Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL28728

Review of Highly Sensitive MEMS Based Capacitive Pressure Sensors with Asymmetric Structures

Qianxun Shao[1*†], Siyue Lin[2†]

[1]*Department of Electrical & Electronic Engineering, University of Manchester, Manchester, United Kingdom*
[2]*Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo, China*
**Corresponding Author. Email: qianxun.shao@student.manchester.ac.uk*
[†]*These authors contributed equally to this work and should be considered as co-first author.*

Abstract. This review examines recent advancements in highly sensitive MEMS-based capacitive pressure sensors with asymmetric structures, focusing on the interrelationships between structural factors, sensitivity, and linearity. Various sensor architectures are systematically analyzed, including different diaphragm geometries, modified electrode configurations, and innovative dielectric layer designs. The study demonstrates that asymmetric electrodes and non-uniform structural designs significantly enhance sensitivity and extend the linear operating range compared to traditional parallel-plate sensors, without requiring additional mechanical amplification. However, high sensitivity often compromises linearity, and fabrication complexity remains a challenge. The shape and architecture of electrodes and dielectric layers are identified as the most influential factors, capable of improving sensitivity by several orders of magnitude. Future work should focus on experimental validation, environmental testing, circuit integration, and further structural optimization to balance sensitivity with linearity.

Keywords: MEMS capacitive pressure sensor, Sensitivity, Linearity, Asymmetric structures, Electrode design

1. Introduction

Micro-Electro-Mechanical Systems (MEMS) technology has revolutionized sensing applications through its unique advantages in miniaturization, low power consumption, and cost-effectiveness [1]. These characteristics have made MEMS devices particularly valuable in automotive systems [2], medical devices [3], and environmental monitoring applications. Considering sensitivity, thermal stability and compatibility with standard CMOS processes, capacitive pressure sensors outshine other MEMS sensors as a result of their exceptional performance [4].

Capacitive pressure sensors measure capacitance changes caused by deformation in mechanical diaphragm. However, these sensors face a fundamental design challenge in balancing sensitivity and linearity albeit their advantages [5]. Research has shown that enhancing sensitivity through structural modifications often compromises linearity, especially under high-pressure conditions. For instance, circular diaphragms demonstrate superior sensitivity compared to square configurations

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[6], while specific thickness-to-gap ratios can significantly improve performance [7]. Recent innovations in structured dielectric layers [8] and touch-mode operations [9,10] have further advanced sensor capabilities, yet challenges persist in fabrication complexity, temperature dependence [11], and nonlinear response across extended pressure ranges.

Environmental factors, particularly temperature variations, substantially impact sensor performance. Thermal effects can induce mechanical stress changes and measurement drift [12], while material properties and external interference may further degrade linearity [13]. These influences underscore the need for design strategies that address environmental sensitivities without compromising overall sensor performance.

The structure and geometry of sensing elements play a crucial role in determining sensor characteristics. Studies have demonstrated that diaphragm architecture significantly affects both linearity and temperature sensitivity [14], while innovative approaches combining microstructures with substrate components can simultaneously optimize sensitivity and linearity [15]. Furthermore, the impact of fabrication uncertainties on sensor performance highlights the importance of robust design methodologies [16].

This review comprehensively examines recent advancements in MEMS capacitive pressure sensor designs, focusing on the interrelationships between structural factors, sensitivity, and linearity. By analyzing various architectural approaches and their performance trade-offs, this work aims to provide insights into current challenges and future directions for high-performance pressure sensing applications.

2. Review of previous designs

2.1. Overview of typical capacitive pressure sensor structures

As illustrated in Figure 1, a typical MEMS capacitive pressure sensor consists of a diaphragm serving as the top electrode (at V_{dd}), a dielectric layer, a grounded bottom electrode, and the substrate.

