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ELECTROMECHANICAL PRESSURE SENSORS BASED ON GRAPHENE: A REVIEW

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ABSTRACT
Nanotechnology can revolutionize the sensor industry by introducing specific nanomaterials to work as sensing elements. Graphene, a two-dimensional carbon allotrope with exceptional electrical and mechanical properties, has emerged as a promising material for developing high-performance pressure sensors. Graphene-based pressure sensors offer significant advantages over traditional sensors, including high sensitivity, wide dynamic range, fast response time, and flexibility. This paper aims to deliver a review on the fundamental mechanisms underlying graphene-based pressure sensors, which includes piezoresistive, capacitive, and field-effect transistor (FET). Recent advancements in graphene-based pressure sensors have opened up new possibilities in various fields, including healthcare, electronics, and robotics. Here, we will highlight these emerging applications and explore the potential future developments of this technology.

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Introduction

Pressure sensors function by transforming physical pressure into an electrical signal. This transformation occurs via a pressure-sensitive component that deforms under pressure, causing a change in its electrical characteristics. The key components of a pressure sensor include a sensitive element, a transducer, and signal conditioning circuits. The sensitive element is the main part that directly interacts with the pressure. It basically transforms the applied pressure into a quantifiable physical alteration, such as a modification in resistance, capacitance, or inductance. The function of the transducer is to transform the physical change detected by the sensitive element into an electrical signal. The electrical signal received from the transducer is amplified and processed by the signal conditioning circuitry, making it suitable for subsequent processing or visualization. There is also the housing that protects the internal units of the pressure sensor and provides a mounting interface. It may also include features for electrical connections and environmental sealing. Figure 1 shows a schematic diagram of a pressure sensor using a piezoelectric diaphragm. In this review, we will explore the use of graphene as a nanomaterial in advancing pressure sensor technology, highlighting mechanisms, and applications that are shaping the future of pressure sensing [1,2].

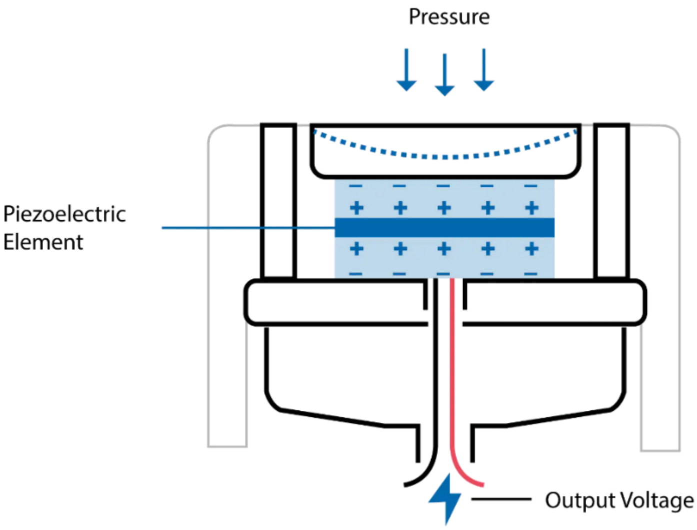

Figure 1. schematic diagram of a pressure sensor using a piezoelectric diaphragm [3]

Methods

When it comes to choosing materials for pressure sensors, there are a number of requirements that must be considered. While providing high precision and durability, these materials must endure mechanical stress, fluctuations in temperature, and exposure to corrosive conditions. Figure 2 shows schematic diagrams of pressure sensors with different mechanisms. Piezoelectric materials are commonly used in pressure sensors. When subjected to mechanical stress, the piezoelectric element will deform, producing a proportional electrical signal that can be measured and correlated to the applied pressure [4,5]. The piezoelectric materials that are mostly used in pressure sensors including Quartz (SiO_2), lead zirconate titanate (PZT), and polyvinylidene fluoride (PVDF). The important features of these materials are the high sensitivity, accuracy, fast response time, and suitability for dynamic pressure measurements. However, moderate pressure ranges and sensitivity to temperature, especially in PZT, are the main limitations of piezoelectric materials [6].

In strain-gauge-based pressure sensors or capacitive sensors, metallic materials with stable mechanical properties are used [7]. Metallic materials such as stainless steel, copper and alloy steel are known for their robustness and ease of fabrication. Due to their resistance to corrosion, high strength, and durability, these materials are included in sensors that are used in harsh environments, such as those in the automotive, aerospace, and oil and gas industries [7,8]. Despite their advantages, metallic materials have relatively lower sensitivity compared to piezoelectric materials, limited flexibility and suitability for miniature sensors.

