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Enhancing Sensitivity in Flexible MEMS Capacitive Pressure Sensors: A Review

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Abstract. Enhancing the sensitivity of flexible MEMS capacitive pressure sensors is vital for applications in wearable electronics, healthcare, and tactile sensing. Recent advancements focus on material innovations like graphene and silver nanowires, structural designs such as pyramidal microstructures and interdigitated electrodes, and fabrication techniques like laser-induced graphene and multilayer architectures. These approaches improve sensitivity, broaden detection ranges, and enhance response times. Despite progress, challenges in stability and fabrication complexity remain. This review summarises current strategies, offering insights into advancing sensor performance for emerging applications.

1. Introduction

Microelectromechanical systems (MEMS) are a class of miniaturized devices that integrate mechanical and electrical components on a single chip [1]. These systems, often fabricated using techniques adapted from semiconductor manufacturing, are capable of sensing, actuating, and processing information. MEMS technology covers a wide range of applications, including inertial sensors, microfluidic devices [1], and pressure sensors, due to its advantages of compact size, low power consumption [2], and high precision [3]. Among these, MEMS capacitive pressure sensors have gained significant attention for their reliable operation and compatibility with modern electronics [4].

2. MEMS Pressure Sensors

In MEMS, pressure sensors are among the most widely used devices due to their compact size, high sensitivity, and low power consumption [2]. MEMS pressure sensors measure external force exerted and convert it into an electrical signal [5]. Pressure sensors can be categorized into various types based on their sensing principles and applications. These include capacitive [6], piezoresistive [7], piezoelectric [8], optical [9], and resonant pressure sensors [10]. Each type of pressure sensor offers unique advantages and is suited for specific applications. Table 2.1 shows various type of pressure sensors.

Table 2.1 Classification of pressure sensors along with their mechanism, operating principle, and applications

Type	Mechanism	Operating Principles	Applications
Capacitive [a]	Electrostatic transduction	Capacitance changes due to air-gap variation caused by diaphragm deflection	Healthcare monitoring, environmental sensing
Piezoresistive [b]	Change in electrical resistance	Resistance changes in piezoresistive elements due to strain in the diaphragm	Automotive (engine monitoring), aerospace
Piezoelectric [c]	Electric charge generation	Electrical charge is generated by the stress-induced polarization of the piezoelectric material	Robotics and prosthetics
Optical [d]	Optical path length/intensity change	Light signal properties (intensity, phase, or wavelength) change due to structural deformation	Hazardous environments (oil and gas), biomedical
Resonant [d]	Change in resonant frequency	Resonance frequency shifts due to mass or tension changes caused by pressure	Meteorology, scientific research

[a] Ref. [11,12,13], [b] Ref. [9,10,11,14,15,16], [c] Ref. [11,17,18], [d] Ref. [19]

2.1 MEMS Capacitive Pressure Sensor

MEMS Capacitive pressure sensors operate based on a simple yet effective design that revolves around the interaction of capacitive electrodes and a diaphragm, typically made of materials like silicon or polysilicon [20-22]. The capacitive electrodes typically consist of two main components: a fixed electrode and a movable diaphragm. The fixed electrode is securely anchored to the substrate, while the movable diaphragm is designed to deform in response to applied pressure. This deformation causes a change in the capacitance between the electrodes, which forms the basis for pressure sensing [20].

The diaphragm is a critical component that significantly influences the sensor's performance. It can be fabricated using various materials such as silicon, silicon carbide, or gold, chosen for their specific mechanical and electrical properties [20,24,25]. Additionally, diaphragms can take on different geometric shapes, including circular, square, or octagonal, depending on the application requirements and the desired sensitivity [26].

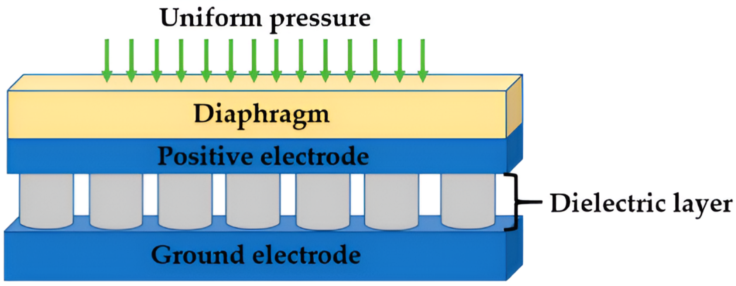

Figure 2.1.1 Schematic diagram of a diaphragm-based capacitive pressure sensor [23].