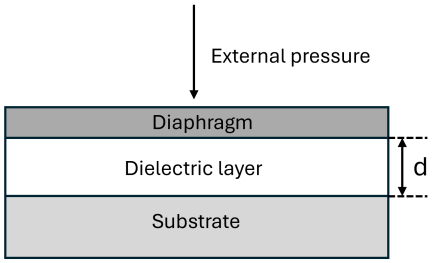

Figure 1. Cross-sectional view of a parallel-plate MEMS based pressure sensor

When external pressure is applied to the diaphragm, the sensor's capacitance increases. Equation (1) below gives the capacitance: C is capacitance (F), ε_0 is the absolute permittivity (8.854 pF/m), ε_r is the dielectric's relative permittivity, A is the electrode overlap area (m^2), and t is the electrode separation (m). Therefore, value of pressure applied is able to be calculated according to analogue signals produced by MEMS based pressure sensors.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{1}$$

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Two important parameters, which are sensitivity and linearity, are used to determine performance of a sensor. Typically, sensitivity is the proportion between capacitance variation (F) and pressure variation (Pa), expressed in F/Pa. Because the size of diaphragm is not a considered parameter, an intensive result (F/Pa/ m^2) is calculated shown by equation below.

$$Sensitivity = \frac{\Delta C}{A \times \Delta P} \tag{2}$$

Linearity is a numerical value between 0 and 1 showing how well the actual result fits the expected results, which is a straight line. It is calculated through equation below, where R^2 = Coefficient of Determination, σ_r^2 = Variance of the residuals, σ^2 = Total variance of the dependent variable, y_i = Actual observed value of change in capacitance for the i-th observation, $\hat{y}_i$ = Predicted value of change in capacitance for the i-th observation, $\bar{y}$ = Mean of the observed values of change in capacitance and n = total number of test results.

$$Linearity = R^2 = 1 - \frac{\sigma_r^2}{\sigma^2} = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{3}$$

There are several methods to optimize parallel-plate pressure sensors including using circular diaphragm instead of square diaphragm, connecting multiple capacitors in parallel, alternating geometric parameters with different values, increasing internal air pressure in dielectric layer and applying double touch mode.

One of them is exploring the impact of different shapes of diaphragm made of silicon with geometry of 100 on sensitivity. Four parallel-plate capacitive pressure sensors using diaphragm with shape of square, circle, golden rectangle and normal rectangle are tested under the same condition, whose overlap areas are approximately 0.61 mm^2 and thickness of diaphragm is 63 μm, using load varying from 1MPa to 10 MPa. According to their research, the circular diaphragm has a better performance in sensitivity compared with other shapes, which is 10.66 fF/MPa/ mm^2 whereas the rectangular diaphragm with clamped edges shows the best linearity [6].

Another research found that thickness of diaphragm as well as size of gap between electrodes are the reason for a sensor with high sensitivity. Both electrodes are aluminum plates with overlap area of 0.144 mm^2 , which have a silicon nitride dielectric layer in between with thickness of 0.3 μm. This model was tested with three different thickness of diaphragm between 5 μm and 6 μm in addition to three different values of dielectric thickness between 2 μm and 3 μm respectively using normal mesh between 9 μm to 50 μm. Among all test results, combination of 5 μm diaphragm and 2 μm gap had largest deviation in capacitance which is 554.10 fF/MPa/ mm^2[7].

Air is a common material of dielectric layer and pressure inside closed cavity has an impact on sensors' sensitivity. Silicon germanium (SiGe) was chosen as the membrane/diaphragm material in this study, enabling monolithic integration of a wide array of MEMS sensors and actuators on top of CMOS. Using a square diaphragm with side length of 400 μm, 70 kPa was required for diaphragm to reach the bottom electrode with gap of 1 μm and no external pressure was applied to it. By contrast, with 30 kPa external pressure, sensitivity of the sensor rises to 12 fF/MPa/ mm^2 , which is ten times larger than the sensor containing a 300 μm-wide circular diaphragm with 0 mbar pressure keeping non-linearity lower than 1% [9].

