quality monolayer graphene at commercial levels [8]. The large players in the industry like Graphenea and GrollTex are also ramping up wire-based manufacturing lines on the basis of CVD in response to electronic, sensing, and photonics needs. Plasma-enhanced CVD, and molecular beam epitrophy are also under consideration based on the factor of reducing the synthesis temperature and control of the property of layers.

3. The working principle of graphene-based flexible pressure sensors

Using the example of the research by Zheng et al. [9] in 2020, they have created a piezoresistive-based piezoresistive effect that is graphene-based wearable physical sensor. Such a porous structure will be formed by adding graphene with polydimethylsiloxane (PDMS) in order to make a porous structure, which will be compressed under pressure. This brings variations in the contact area and distance between the graphene layers and detection of pressure can be done by observing the resistance variations. This is a performance of 30 milliseconds response time and a detection threshold of less than 1 Passel, which proves the piezoresistive effect to be better than other detection methods in terms of high sensitivity in pressure detection.

The optimization of sensor design has been made possible by using a serpentinelike shaped graphene piezoresistor [10], with a maximum sensitivity of 24.50 mV/psi and an extremely low nonlinearity rate of 0.06 FSS in the 0-3 psi range.

The other important mechanism is the capacitive effect that works on the principle of changing the value of the capacitance by modifying the pressure on the electrode or dielectric constant. The dielectric layer thickness is also reduced when the dielectric is externally compressed and forces the electrode gap. As per the capacitance formula, C=ε0 A0E A/ d, the value of capacitance grows in line with the capacitance formula. This mechanism was used in a study described in ACS Nano in 2024 and a biomimetic ionic skin capacitive pressure sensor was developed. When pressure is applied, change in thicknesses of dielectric layers alters the values of capacitance. The sensor has a sensitivity of 8.5 kPa^{-1} and a response time of only 0.01 milliseconds, and it is capable of operating over the dynamic range of 0.1 -100 kPa. Together with the deep learning algorithms to reconstruct the pressure distribution, it provides error with less than 3 percent, providing new solutions in bionic touch sense.

Yang et al. [11] made a flexible high sensitive electronic skin by applying three dimensional conformal graphene microstructures. This sensor uses the principle of capacitive effect which saw it attain 2.1 kPa^{-1} sensitivity in a pressure range of 0-2 kPa, but gave it sensitivity enough to detect small pressure changes.

It was created based on the cross-laminated 2D graphene film and 3D graphene foam to produce a novel biomimetic tactile-pressure sensor [12]. This sensor was more accurate and had a wide range measurement at the same time with the measurement interval of 0- 2 N and 2-40 N. When the force was 0 -2 N, the sensitivity value was 472.2C with force resolution being 0.01N and when the force was 2-40 N the sensitivity was 5.05C with the force resolution of 1N. It is a dual-range design that has found tremendous use in medical equipment and artificial limbs.

A highly sensitive graphene MEMS pressure sensor based on the membrane and cross-beam with cavity (MCBC) composite structure was created [13], balancing sensitivity and natural frequency for extended pressure range testing.

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4. Current applications

4.1. Wearable devices

Professor Qu Lijun and Professor Tian Mingwei of the College of Textiles and Clothing at Qingdao University invented a flexible multifunctional sensor relying on laser induced graphene in the field of wearable technology. They layered laser induced graphene on thin sheets of PDMS that were woven into elastic sports fabric of cotton. A vertically arranged pressure sensor was created with a two-layer pressure sensor in the form of two lasers-oriented layers. The sensor integrated into volleyball uniforms can monitor sports data such as spike load and player position, providing a scientific basis for training and match strategy. Not only does it help athletes to get accurate training and training on how to improve their performance, but it also offers scientific basis to coaches regarding how to formulate the strategy of the matches they are to play. At the same time, it enables analysis and simultaneous gathering of sports data in real-time. It is cheap and this makes it appropriate to use it on a large scale.

The piezoresistive sensor that has been created by Professor Yaping Zhao and his team of Shanghai Jiao Tong University uses a carbon aerogel based on graphene as the sensing material with a layer of superhydrophobic pyramidal structures, a layer of ecoflex rubber that functions as the elastic support, and a layer of the electrode that is made out of superhydrophobic graphene-nylon fabrics. This sensor has a high sensitivity and a wide linear range, which means that it is able to monitor physiological parameters of human beings in real-time such as breathing, talking or activity. This sensor has high sensitivity and a wide linear range, enabling real-time monitoring of human physiological parameters such as breathing and movement, with superhydrophobicity, breathability, and biocompatibility.

Recent developments in textile sensors have shown positive results [14], with graphene-impregnated nonwoven textile piezoresistive sensors demonstrating low initial resistance (≈0.15 kΩ) and high sensitivity (10.5 kPa^{-1}).

4.2. Biomedical monitoring

The 2D-BioPAD project of the EU Graphene Flagship has designed a bedside decision help tool based on graphene. Through a combination of graphene field-effect transistors, microfluidics technology, it can be used to detect five biomarkers in blood or cerebrospinal fluid to diagnose early Alzheimer's disease with over 95 percent accuracy and a detection sensitivity of 0.1 pM.