When pressure is applied, the diaphragm deflects, thereby altering the air gap between the two electrodes. This change in the air gap directly modifies the capacitance value, which is then measured and correlated to the pressure applied [20,21,26]. Each sensor type leverages a distinct operating principle, offering unique benefits tailored to specific applications.

Table 2.1.1 presents a comparative overview of various pressure sensor types, highlighting their structural features.

Table 2.1.1 Feature of various pressure sensors

	Pressure Sensors				
Feature	Capacitive [a]	Piezoresistive [b]	Piezoelectric [c]	Optical [d]	Resonant [d]
Sensitivity	High	Moderate to High	High	High	High
Power Consumption	Low	Moderate	Moderate	Low	Low
Temperature Stability	High	Moderate	Low to Moderate	Low	Low
Dynamic Range	High	Moderate to High	High	High	High
Integrated Circuit (IC) Compatibility	High	Moderate	Low to Moderate	Low	Low
Mechanical Robustness	High	Moderate	Moderate	High	High

[a] Ref. [18,19,20,21,22,23,24,25,26,27], [b] Ref. [27,28,29], [c] Ref. [30], [d] Ref. [31]

From the table, it is apparent that MEMS capacitive pressure sensor outperform piezoelectric, piezoresistive, optical, and resonant sensors in several aspects, including sensitivity, power efficiency, temperature stability, dynamic range, and mechanical robustness [20,32-37].

These advantages, combined with their IC compatibility and cost-effectiveness, make capacitive sensors a versatile and indispensable tool for modern sensing applications [38]. Their capabilities position them as a preferred choice for industries ranging from healthcare to aerospace, where precision, reliability, and efficiency are critical [39-40].

2.2 Sensitivity and Capacitance

Sensitivity refers to the ability of a pressure sensor to detect small changes in pressure and convert them into measurable signals. It is often defined as the ratio of the change in output (e.g., capacitance, resistance) to the applied pressure change. Higher sensitivity allows the sensor to respond to finer pressure differences, enabling more precise measurements. High sensitivity is crucial for applications that require precise pressure monitoring.

In the context of capacitive pressure sensors, sensitivity refers to the sensor's ability to detect small changes in pressure and convert them into measurable variations in capacitance. Sensitivity is influenced by several factors, including the material properties, diaphragm structure, dielectric layer thickness, and electrode area [20,21,41]. The sensitivity of a capacitive pressure sensor is defined as the change in output capacitance (ΔC) divided by the change in applied pressure (ΔP):

$$S = \frac{\Delta C}{\Delta P} \tag{1}$$

Where:

- S is the sensitivity of the sensor (typically in F/Pa or F/N),
- ΔC is the change in capacitance (in farads),
- ΔP is the change in applied pressure (in pascals).

For a MEMS capacitive pressure sensor, the sensors operate by converting externally applied pressure into changes in capacitance, which serves as the output signal [26,42]. Capacitance, denoted by C, is a measure of the sensor's ability to store electrical energy as charges. The capacitance of a parallel plate capacitor in a vacuum can be defined as:

$$C = \frac{\varepsilon_o A}{d} \tag{2}$$

Where:

- ε_0 permittivity of free space,
- A is the effective area of the plates,
- d is the distance between the parallel plates.

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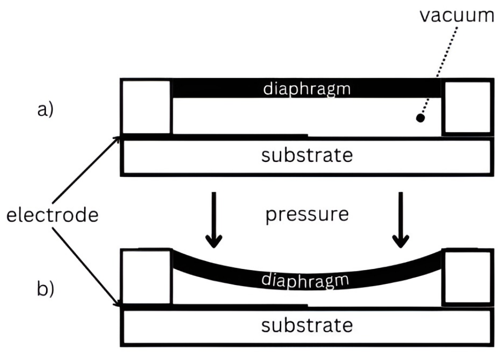

Figure 2.2.1 (a) A cross section of a MEMS diaphragm-based capacitive pressure sensor (b) Deformation of diaphragm due to applied pressure [43].