Silicon, a common semiconductor material, is extensively used in modern pressure sensors, especially within microelectromechanical systems (MEMS) technology [9]. Silicon-based sensors leverage the piezoresistive effect, a phenomenon where a semiconductor's electrical resistance is altered by mechanical stress [9–11]. MEMS-based pressure sensors often combine the sensing element and electronics into a single, miniature package, resulting in compact and affordable sensor designs. Gallium Arsenide (GaAs) is another semiconductor material that is sometimes used in high-frequency or high-temperature environments, thanks to its higher electron mobility compared to silicon. The practical use of semiconductors in pressure sensors is limited due to their susceptibility to environmental factors (e.g., temperature and humidity) and complexity of manufacturing processes [12–15].

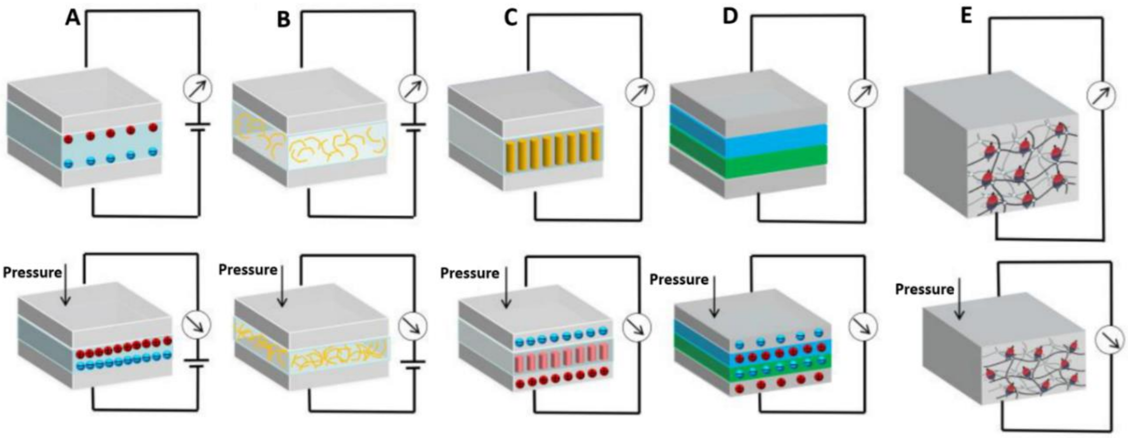

Figure 2. Different working principles of pressure sensors with: (A) Capacitive; (B) Piezoresistive; (C) Piezoelectric; (D) Triboelectric; (E) Magnetoelastic. Reprinted/adapted with permission from Ref. [16] . Copyright 2023, Multidisciplinary Digital Publishing Institute (MDPI).

Polymers are becoming increasingly considered for pressure sensor applications due to their flexibility, lightweight nature, and ease of fabrication. Specifically, piezoresistive polymers and conductive elastomers are gaining popularity in low-cost and flexible pressure sensing applications [16–18]. Polyimide (PI) is often used in flexible sensor designs. When it is combined with other materials like conductive polymers or nanomaterials (e.g., Carbon Nanotubes (CNTs)), sensor's sensitivity can be enhanced [17,18]. One limitation of polymers is their lower accuracy compared to other materials such as silicon or piezoelectric materials.

Using conventional materials in traditional pressure sensing, such as piezoelectric and capacitive sensors, have limitations in terms of sensitivity, size, response time and durability. Nanomaterials, with their unique properties at the nanoscale, offer a solution to these challenges, enabling the development of highly sensitive, compact, and robust pressure sensors [19]. Nanomaterials, including carbon-based nanomaterials (such as graphene and carbon nanotubes), exhibit exceptional mechanical, electrical, and thermal properties that make them ideal for enhancing pressure sensor performance. The high surface-to-volume ratio these nanomaterials allow for the detection minute pressure change [20]. In addition, tunable electrical conductivities, and remarkable mechanical strengths allow for greater sensitivity to small changes in pressure, faster response times, and improved resilience to harsh operating conditions.

Results and Discussion

Why Graphene?