The fourth approach introduces a dual-contact (double-touch) mode in the pressure sensor, in which a cuboid cavity (length 50 μm, depth 1 μm) is etched at the center of the silicon substrate, serving as the bottom electrode, as shown in Figure 2(a). Within normal mode, whose pressure is

DOI: 10.54254/2755-2721/2025.GL28728

from 0 to 0.2 MPa, improvement in sensitivity for this design is insignificant. However, for touch mode, sensitivity increases to 41.67 pF/MPa/ mm^2 , which is almost doubled compared with single touch mode sensors at pressure from 0.28 MPa to 2 MPa [10]. Additionally, it was optimized in 2024 replacing the cuboid hollow with a conical with dpth of 2 μm shown in Figure 2(b), whose sensitivity increased to 199.07 pF/MPa/ mm^2 . Both sensors with double touch mode have remarkable linearity in touch mode [17-19].

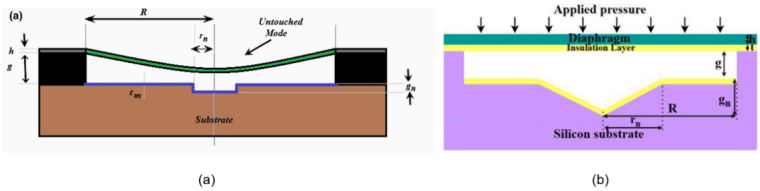

Figure 2. Double touch mode MEMS based capacitive pressure sensor: (a) with cuboid hollow [10]; (b) with conical hollow [19]

Placing multiple capacitors together as well as connecting them in parallel is another way to improve sensitivity by increasing change in capacitance. Both membrane with thickness of 2.5 μm in addition to diameter of 2.3 mm and substrate containing 180 hexagonal capacitors with side length of 75 μm are made of silicon whereas ring shaped insulation is silicon dioxide. At touch mode with pressure from 0.2 MPa to 0.6 MPa, Sensitivity of this sensor, whose gap distance is 420 nm, is 182.92 pF/MPa/ mm^2[12].

2.2. Structural factors influencing sensitivity and linearity

Apart from typical optimization method introduced in section 2.1, various structural properties would affect performance including sensitivity and linearity of a MEMS based capacitive pressure sensors as well. To improve sensor performance for proposed design with novel structure, factors influencing it is analyzed by review of previous sensor designs.

According to typical methods described above, performance of sensors improves gradually, and sensitivity of asymmetric electrodes is apparently higher than others, so review for innovative pressure sensors after 2020 is focused on those with similar features including wing shaped dielectric layer and comb shaped electrodes as examples.

Research is made to improve sensitivity of a MEMS based pressure sensor by cutting off two 0.5 μm^2 rectangular pieces on each edge of a square diaphragm in addition to selecting GaAs as the material of diaphragm due to its highest sensitivity shown in Figure 3, which is 333.3 pF/MPa/ mm^2 in the test. From graph plotted in the article, GaAs also has the most linear result at the same time [16].

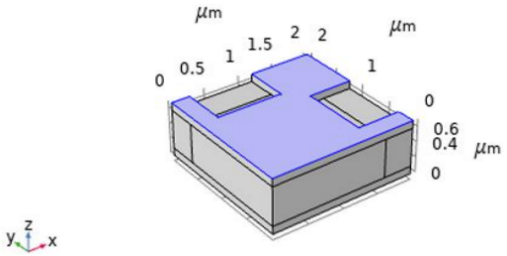

Figure 3. MEMS based capacitive pressure sensor with 2 edges cut [16]

