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Electromechanical Pressure Sensors Based on Graphene: A Review

Asaad K. Edaan Al-mashaal
Material Science Department, Polymer Research Centre, University of Basrah, Basrah 61004, Iraq

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ABSTRACT

Nanotechnology is set to transform the industry via the advent of specialized nanomaterials intended for deployment as sensing components. Because of its extraordinary electrical and mechanical characteristics, a two-dimensional variant of carbon referred to as graphene has sparked considerable excitement regarding high-performance pressure sensors. Graphene-based pressure sensors display advantages over traditional sensors, especially concerning their heightened sensitivity, broad dynamic range, and swift response times; however, they also provide a certain level of flexibility. This paper offers a review of the essential mechanisms that underpin graphene-based pressure sensors, encompassing (but not limited to) piezoresistive, capacitive, and field-effect transistor types.

INTRODUCTION

Pressure sensors are critical devices that transform physical pressure into electrical signals using components that bend under pressure, altering their electrical properties. These sensors are made up of three main components: the sensitive element, which interacts with pressure and measures changes in resistance, capacitance, or inductance; the transducer, which converts these changes into electrical signals; and signal conditioning circuits, which improve the clarity of the signals for future use. Furthermore, pressure sensors are encased in protective enclosures to protect their internal components and allow for easy connection to other systems. Figure 1 shows a schematic diagram of a pressure sensor using a piezoelectric diaphragm. The following review will look at the novel use of graphene as a nanomaterial to advance pressure sensor technology, with an emphasis on its mechanics and prospective applications [1,2].

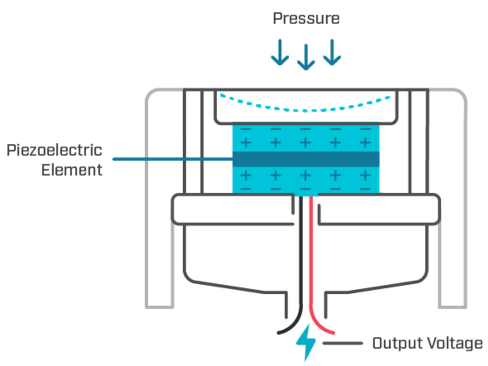

Figure 1. schematic diagram of a pressure sensor using a piezoelectric diaphragm [3]

RESEARCH METHOD

There are a few key requirements for choosing a particular material for pressure sensors. The selected materials should offer relatively high accuracy and durability while withstanding temperature fluctuations, mechanical stress, and corrosive environments. Most recent pressure sensors operate based on piezoelectric, piezoresistive, or capacitive mechanisms, depending on the sensing material used in the device. Figure 2 shows schematic diagrams of pressure sensors with different mechanisms. Pressure sensors using sensitive elements made of piezoelectric materials are in demand. Among them are quartz (SiO_2), polyvinylidene fluoride, and lead zirconate titanate [4,5]. This explains their importance in pressure sensing, for they guarantee fast response times, high sensitivity, and application feasibility for static and dynamic pressure measurements. The piezoelectric element deforms or bends when mechanical stress is applied to it, producing a related electrical signal to the applied pressure, which is further measured and correlated with the pressure. These materials, however, have their drawbacks, such as a moderate range of pressure and temperature sensitivity [6].

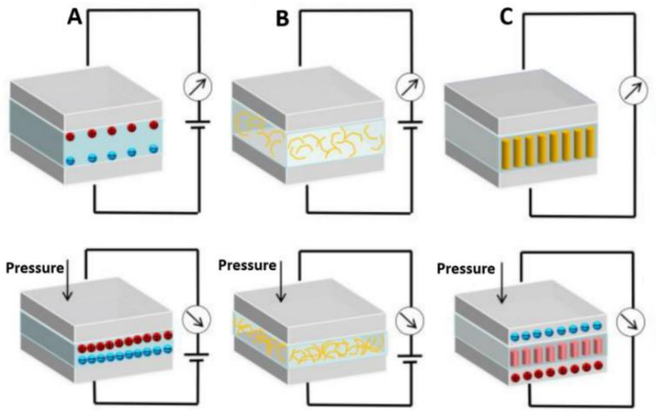

Figure 2. Different working principles of pressure sensors (**A**) Capacitive mechanism; (**B**) Piezoresistive mechanism; (**C**) Piezoelectric mechanism. Reprinted with permission from Ref. [7] . Copyright 2023, MDPI.