Graphene is a single layer of carbon atoms arranged in a two-dimensional (2D) hexagonal lattice, resembling a honeycomb structure. It serves as the fundamental unit for other carbon allotropes like graphite, carbon nanotubes, and fullerenes [21]. In graphene, each carbon atom forms covalent bonds with three neighbouring carbon atoms, while the fourth outer-shell electron is involved in a delocalized π-bond [22]. This delocalization of electrons is key to graphene's exceptional electronic properties. Graphene was first isolated in 2004 by physicists Andre Geim and Konstantin Novoselov at the University of Manchester, who were awarded the Nobel Prize in Physics in 2010 for their pioneering work. They used a simple method known as mechanical exfoliation, or "scotch tape method," to peel graphene layers from a piece of graphite. This breakthrough sparked a global wave of research into graphene’s properties and potential applications [22–24].

Graphene is widely used in pressure sensors because of its unique combination of properties that make it highly sensitive, flexible, and efficient in detecting even small changes in pressure. Properties of graphene are presented in Table 1. Since graphene is considered as an excellent conductor of electricity, meaning that its electrical resistance changes significantly under mechanical stress. This results in accurate and precise measurements. Thanks to its extremely large surface area (~2630 m^2/g), graphene provides a large number of active sites that react to any external pressure. Thanks to its extremely surface area graphene provides a large number of active sites that interact any external pressure [23]. This high surface area enhances the sensitivity of graphene-based sensors to small changes in pressure. In addition, Graphene is renowned for its extraordinary strength and flexibility, making it able to endure deformation and pressure. Such characteristics would enable the realisation of wearable devices, flexible electronics, and soft robotics [19,25].

Table 1. Properties of Graphene

Parameter	Value
Thickness	0.32 nm
Specific Surface Area	~ 2600 m^2/g
Electron Mobility	200,000 cm^2/Vs
Thermal Conductivity	3000–5000 Wm/K
Optical Transparency	97.4%
Young’s Modulus	1 TPa

Numerous studies have been devoted to exploiting graphene in pressure sensors. The foundational work by [26] outlines the remarkable potential of graphene as an ultrathin material for pressure sensors, emphasizing its mechanical robustness, sensitivity, and cost-effectiveness compared to other materials. The authors highlight the advantages of suspended graphene as an ideal sensing membrane, which allows for enhanced molecular sensitivity and interface accessibility, setting the stage for subsequent advancements in the field. Smith [27] has reported on the electromechanical piezoresistive sensor using suspended graphene membranes, revealing that these sensors exhibit sensitivity levels significantly higher than traditional MEMS sensors. Piezoresistive pressure sensors based on graphene membranes have been demonstrated by investigating the influence of biaxial piezoresistive properties on the charge-carrier density and mobility in strained graphene [28].

Mechanisms of Graphene Pressure Sensors

The development of highly sensitive, flexible and robust graphene-based pressure sensors requires consideration of many factors. Factors such as fabrication techniques, graphene quality, device architecture, and materials selection are just a few to name. To wisely exploit the inherent properties of graphene, it is crucial to understand the mechanism by which a graphene-based sensor operates.

Piezoresistive Mechanism

When mechanical stress is applied to a material, its electrical resistivity changes [29]. This phenomenon is called the piezoresistive effect. Graphene-based pressure sensors primarily function relying on the piezoresistive principle, where the material's electrical resistance is altered by mechanical deformation [30]. After applying pressure, the lattice of graphene undergoes strain, altering the electron mobility and thus changing the resistance. In other words, pressure modifies the band structure of graphene, changing the distance between carbon atoms, which may change the overlap of p orbitals, and thus affect conductivity. For example, the resonance frequency of a drum-based graphene pressure sensor is shown in Figure 3. It can be seen even for such small drum how sensitive is the graphene membrane to the applied pressure. Such change in resistance can be measured to determine the applied pressure. One of the distinctive features of using the piezoresistive effect in graphene pressure sensors is that it allows for high sensitivity to pressure changes [5,31]. Even slight fluctuations in stress can lead to substantial changes in resistance, allowing these sensors to detect even the smallest pressure variations.