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A novel structure was introduced for comb shaped pressure sensor, where electrodes are classified into moving combs and fixed combs in 2024. Unlike typical straight plate electrodes, spiral type made of gold is used with a silicon diaphragm, and air being used as dielectric layer displayed in Figure 4(a). Geometric parameters were selected for this design, which is simulated using COMSOL Multiphysics and pressure range from 0 to 50 kPa is set, to maximize both mechanical sensitivity as well as capacitive sensitivity. With 10-μm-thick and 500-μm-long diaphragm, 3-μm-thick and 60-μm-high electrodes, 2-μm-wide gap as well as 30-μm long overlap electrode, sensitivity of sensor ascents to 5.33 pF/ MPa/ mm^2 . For practical experiments, optimized sensor with horizontal placement, whose R^2 is 0.99135, had better performance compared to not only sensors with straight plate comb electrodes but also spiral electrodes with vertical placement [18]. Another way to optimize sensors with straight comb electrodes is to connect multiple comb shaped capacitors with coupling beam length of 1.55 mm shown in Figure 4(b). It is designed in this way for reducing complexity of manufacturing as well as improving sensitivity and minimizing non-linearity. Capacitor is built up with 24 identical segments with length of 100 μm and width of 5 μm, whose sensitivity is 8.833 nF/MPa/ mm^2 within pressure range of 0 Pa to 100 kPa and its non-linearity is 0.39% which is extremely low. However, with more complex structure, its volume is larger than other sensors [20-22].

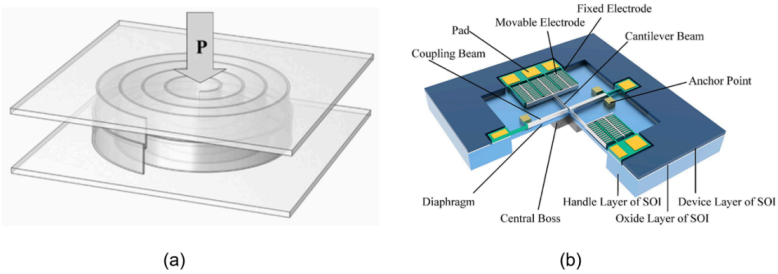

Figure 4. MEMS based capacitive pressure sensor with comb electrodes: (a) spiral [18]; (b) coupling beams [22]

Apart from redesigning either shape or structure of electrodes, improvement could be done through innovation on dielectric layer as well. For instance, silicon nitride dielectric layer is wing shaped with slant angle of 33.8° and 3.6 μm in length in this design shown in Figure 5 aiming to enhance sensitivity and widen linear operational region by increasing contact area. Using equation 1, for a diaphragm 10 μm thick and 180 μm in radius, the sensitivity under external pressures from 0.28 to 1.75 MPa is 392 pF/MPa/ mm^2 , with acceptable linearity [23].

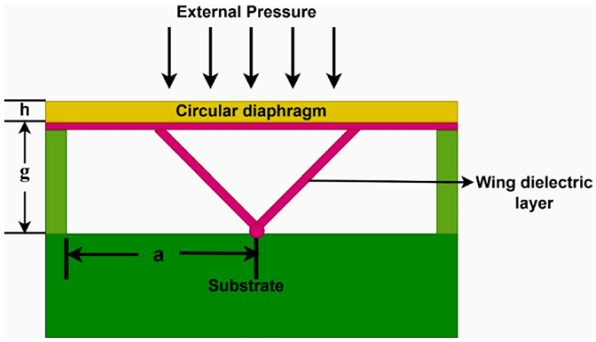

Figure 5. MEMS based capacitive pressure sensor with wing shaped dielectric layer [23]

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Another design is replacing insulation layer with massive dielectric cylinders with thickness of 0.1 mm shown in Figure 6. Through multiple tests with different shape and mesh level of dielectric layer, combination of circular diaphragm and finer mesh shows the best sensitivity of 5.959 nF/MPa/ mm^2 at pressure of 200 kPa and its desirability is 90.5% representing a great performance in linearity as well. Compared with other designs, materials used in this sensor are different, containing a polydimethylsiloxane diaphragm and a polyvinylidene fluoride dielectric layer, which may rise difficulty in manufacturing process [20].