Metallic materials are also used in pressure sensors, especially in strain-gauge sensors where high mechanical properties are required. From a manufacturing point of view, metallic elements such as copper and stainless are easy to fabricate [8]. In harsh environment applications (e.g. oil and gas sectors, aerospace), there is a need for pressure sensors made from materials that are robust, durable, and resistant to corrosion [8,9]. The problem with metallic materials, when compared with piezoelectric materials, is that their sensitivity is smaller. Another drawback is that they have limited flexibility.

For a long time, it has been seen that semiconductor materials are the most widely used materials in all types of sensors, including pressure sensors. Silicon-based pressure sensors, for instance, have many applications in modern sensing sectors, thanks to the rapid development of integrating silicon with MEMS devices. [10]. The working principle of semiconductor pressure sensors relies on the piezoresistive effect. In such a case, when a semiconductor material is exposed to mechanical force, its electrical resistance changes accordingly [10–12]. In high-frequency applications, it is important to employ a material that has high electron mobility. For this reason, gallium arsenide (GaAs) can be employed in pressure sensors that work in specific environments. However, semiconductor-based pressure sensors have some limitations like their susceptibility to environmental factors (e.g., temperature and humidity) [13–16].

In flexible-like applications, soft and durable materials are recently applied. Polymers are considered lightweight materials and they offer higher flexibility over metallics and semiconductors. Since they are relatively cheap and easy to fabricate, polymeric materials such as conductive elastomers have been widely exploited in flexible-based pressure sensors [16–18]. For example, the pressure sensor's sensitivity can be further enhanced when a polymer material, like polyimide (PI), is integrated with other polymers or carbon-based nanomaterials [17,18]. Compared to metals and semiconductors, pressure sensors based on polymers suffer from low precision or a small response to the externally applied pressure.

To overcome the limitations associated with the use of conventional materials in pressure sensors, nanomaterials have been introduced as an excellent alternative. Due to the unique properties of nanomaterials, robust and highly sensitive pressure sensors have been developed [19]. Featured characteristics such as tuneable electrical and thermal conductivities, high mechanical strengths, and surface-to-volume ratio, would make nanomaterials highly suitable for ultra-sensitive pressure sensors [20].

RESULTS AND DISCUSSION

Why Graphen?

Graphene is a unique material that is composed of a single layer of carbon atoms. The structure of graphene is honeycomb-like, in which carbon atoms are arranged in a two-dimensional (2D) hexagonal lattice [21]. Graphene belongs to the carbon allotropes family (e.g., carbon nanotubes, fluorene, and graphite). After being exfoliated in 2004, graphene has gained lots of attention from researchers and industry sectors. The interest in graphene is related to its exceptional physical and chemical properties [22]. To exploit graphene properties wisely, many devices have been designed, fabricated, and used in numerous applications [22–24]. A list of graphene properties is presented in Table 1.

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

Among its applications in sensor devices, graphene has been an active sensing element in pressure sensors. It is very thin which makes it highly sensitive to even a small change in applied pressure. Thanks to graphene's excellent conductivity and extremely large surface area (~2630 m^2/g), pressure sensors made from graphene have the advantage of being an efficient device to detect tiny changes in the pressure applied to the sensor [23]. Highly demanded applications of graphene-based pressure sensors are soft robotics, wearable devices, and flexible electronics [19,25]. The attractive feature of graphene in these applications is its extraordinary strength and flexibility. In such cases, the graphene pressure sensor can endure large deformation or bending.

Numerous studies have been conducted on graphene and its derivatives in sensing devices. -based pressure sensors. The foundational work by [26] outlines the remarkable potential of graphene as an ultrathin material for pressure sensors, emphasizing its robustness, sensitivity, and cost-effectiveness compared to other materials. Smith [27] has reported on the electromechanical piezoresistive sensor using a suspended membrane of graphene, revealing that these sensors exhibit sensitivity levels significantly higher than traditional MEMS sensors. The influence of biaxial piezoresistive properties of graphene piezoresistive pressure sensors has been demonstrated [28].