Figure 2.1 illustrates a MEMS capacitive pressure sensor that utilizes a diaphragm, the primary mechanical part of the sensor, and a cavity to measure pressure. As pressure is applied, the diaphragm deforms, altering the distance between the diaphragm and the fixed electrode, thus changing the capacitance [20,26,42]. The change in capacitance, ΔC can be expressed as:

$$\Delta C = \frac{\partial C}{\partial P} \Delta P \tag{3}$$

Where:
- $\partial C/\partial P$ is the pressure-to-capacitance sensitivity coefficient, which depends on the diaphragm deflection and the mechanical properties of the sensor,
- ΔP is the pressure difference between two measured values

2.3 Flexible MEMS Capacitive Pressure Sensor

Flexible MEMS capacitive pressure sensors operate on the same basic principle as traditional MEMS devices, consisting of two conductive layers separated by a dielectric layer. However, the primary distinction between flexible and traditional MEMS sensors lies in the materials used and their ability to adapt to dynamic environments. Traditional MEMS are made from rigid materials like silicon, which provide structural integrity in stable, flat conditions. These sensors are well-suited for applications that do not require movement or deformation, such as automotive, industrial, and aerospace systems. However, they are limited in their ability to conform to curved or dynamic surfaces, making them unsuitable for environments that require flexibility.

In contrast to the rigid substrates used in traditional capacitive pressure sensors, flexible MEMS integrate flexible substrates made from materials such as polydimethylsiloxane (PDMS) [44], polyimide (PI) [45], or polyethylene terephthalate (PET) [46]. Replacing rigid silicon with flexible polymers allows MEMS capacitive pressure sensors to better conform to curved surfaces and provide more accurate readings under deformation. This flexibility also enables more efficient integration into wearable devices, biomedical implants, and other advanced technologies.

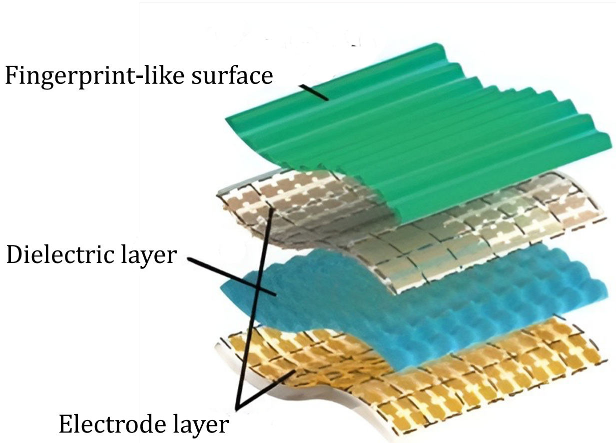

Figure 2.3.1 Structure of a flexible MEMS capacitive pressure sensor [47].

Figure 2.3.1 shows the fundamental structure of capacitive sensing in flexible pressure sensors where these sensors consist of two electrode layers that is made from metals or conductive polymers, and a dielectric elastomer layer in between of the electrodes.

Table 2.3.1 Comparison of the traditional and flexible MEMS capacitive pressure sensor

Aspect	Traditional MEMS Capacitive Pressure Sensor	Flexible MEMS Capacitive Pressure Sensor
Structure	Silicon membrane, fixed electrode [a]	Flexible substrates, polymer-based materials [d]
Fabrication	Silicon micromachining [a]	Magnetron sputtering [d]
Sensitivity	High [a,b]	High, enhanced by flexible materials and micro/nanostructures [d]
Flexibility	Limited [a]	High, suitable for curved surfaces [d,e]
Applications	Medical devices, industrial sensors [c]	Wearable electronics, electronic skin [d,e]

[a] Ref. [36,48,49], [b] Ref. [41], [c] Ref. [40,54], [d] Ref. [50,51,53], [e] Ref. [52]

Table 2.3.1 compares between the traditional and flexible MEMS capacitive pressure sensors in terms of their structure, fabrication processes used, sensitivity, flexibility, and applications, and it shows that flexible version are superior. However, further advancements are needed to improve their sensitivity, durability, and overall performance [55]. This paper will focus on key components influencing sensor sensitivity, including the substrate, diaphragm, dielectric layer, and electrodes. By reviewing current advancements and strategies to optimize these components, the paper aims to provide insights into overcoming existing limitations and guiding future developments in flexible MEMS capacitive pressure sensors [2,40-48].