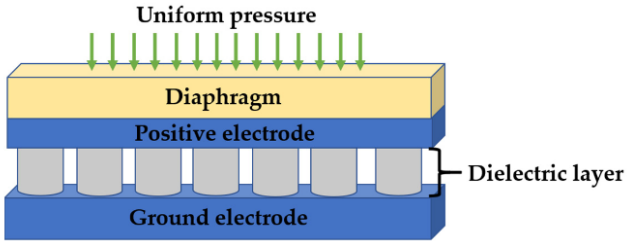

Figure 6. MEMS based capacitive pressure sensor with dielectric cylinders [20]

Based on previous research, structural factors influencing both sensitivity and linearity include material of sensors, sensors' geometric parameters, such as thickness and overlap area, in addition to shape and architecture of electrodes and dielectric layer. Among them, shape and architecture of electrodes and dielectric layer is the most influential factor, which increases sensitivity by almost 1 million times.

2.3. Summary of advantages and limitations of existing designs

Overall, to compare all sensors mentioned above clearly, both advantages and disadvantages including corresponding parameters are summarized in Table 1 shown below sorted by sensitivity.

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Table 1. Sensitivity, linearity and key features of previous MEMS based pressure sensor designs in conclusion

Type of design	Sensitivity (F/MPa/mm^2)	Linearity (R^2)	Key features	Limitations
Comb shaped [22]	8.333n	99.61%	Lever amplification boosts displacement	Comb uniformity critical
Dielectric cylinder layer [16]	5.959n	90.5% (desirability)	High desirability via DoE	Sensitivity depends on temperature
Wing shaped dielectric layer [23]	392p	remarkable	Wider linear range	Complex wing fabrication
Modified square diaphragm [16]	333.3p	good	High sensitivity with small size	Unmentioned linearity under tests with large pressure range
Conical notch [19]	199.07p	99.61%	Larger touch area	Requires precise cone geometry
Micromachined [12]	182.92p	99.61%	Highest absolute sensitivity	Large die size; hysteresis without DC bias
DTMCPS with cuboid hollow [10]	41.67p	99.93%	Dual-touch points extend linear range	Higher fabrication complexity
Spiral comb electrodes [18]	5.333p	99.135%	Capacitance change dominated by electrode overlap	Absolute capacitance in specific range demands ultra-high-resolution readout
Parallel plate with specific ratio of thickness [7]	554.1f	good	Tailored for biomedical use	Limits integration in ultra-miniaturized systems.
Sealed cavity [9]	12f	>99%	Tunable cavity pressure for linearity	Sensitivity drops at higher cavity pressure
Conventional circular diaphragm [6]	10.66f	>99%	Good linearity at high pressure	Lowest sensitivity

From table above, high sensitivity would sacrifice linearity of signals produced by the sensor. Apart from that, sensors with asymmetric electrodes have better performance than other designs.

3. Conclusion

In this investigation, a review of recent advancements in MEMS capacitive pressure sensor designs was conducted, focusing on the interrelationships between structural factors, sensitivity, and linearity. Various architectural approaches, including different diaphragm geometries, modified electrode configurations, and innovative dielectric layer designs, were analyzed. The results indicate that non-uniform electrode designs and asymmetric structures can enhance sensitivity and widen the linear operational range compared to traditional flat-plate sensors. These improvements can be achieved without the need for additional mechanical amplification mechanisms.

The study highlights that the shape and architecture of electrodes and dielectric layers are the most influential factors in improving sensor performance, potentially increasing sensitivity by several orders of magnitude. However, high sensitivity often comes at the cost of linearity, and fabrication complexity remains a challenge.

DOI: 10.54254/2755-2721/2025.GL28728

This review is based on previously published research and simulations. As a result, the actual performance of some of the proposed designs in real-world scenarios might differ from the reported outcomes due to factors like fabrication tolerances, variations in material properties, and environmental influences.

Future work should focus on several aspects. Firstly, the fabrication of promising sensor designs can be realized to validate simulation results experimentally. Secondly, fabricated sensors would be tested under various pressure conditions and environmental settings to evaluate their actual sensitivity, linearity, and reliability. Thirdly, the integration of sensors with interface circuits could be explored to assess overall system performance. Eventually, electrode geometries and sensor structures would be optimized further to balance the trade-off between sensitivity and linearity.

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