Mechanisms of Graphene Pressure Sensors

There are several factors must be taken into consideration regarding the development of highly sensitive, flexible, and robust graphene-based pressure sensors. Issues 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 an external force is applied to a pressure-sensitive 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, modifying the distance between atoms, and thus affecting the membrane conductivity. In Figure 3, a drum-based graphene pressure sensor is depicted. It can be seen even for such a 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.

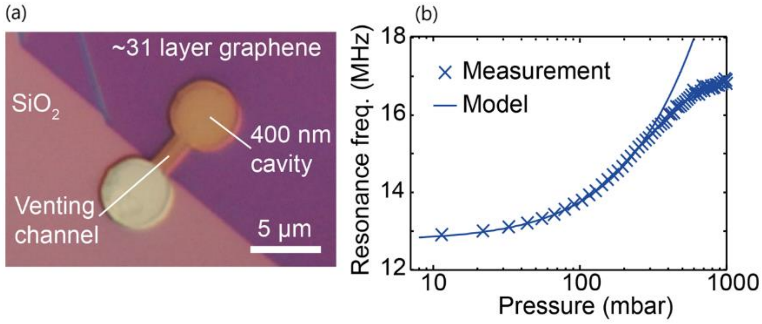

Figure 3. The pressure sensor of graphene. (a) Optical illustration of graphene flake in drum configuration; (b) The resonance frequency of the graphene sensor as a function of pressure. Reproduced with permission from [32]. Copyright 2015, ACS.

Capacitive Mechanism

A typical configuration of a capacitive pressure sensor includes two conductive plates or electrodes separated by an insulating medium [9]. In the case of a pressure sensor based on graphene, one of the plates is 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. The distance between these two plates/electrodes is influenced by the external pressure applied to the sensor. In the case of a flexible sensor setup, an increase in pressure can compress the dielectric material or cause deformation in one of the graphene layers, thus altering the gap between plates. In this way, any change in applied pressure leads to a change in the device's capacitance, see Figure 4. The changes in capacitance are measured using capacitance measurement circuits. Ultimately, these changes are then converted into a readable electrical signal [35–37].

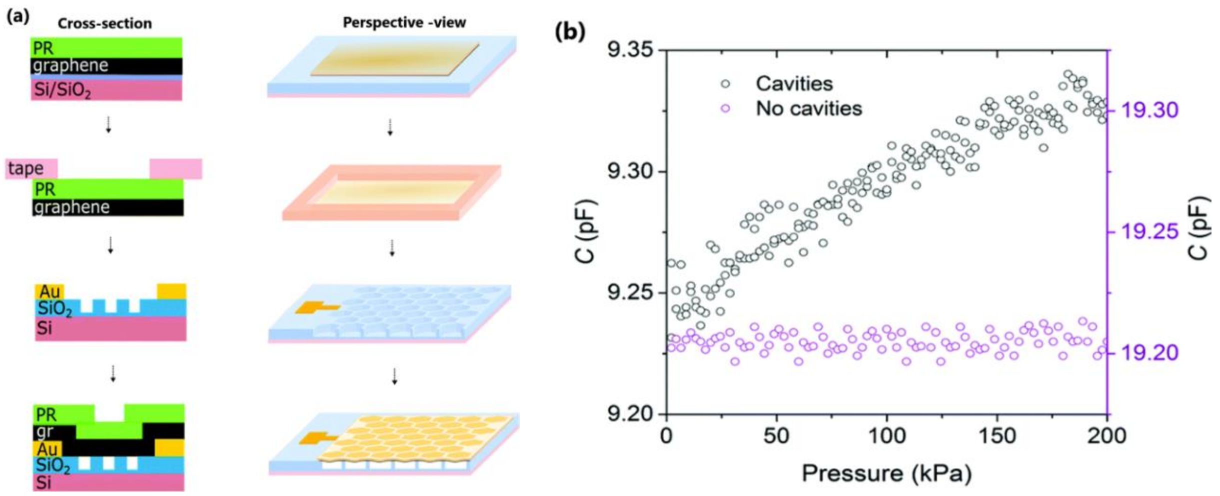

Figure 4. (a) Schematic illustration of the fabrication process of graphene–polymer capacitive pressure sensor; (b) Measured sensor capacitance as a function of applied pressure. Reproduced with permission from [37]. Copyright 2021, RSC.