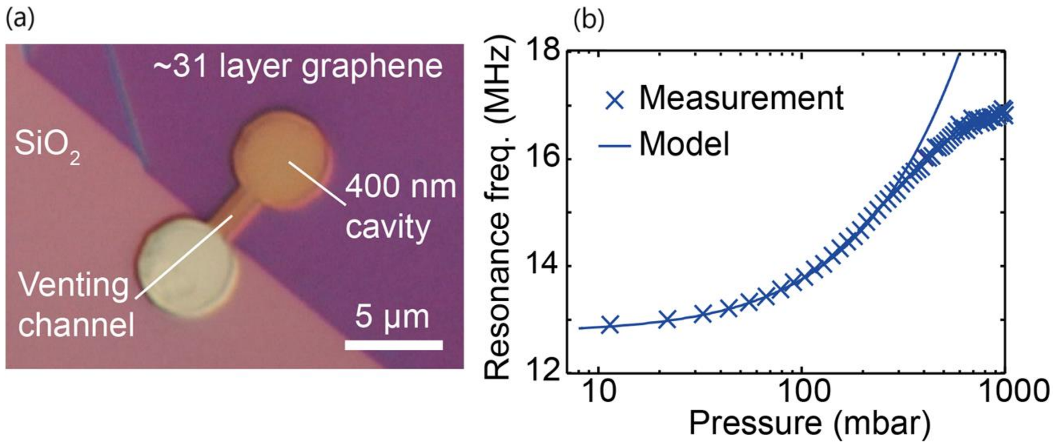

Figure 3. Graphene-based piezoresistive pressure sensors. (a) Optical image of graphene flake in a drum configuration; (b) The resonance frequency of the graphene sensor as a function of pressure. Reprinted with permission from [32]. Copyright 2015 American Chemical Society (ACS).

Capacitive Mechanism

A typical capacitive pressure sensor consists of two conductive plates separated by a dielectric material [8]. In the case of graphene-based sensors, one of the plates may be made from graphene itself, while the other can be another conductive material [33,34]. The dielectric layer can also be a polymer or another non-conductive material. When external pressure is applied to the sensor, it affects the distance between these two plates. In a flexible sensor setup, an increase in pressure can compress the dielectric material or cause deformation in one of the graphene layers, altering the gap. The change in capacitance is proportional to the applied pressure, allowing for precise pressure measurements, see Figure 4. Various electronic circuits, such as capacitance measurement circuits can be used to measure the changes in capacitance. Ultimately, these changes are then converted into a measurable electrical signal that correlates directly to the applied pressure [35–37].

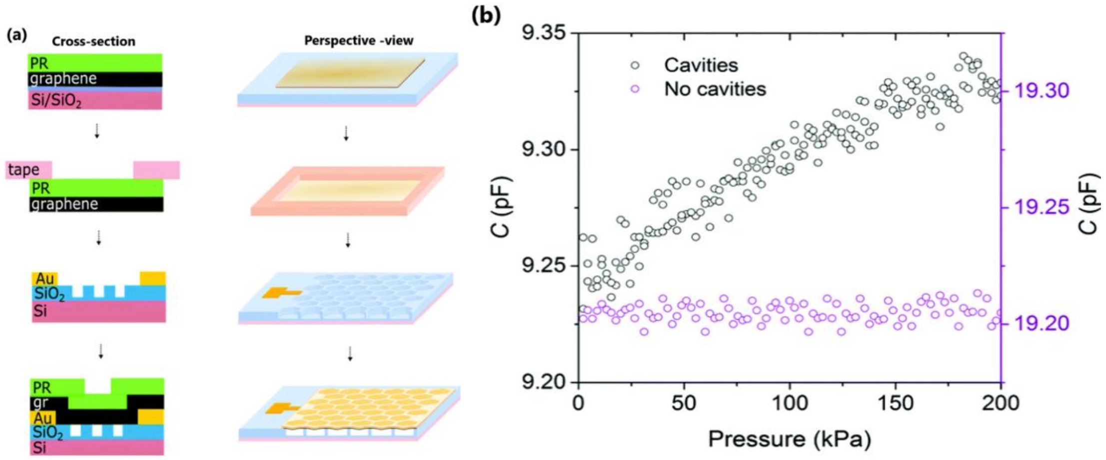

Figure 4. Graphene–polymer capacitive pressure sensor. (a) Schematic of fabrication process; (b) Pressure versus capacitance measurements of the sensor with and without cavities. Reprinted with permission from [37]. Copyright 2021 The Royal Society of Chemistry (RSC)