3. Sensitivity Enhancement of Flexible MEMS Capacitive Pressure Sensor

Flexible MEMS capacitive pressure sensors rely on the integration of several key components that collectively determine the performance and sensitivity of the sensor. The sensors rely on the design and materials used in each component. To enhance the sensitivity of flexible MEMS capacitive pressure sensors, several strategies involving substrate materials and structural modifications can be employed.

3.1 Flexible MEMS Capacitive Pressure Sensors Substrate Materials and Structures

3.1.1 Substrate Materials

The substrate serves as the foundation of the sensor. In flexible MEMS sensors, the choice of substrate for flexible MEMS capacitive pressure sensors depends on the specific application requirements, such as flexibility, chemical resistance, and environmental stability. There are wide variety all viable materials, each offering unique advantages for different use cases. Table 3.1.1 compares various flexible substrates for MEMS capacitive pressure sensors, focusing on their advantages, and applications.

Table 3.1.1 Comparison of material advantages and applications of various flexible substrates

Substrate Material	Advantages	Applications
Polydimethylsiloxane, PDMS [a]	Flexibility, bending stability, cycling stability	Printed circuit processing, pressure sensors
Liquid Crystal Polymer, LCP [b]	Dimensional stability, flexibility, chemical resistance	Wearable devices, electronic skins
Parylene C [c]	Biocompatible, flexible	Intraocular pressure sensors
Polyimide, PI [d]	Flexible, robust	Smart skins, tactile sensors
Silicon Carbide, 3C-SiC [e]	Mechanical strength, temperature resistance	Harsh environment sensors
Kapton [f]	High flexibility, durability	Medical monitoring, stress measurements

[a] Ref. [56,57], [b] Ref. [24], [c] Ref. [52,58], [d] Ref. [53,59], [e] Ref. [60], [f] Ref. [61,62]

Based on this comparison, PDMS stands out for its unique combination of flexibility, micro-structuring capability, low dielectric constant, and compatibility with nanomaterials, making it a highly effective material for significantly improving the performance of flexible MEMS capacitive pressure sensors. As a result, further investigation into PDMS is conducted to enhance sensor performance.

Table 3.1.2 below provides the overall characteristic of PDMS as a material, and it emerges as the most favourable material for flexible MEMS capacitive pressure sensors given the advantages using the materials compared to materials listed in Table 3.1.1. PDMS enhances flexible MEMS capacitive pressure sensors by providing flexibility, improving sensitivity through micro-structuring, reducing dielectric constant, and enabling integration with nanomaterials.

Other materials have their advantages in specific contexts, but their limitations in flexibility, thermal stability, or cost- efficiency make them less suitable to further enhance the sensitivity of a flexible MEMS capacitive pressure sensor.

Table 3.1.2 Comparison of material advantages and applications of various flexible substrates

Feature/Approach	Description	Advantage/Outcome
Flexibility and Elasticity [a]	High flexibility and elasticity, adaptable to curved surfaces	Suitable for wearable devices, enabling real-time monitoring
Sensitivity Enhancement [b]	Micro-structured PDMS (e.g., micro-arrayed or porous designs) enhances sensitivity	Sensitivity of 2.04 kPa^{-1} with micro-arrayed PDMS; 0.0083 Pa^{-1} in low-pressure ranges
Low Dielectric Constant [c]	Reduces parasitic capacitance noise, improving the signal-to- noise ratio	Enhanced sensor performance via techniques like UV exposure and ethanol-toluene buffer washing
Integration with Nanomaterials [d]	Combines with nanomaterials like Silver Nanowires (AgNWs), Carbon Nanotubes (CNTs), and graphene to improve electrical properties	Achieves high sensitivity (e.g., 2.94 kPa^{-1} with AgNWs coating on PDMS)

[a] Ref. [44,63,64,65], [b] Ref. [56,63,66], [c] Ref. [67], [d] Ref. [63,64,68,69,70], [e] Ref. [71,72]

3.2 Substrate Structure

The substrate of the flexible MEMS capacitive pressure sensors are commonly incorporate micro-arrayed patterns, hemispherical microstructures, or hollow cavities, which enable the sensor to better deform under pressure, increasing the effective surface area and improving sensitivity.