Piezoelectric Mechanism

The piezoelectric effect describes the capacity of some materials to create an electrical current in response to mechanical stress. This phenomenon occurs in materials lacking a center of symmetry in their crystal structure [6]. In other words, the crystal lattice of the material distorts depending on the magnitude of applied stress. When pressure sensors are made from a piezoelectric material, 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, no change in current has been recorded (Figure 5a). This indicates that no distortion in the graphene lattice has occurred. Moreover, a negative response has been recorded in nanowire-graphene pressure sensors. As shown in Figure 5b, a sharp decrease in the current has been obtained. Such a useful mechanism can be exploited particularly in applications requiring high sensitivity and fast response times.

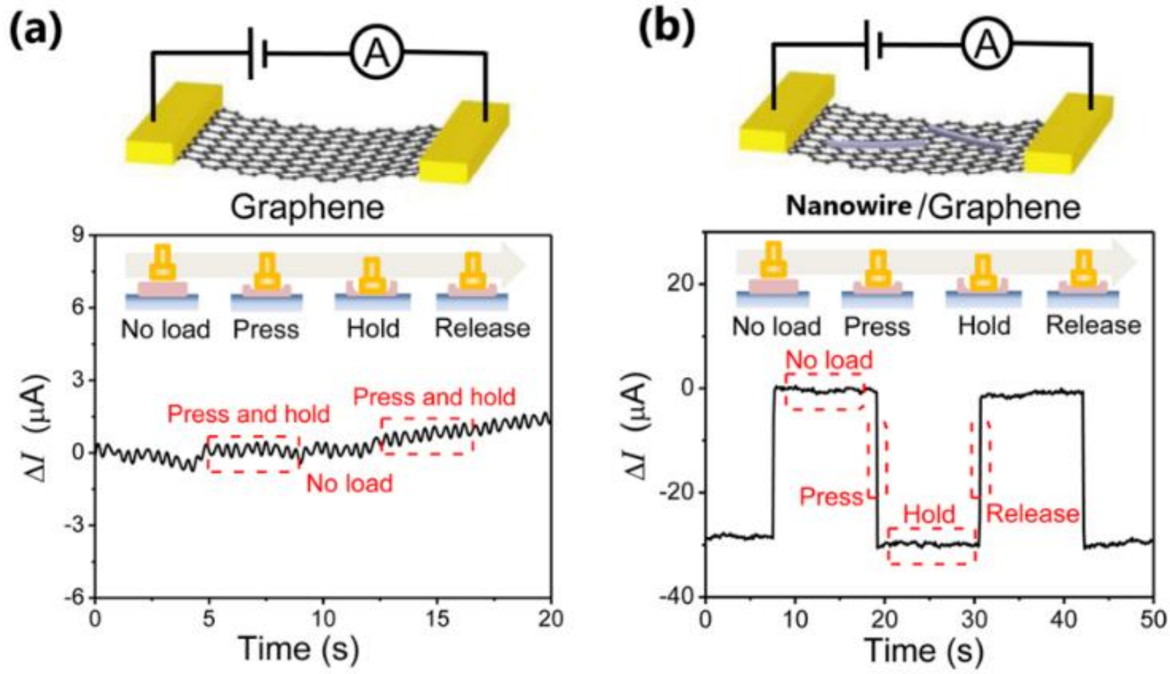

Figure 5. Graphene-based piezoelectric pressure sensor. Measured current change (ΔI) for (a) pure graphene and (b) graphene/nanowire. Reproduced with permission from [38]. Copyright 2017, ACS.