Graphene-based sensors have contributed greatly to the field of cardiac monitoring, as well [15]. The sensors use the special mechanical, electrical, thermal as well as optical characteristics of graphene to improve the performance of cardiac sensors and actuators. Nanotechnology based on graphene in the cardio field has provided some of the most entirely new technological possibilities and has transformed the applications of numerous biomedical fields.

A flexible pressure sensor with ink-printed porous graphene was developed for continuous cardiovascular status monitoring [16], accurately detecting vital signs such as heart rate, respiratory rate, and blood pressure.

4.3. Human-machine interaction

In the human-machinery interaction, a flexible 3D structure electrostatic pressure sensor was proposed by Professor Gu Guoying in Shanghai Jiao Tong University. They incorporated hydrogel

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lattices in origami-like elastic structures by using cryogenic 3D printing. This sensor is based on the principles of supercapacitive and thus it presents wide-range linear response, high-resolution detection as well as rapid response time under extreme loads. Fits the wearable human-machine interface with tactile interaction modes providing rich control interfaces.

The pressure / stress sensor graphene/P(VDF-TrFE) heterostructure sensor invented in Clemson University research paper involves the use of a new type of heterostructure made of graphene. This fully flexible, high-sensitivity, and biocompatible sensor can be attached to human skin without an external power source, identifying multi-joint movements, standing, walking, and running. Its fast reaction (milliseconds) and sportswear fabricibility characteristics make it a preference choice when it comes to actual wearable concepts, which will provide a fresh technical answer to in vivo medical monitoring.

Graphene and polyurethane sponge piezoresistive haptic glove object recognition haptic glove was created [17]. Integrating machine learning techniques (Residual Network), the system recognized 15 objects with a recognition accuracy of 95.67 percent, which shows that the flexible tactile sensors can be used in new applications as well.

A combination of artificial intelligence and the graphene-based sensors is one potential way forward in the future [18]. Recently, the use of an extreme learning machine (ELM) in near-real-time kidney monitoring through urine neutrophil gelatinase-associated lipocalin (NGAL) detectionusing a 3D graphene electrode was demonstrated. This study has indicated the possibility of reducing the size of AI-enhanced sensors to make them useful in actual implementation.

5. Challenges and development

5.1. Shortcomings in the existing research

Although the material design, performance optimisation and applications expansion of graphene-based flexible pressure sensor has gone a long way, there are still lot of issues to be dealt with before the gap between laboratory research and application can be eaten. First, it is expensive and sophisticated to manufacture large quantities of fabricated materials, and this is a significant constraint to mass production. Majority of the high performance sensors that exist today are based on the high accuracy methods that include chemical vapour deposition and laser-based methods. Besides requiring large amounts of investments to acquire expensive equipment, these methods also have strict demands on operating conditions and process parameters. As a result, the price per unit area is still prohibitively expensive, and does not match low-priced sensor requirements in other areas of the consumer electronics and healthcare industries. Secondly, the stability of these sensors and their adaptability to the environment are supposed to be improved in the long run. The Graphene materials tend to structurally wear and experience degradation in a damp and high temperature or chemically corrosive environment. These problems drastically reduce sensor dependability and service-life of the sensor in practice.

5.2. New directions of development

To address these drawbacks in the existing research, future graphene-based flexible pressure sensor progress will go towards simplified methods of fabricating and producing its products, optimisation of the product-function, and increasing its uses.In relation to fabrication and manufacturing processes, the future of the research will be aimed at ensuring the development of low cost and scalable production methods. As an example, roll-to-roll manufacturing along with improved plasma-enhanced chemical vapour deposition is expected to bring the cost of production by a factor of five, by 2028, and at the same time raise yield rates to more than 85.Low cost fabrication processes such as solution processing and inkjet printing will also be further developed and used. Material optimization In design of inks, better approaches to graphene composites and heterostructures will be developed. In large-scale production and patterning High-precision Ink Ink refinements The production of graphene sensors will be constructed with high precision and at large scale. This is in addition to designing high sensitivity and selectivity sensing interfaces through modification of graphene with metal-organizational frameworks (MOFs) and metal phthalocyanines (MPc). Simultaneously, composite systems incorporating graphene with new two-dimensional compounds like TMDs (transition metal dichalcogenides) and MXenes will be considered in order to optimize the performance by the synergy effect.

6. Conclusion

In this paper, the systematic review of the present state of research regarding graphene-based types of flexible pressure sensors is provided, including their fabrication, mechanism of sensing, the properties of performance, and the potential of their use. Studies reveal that flexible pressure sensors based on graphene have a high potential of application in wearable, biomedical monitoring and human-machine interaction subjects.

However, there are still certain issues with fabrication, high costs, and the problems with mass production, which are still suitable challenges of existing research. Further optimisation of the fabrication in future studies, cheaper manufacturing, higher stability performance, multifunctional integration, and more areas of application should be made to the development of flexible electronics. The paper offers theoretical background and technical advice towards the advocacy of experimental use of graphene-based flexible pressure sensors.

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