Table 3.2.1 Comparative Performance Metrics of Sensor Types

Sensor Type	Structural Feature	Sensitivity	Applications
Hemispherical + Hollow Cavities in PDMS [a]	Curved microstructures, hollow cores	7.99 kPa^{-1}	Biomedical sensors
Sealed PDMS Cavity with IDE Electrodes [b]	Flat cavities, IDE configuration	3.35 fF/psi	General pressure sensing
Pyramid-Shaped Microstructures in PDMS [c]	Geometrically rigid microstructures	0.22% Pa^{-1}	Wearable physiological monitoring

[a] Ref. [74], [b] Ref. [78], [c] Ref. [44]

Table 3.2.1 shows various incorporation of designs on the substrate layer. The combination of microstructures and hollow cavities in the PDMS substrate poses significant impact in achieving high sensitivity and reliable performance [44,74,78].

3.2.1 Composite Substrates

A composite substrate in the context of MEMS capacitive pressure sensors refers to a multi-material structure that combines a base material (like PDMS) with other functional materials to enhance its physical, electrical, or mechanical properties. The goal is to optimize the sensor's performance by leveraging the synergistic benefits of the combined materials.

Table 3.2.1.1 Comparison of material advantages and applications of various flexible substrates

Material Integrated	Role in Composite	Performance Impact	Applications
AgNWs [a]	Enhances electrical conductivity, serves as electrode material	Improves sensitivity and signal stability	Wearables, biomedical devices
MWNTs [b]	Embedded conductive elastomer; creates elastomer wires and electrodes	Increases conductivity, enhances mechanical stability	Flexible electronics, soft robotics
CCTO [c]	Enhances dielectric constant of PDMS	Enhances dielectric constant of PDMS	Pressure sensing for wearables, industrial sensors
BTO [d]	Forms porous-elastic matrix within PDMS	Increases sensitivity and linearity under low-pressure conditions	Robotics, prosthetics, low- pressure applications

[a] Ref. [63], [b] Ref. [80,87], [c] Ref. [88], [d] Ref. [89]

Table 3.2.1.1 shows enhancement that can be made for when PDMS is integrated with various materials. The use of composite substrates allows for greater customization of the sensor’s properties, such as improving electrical conductivity, enhancing flexibility, and optimizing the mechanical response to pressure. By combining PDMS with conductive or dielectric-enhancing materials results in superior sensitivity, flexibility, and functionality [63,80,87-89].

In summary, the substrate structure is essential in dictating the performance of flexible MEMS capacitive pressure sensors. The material choice, integrated microstructures, and overall design all play a significant role in improving sensitivity, stability, and flexibility. These features make the sensor adaptable for a wide range of applications, from wearable electronics to biomedical sensors [88-89].

3.3 Dielectric material

Dielectric materials are insulating substances that do not conduct electricity but can support electrostatic fields, making them essential in various electronic applications. Their primary function in capacitive pressure sensors is to enhance capacitance by polarizing under an applied electric field. The dielectric constant, a measure of a material's ability to store electrical energy, is a critical property determining their effectiveness.

Materials with higher dielectric constants significantly improve the sensitivity of sensors by amplifying the capacitance changes induced by pressure variations. In the context of MEMS capacitive pressure sensors, dielectric materials are used in various forms, ranging from solid composites to liquids. Conventional solid dielectric materials, such as polymers and composites, have been the cornerstone of sensor design due to their structural stability, ease of fabrication, and reliable performance. However, these materials often face limitations in achieving ultra-high sensitivity, especially for applications requiring precise measurements over a wide range of pressures.