Piezoelectric Mechanism

Piezoelectricity describes the generation of an electrical charge in response to applied mechanical stress. This phenomenon occurs in materials lacking a centre of symmetry in their crystal structure [6]. When such materials undergo mechanical stress, their crystal lattice distorts, leading to the separation of positive and negative charges and the generation of an electric potential. In these sensors, the applied pressure generates a voltage across the material, which can be measured to determine the pressure [38,39]. Although pure graphene is not piezoelectric, functionalized graphene or graphene-based composites can exhibit piezoelectric properties, see Figure 5. It appears that in a sensor made of graphene only, under a pressure of 0.4 N with an applied voltage of 1 V, no change in current has been recorded (Figure 5.a). This indicates that no distortion in graphene lattice has occurred. In nanowire/graphene pressure sensors, the current decreases quickly and exhibits a negative response as seen in Figure 5.b. Piezoelectric mechanism is particularly useful for applications requiring high sensitivity and fast response times.

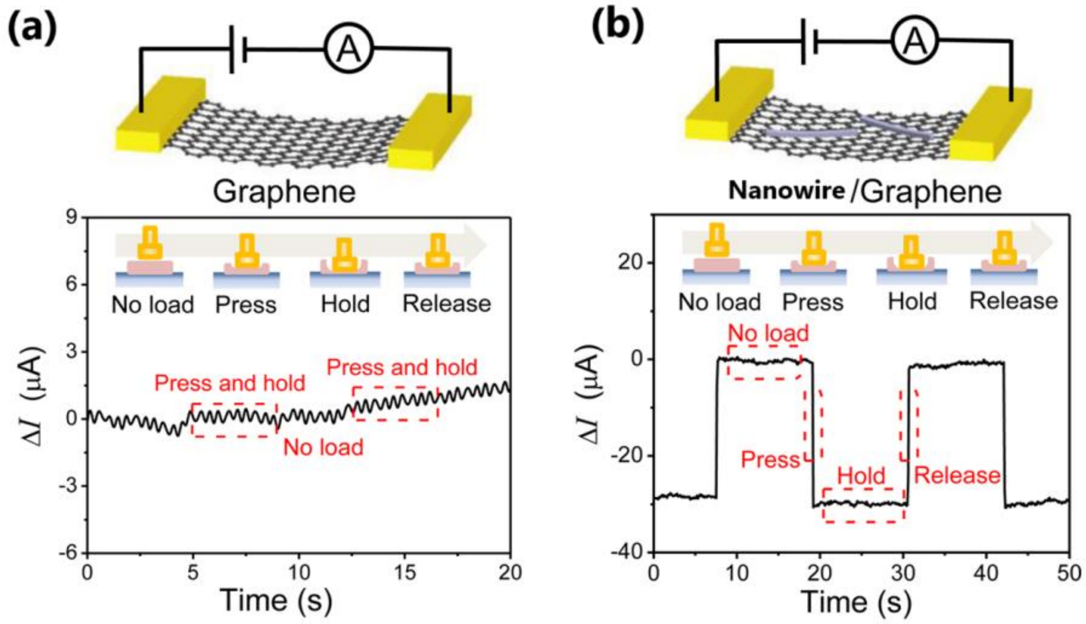

Figure 5. Graphene–based piezoelectric pressure sensor. Pressure response has been obtained by measuring absolute variation of electronic current (ΔI = IP − I0, where I0 and IP denote the current without and with applied pressure, respectively). (a) Response of pure sensor of graphene only; (b) Response of nanowire/graphene sensors. Reprinted with permission from [38]. Copyright 2017 American Chemical Society (ACS).

Field-Effect Transistor (FET)

The fundamental principle underlying a graphene field-effect transistor (GFET) involves the modulation of electrical current in response to pressure fluctuations [40–42]. In a FET configuration, a graphene-based conductive channel is established, where the flow of charge carriers (electrons or holes) is regulated by an electric field applied through a gate electrode. In other words, graphene serves as the conducting channel in a FET configuration, where the current flow is governed by an applied voltage at the gate terminal. When pressure is applied to the graphene layer, the mechanical deformation induces changes in the charge carrier density and mobility within the graphene, as shown in Figure 6. These alterations result in variations in the graphene channel's conductivity, which can be measured as fluctuations in output current or voltage (inset in Figure 6.b), thus enabling pressure detection. Integrating graphene into the FET structure optimizes the interaction between mechanical stress and electrical performance, enabling highly sensitive detection of pressure changes across a wide range. The utilization of FET architecture facilitates straightforward signal amplification and readout, enhancing the overall sensor performance.