Field-effect transistor (FET)

A graphene-based field-effect transistor (GFET) works relying on the modification of the electric charge in the transistor's channel. In the pressure sensor structure, this change is obtained through the application of external pressure on the active element of the sensor [40–42]. In other words, graphene serves as the conducting channel in an FET configuration, where the current flow is governed by an applied voltage at the gate terminal. Any deformation in the graphene membrane in response to an external pressure induces changes in the charge carrier density and mobility within the graphene, as shown in Figure 6. Recently, graphene has been integrated into modern FET structures. Such integration plays an essential role in enhancing the performance of graphene-based FET pressure sensors. This is useful as it enables precise detection of pressure with ultra-high sensitivity.

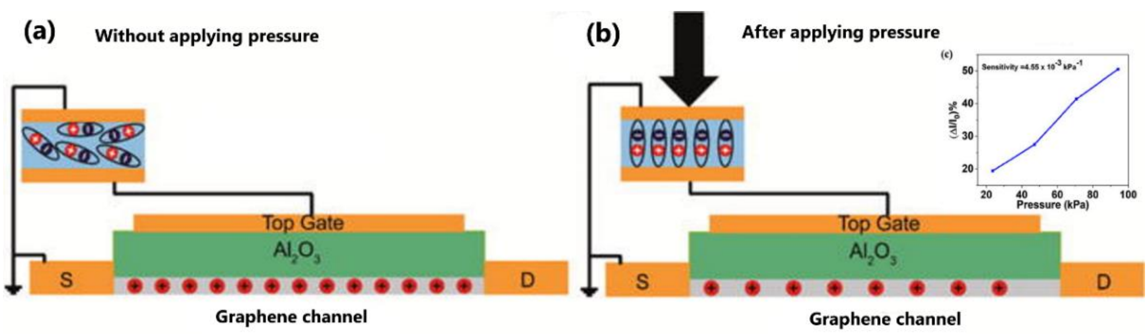

Figure 6. Illustration of graphene-based pressure sensors with an FET configuration. (a) Without applying pressure; (b) After applying pressure (inset is the change in current vs pressure). Adapted with permission from [43]. Copyright 2018, AIP.

Applications

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 are developed, thanks to graphene's high surface area and dispersion[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 can be realized [44]. Such features have made graphene and its derivatives dominate the market in most fields. Generally speaking, the applications of graphene are enormous. In the following subsections, we have summarized the most common applications of graphene-based pressure sensors.

Industrial Applications

Graphene pressure sensors are extensively used in industrial aspects to provide many processes such as control and monitoring. Key applications of graphene sensors include 3D strain sensors, energy harvesting, and the 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

Biocompatibility is one of the unique properties of graphene. In the biomedical field, graphene-based 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 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 Applications

Graphene pressure sensors are also finding applications in consumer electronics, such as touchscreens, keyboards, and gaming controllers. As mentioned earlier, the response of the graphene pressure sensor is ultra-fast with high sensitivity. Such features are valuable in consumer products [25,40,41,46]. Additionally, with the enhanced integration of graphene and other flexible materials, high-performance electronic systems can be developed[25,40,41,46].

Challenges and prospects

Even though the field of graphene-based pressure sensors has been advanced in many ways, there are still some challenges that need to be addressed. The main challenge is to obtain high-quality graphene with minimum defects. The synthesis of graphene is also costly. In some applications, there is a need for a large area membrane of graphene. This, however, is not always possible which may limit the usefulness of graphene. Therefore, it is very important to develop innovative scalable fabrication techniques. To overcome these challenges, further study and deep research are highly demanded. Future work is expected to solve many problems related to graphene, thus producing reliable pressure sensors with high performance.

CONCLUSION

Graphene with its exceptional physical and chemical properties is considered an ideal component for many sensing applications. Here, we have covered the main mechanism behind the operation of graphene-based pressure sensors. Working principles based on piezoelectric, capacitive, piezoresistive, and FET effects have been discussed briefly in this article. Unbeatable features such as high mechanical strength, high conductivity, lightweight, durability, and flexibility have enabled graphene to dominate the market of the sensing materials sector. The potential applications of graphene-based pressure in biomedical, industrial, and consumer sectors have been explored. Challenges associated with the production of high-performance pressure sensors of graphene are addressed.

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***Asaad K. Edaan Al-mashaal (Corresponding Author)**
Material Science Department, Polymer Research Centre, University of Basrah, Basrah 61004, Iraq
Email: asaad.edaan@uobasrah.edu.iq