Table 3.3.1 Comparison of Dielectric Materials

Material	Dielectric Constant	Flexibility	Sensitivity
Deionized Water [a]	~80	High	High (5x air)
Glycerine [a]	~47	High	High (5x air)
PDMS with BaTiO3/STO [b]	Varies, High	High	High (7.847 kPa^{-1})
RGO-PDMS Composite [c]	38	High	Moderate (0.4321 kPa^{-1})
Porous PDMS [d]	Varies	High	Moderate (0.694 kPa^{-1})

[a] Ref. [51], [b] Ref. [91], [c] Ref. [93], [d] Ref. [94]

Table 3.3.1 compares performance metrics of various methods to enhance dielectrics materials for the flexible MEMS capacitive pressure sensor. For flexible MEMS capacitive sensors, using high dielectric materials like deionized water, glycerine, and composites such as PDMS with dielectric fillers or RGO can significantly enhance sensor performance. These materials maintain flexibility while providing high sensitivity, making them suitable for a wide range of applications including wearable sensors, medical devices, and human motion monitoring.

3.4 Electrodes

An electrode is a conductive material that plays a critical role in the device's operation. It serves as one of the two plates of a capacitor, enabling the generation and measurement of electrical signals that correspond to pressure changes. Electrodes are arranged in a parallel plate configuration, with a dielectric layer (e.g., PDMS) sandwiched between them. The top electrode is often flexible to allow deformation under pressure, while the bottom electrode is usually fixed to a substrate. To improve the performance, it requires optimization of materials, designs, and fabrication techniques to achieve higher sensitivity, better stability, and a wider detection range.

Innovative structural designs are crucial for amplifying the performance of flexible sensors. Studies have shown that interdigitated electrodes (IDE) effectively reduce output non-linearity by serving as a pressure-magnifying structure [95-96]. The design can also manipulate the electrical properties of the graphene structural properties when pressure is applied in Z-direction. Precise adjustments to electrode spacing in IDE structures as shown in Figure 3.4.1. ensures uniform strain distribution, further improving sensor sensitivity and detection accuracy [95].

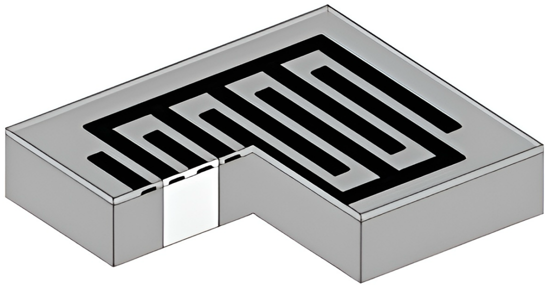

Figure 3.4.1 Geometry of the interdigitated graphene-based pressure sensor unit cell [95].

Additionally, Graphene offers superior flexibility, high conductivity, and mechanical strength, making it ideal for sensors requiring consistent performance under strain [95-96].

4.1 Conclusion

The development of flexible MEMS capacitive pressure sensors has seen significant advancements through structural modifications and material innovations. Enhancing flexible MEMS capacitive pressure sensors involves optimizing the substrate, dielectric, and electrode. Micro-structured and multilayer substrates improve flexibility and sensitivity. High-k dielectric materials and liquid-based dielectrics enhance capacitance response. Advanced electrodes like AgNWs composites ensure conductivity and stability.

Table 4.1 Summary of sensitivity enhancement of flexible MEMS capacitive pressure sensors

Category	Approach	Sensitivity Improvements
Substrate [a]	Composite materials, Micro-structured substrate configurations	High sensitivity, flexibility
Dielectric [b]	Highly dielectric materials	High dielectric constant, flexibility
Electrode [c]	Composite materials, nano-structured configurations	Potential for optimization

[a] Ref. [103], [b] Ref. [67] [c] Ref. [51,106]

Table 4.1 summarizes the numerous strategies that can be utilised to enhance sensitivity in Flexible MEMS Capacitive Pressure Sensor. These innovations cater to diverse applications, and positions flexible MEMS capacitive pressure sensors as ideal candidates for next-generation technologies. Future research focusing on further material innovation and optimization of fabrication techniques will continue to push the boundaries of performance and reliability in these sensors.

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