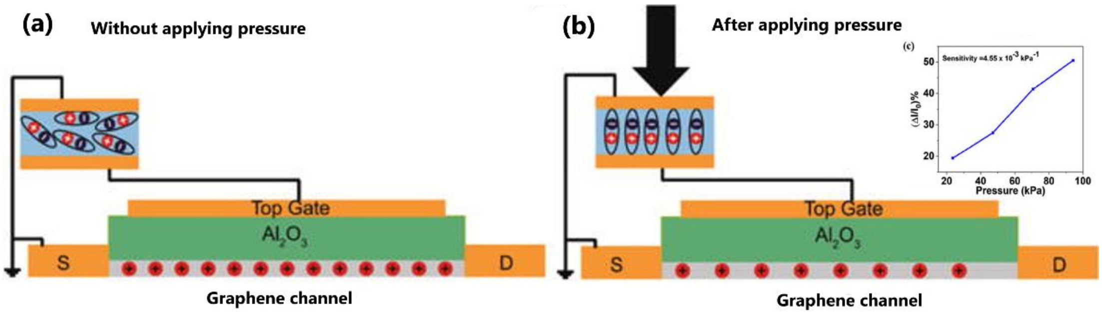

Figure 6. Schematic diagram of graphene field-effect transistor (GFET) based pressure sensor. (a) Without applying pressure; (b) After applying pressure (inset is the change in current vs pressure). Reprinted with permission from [43]. Copyright 2018 American Institute of Physics (AIP)

Applications of Graphene Pressure Sensors

Instead of using ordinary rigid elements, flexible pressure sensors based on graphene have become a perfect choice for wearable electronic products as well as application prospects in soft robotics and biomedicine. Scalable and sensitive tactile sensing systems can be developed depending on the dispersion and high specific surface area to volume ratio of graphene [41]. Undesirable deformations such as bending and twisting in wearable/foldable devices can be avoided when graphene is used rather than conventional rigid materials. Graphene has also been considered in artificial intelligence, where synaptic transistors and memristors based on graphene have been developed [44]. Such features have made graphene and its derivatives to dominate the market of most fields. Generally speaking, graphene has found its way to a wide range of applications. A summary of popular applications of graphene-based pressure sensors is presented in the following subsections.

Industrial Applications

Graphene pressure sensors are extensively used in industrial aspects to provide a number of processes such as control and monitoring. Key applications of graphene sensors include 3D strain sensors, energy harvesting, and steel industry. In addition, graphene-based pressure sensors are ideal components for pressure monitoring in pipelines, machinery, and manufacturing processes [45]. In general, graphene has high sensitivity and stability when operating in harsh environments and can withstand high pressures, which enhances its utility in industrial applications.

biomedical Applications

An important feature of graphene is its biocompatibility. In the biomedical field, graphene pressure sensors are used for various applications, including non-invasive blood pressure monitoring, wearable health monitoring devices, and prosthetics. Characteristics such as high sensitivity, fast time response and recovery would make graphene-based pressure sensors suitable for the heartbeat surveillance and for the analysis of the arterial pulse wave. Since these products are wearable, they can be used to detect respiratory dynamics.

Consumer Electronics

Graphene pressure sensors are also finding applications in consumer electronics, such as touchscreens, keyboards, and gaming controllers. In some applications where precise pressure detection is required, graphene-based pressure sensor is highly recommended due to its high sensitivity and fast response times [25,40,41,46]. Moreover, it is possible to develop innovative electronic devices with unique form factors by integrating flexible substrates with graphene [25,40,41,46] .

Challenges and Future Directions

Despite the significant advancements in graphene pressure sensors, several challenges need to be addressed for their widespread adoption. These include the high cost of graphene synthesis, the need for improved long-term stability, and the development of scalable fabrication techniques. Future research should focus on overcoming these challenges to enhance the performance and reliability of graphene pressure sensors

Conclusion

Graphene-based pressure sensors have demonstrated remarkable potential in a wide range of applications due to their unique properties. Piezoresistive, capacitive and piezoelectric mechanisms enable precise pressure measurements, while graphene's high flexibility and biocompatibility make it revolutionary in a variety of industries, from healthcare to consumer electronics. Ongoing research aims to address the current challenges and further enhance the performance of these pressure sensors, paving the way for their widespread adoption in industrial, biomedical, and consumer electronics sectors.

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