A Review of MEMS based Capacitive Pressure Sensor

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Abstract: *This paper presents a review of the capacitive pressure sensor. Firstly, the different types of sensors available are compared. For applications requiring high sensitivity and very low effects due to temperature, the capacitive sensor is preferred. Various methods to change the capacitance are also compared, which leads to the conclusion that the method involving changing the distance between the plates has the highest sensitivity. The different diaphragms available are also compared in this paper. The result of the comparison shows that the square diaphragm is most suitable. Further study shows that the diaphragm with a bossed structure has the highest sensitivity and the lowest nonlinearity. After the structural analysis, the pull-in effect phenomenon present during anodic bonding is also studied. The analysis of the pull-in effect showed that the dimension of the sensor should be chosen such that the electrodes do not stick during the anodic bonding. Different capacitive sensing schemes are also shown in this paper. The parasitic capacitances and the noise are major factors limiting the performance of the sensor. So the sources and methods to mitigate such effects are also presented. The ASICs available for the conversion of the capacitance to voltage or digital output are compared based on different parameters.*

Key words: **Capacitive pressure sensor, sensitivity, nonlinearity, bossed diaphragm, pull-in effect, differential structure, capacitance to voltage circuit**

1. INTRODUCTION

MEMS stands for microelectromechanical systems. MEMS technology combines microelectronics and mechanical systems. MEMS sensors and actuators are used in almost every modern system. MEMS sensors have accommodated a major part of the sensor market in recent years and are fast developing with new capabilities. The MEMS pressure sensors are being used in various areas like biomedical, defence, automobile, consumer products, industries, and many more civilian and domestic applications. MEMS pressure sensors claim 72% of revenue, medical electronics at 12%, industry segments at 10%, and the rest 6%, split between consumer electronics and military/aerospace applications. The current pressure sensors are being used in the pressure range from a few Pascals to mega Pascals. The sensors are to being used in the temperature ranges between – 25 oC to 125 oC and advancements are being made to operate the sensors above 600 oC. Among the various pressure sensors, piezoresistive and capacitive sensors are widely used. Piezoresistive pressure sensors provide high sensitivity, and they have linear operation for a wide range of pressure. Capacitive pressure sensors are preferred as they provide high sensitivity and the change due to temperature is very small. MEMS pressure sensors include a flexible diaphragm that deforms on the application of pressure, and this deformation is converted to an electrical signal, generally voltage or digital signals. Bulk micromachining is generally used to create the silicon membrane in the pressure sensors. Piezoresistors are patterned across the diaphragm. The sensor is generally designed and packaged so that the topside of the diaphragm is exposed to the environment for the application of pressure. (Balavalad et al., 2015) The change in pressure forces a deformation of the diaphragm; this deformation results in a change in resistance of the piezoresistors and, in turn, a change in voltage by on-chip electronics (Wheatstone bridge). Capacitive sensors consist of a fixed electrode and a movable electrode, The movable electrode displaces under the applied pressure, which results in a change in capacitance. The change in capacitance depicts the applied pressure.

This paper aims to provide a review of the technological advancements in pressure sensor technology. The main focus of this paper is the capacitive pressure sensor, the advancements in its structure, and various factors affecting its design.

2. Evolution of the mems pressure sensor

2.1 Strain Gauge Sensors

The first developed pressure sensors was a metal strain gauge. This sensor is still being widely used in the mechanical transducers used in the industries. These sensors change their resistance on the application of force, pressure or any external physical quantity leading to the deformation in the sensor (Hilal M & Mohamed.S. 2011).

Strain gauges were made of metal foil as well as metal wire in these sensors. (Bao et al., 2005) the strain gauge sensors were fabricated by conventional machining technique. The effect of the metal strain gauge is isotropic. (Oluwole O.O et al., 2015) carried out a uniaxial stress analysis testing with the designed strain gauge measurement instrument on a clamped wooden beam that has a modulus of elasticity 10700 N/mm^2, length of 250mm and cross-sectional area of h = 4.5 mm , b = 25mm applying load in an incremental succession, the strain and stress at different load interval was determined. For applied load 0.9806 N the experimental strain value was 250.14×10^{-6} while the theoretical strain value was 271.54×10^{-6} and for applied load 1.4709 the experimental strain value was 362.12×10^{-6}, while theoretical strain value was 407.31×10^{-6}. (Isrel et al., 2021) performed experimental stress analysis with a full wheatstone bridge created with strain gages. The analysis involved stepwise stress measurement by keeping the application piece with Wheatstone bridge connection by increasing from 5-50 kN with 5 kN increments for certain periods of time. The results showed a strain of 22.95 MPa for 50 kN.

2.2 Piezoresistive Sensor

In 1954 the piezoresistance effect in the semiconductors was discovered by S.C Smith. He discovered that the change in the resistance in semiconductors like silicon and germanium was higher than in the metal strain gauges. This higher change was due to the fact that the change in the resistance in the piezoresistors based on semiconductor was basically due to the change in the resistivity of the material rather than change in resistance due to geometric deformation as in the metal strain gauge sensors. Therefore the effect of the piezoresistances was two order higher than the metal strain gauge sensors (Bao et al., 2005). The resistivity change in piezoresistors is due to changes in inter-atomic spacing resulting from strain which affect the bandgaps, making it easier (or harder depending on the material and strain) for electrons to be raised into the conduction band as reported in [3]. The effect of piezoresistance is generally anisotropic. Within a certain range of strain this relationship is linear, so that the piezoresistive coefficient are constant [3].

$$\rho\sigma = \frac{\left(\frac{\partial\rho}{\rho}\right)}{\varepsilon} \tag{1}$$

Where

$\partial\rho = Change\ in\ resistivity$

$\rho = Original\ resistivity$

$\varepsilon = Strain$

With the discovery of piezoresistance effect, it was realized that the large effect of resistance change in this effect would have important applications in sensors, especially in the mechanical sensors which were dominated at that time by metal strain gauge sensor.

(Jing et al., 2020) prepared a piezoresistive sensor based on the graphene-PDMS @ sponge by fixing graphene on a sponge skeleton using PDMS. This piezoresistive sensor exhibited high elasticity (strain up to 85%), high sensitivity (0.075 K Pa^{-1}), a wide responding range (0–50 KPa) and high stability (2000 cycles pressure test).

(Zhang et al., 2016) reported a simple process to manufacture a piezoresistive sensor with high elasticity. The process was based on repeatable dipping and coating. The sensor was based on a homogeneous 3D hybrid network of carbon nanotubes@silver nanoparticles (CNTs@Ag NPs) which were anchored on a skeleton sponge. The sensitivity of the sensor was increased to a great extent after adding more Ag NPs. For the ratio of 1:20, the sensitivity was 2.12 kPa^{-1} at 2.24−11 kPa and about 9.08 kPa^{-1} at 11−61.81 kPa.

(Tian et al.,) reported that a flexible piezoresistive tactile sensor can exhibit a sensitivity up to 0.96 kPa^{-1} by integrating two face to face laser patterned graphene films. (Pang et al.,) reported a mechanical sensor achieve pressure and strain-sensing properties with a combination of graphene porous network (GPN) and polydimethylsiloxane (PDMS), which shows a sensitivity of 0.09 kPa^{-1}.

(Lee et al., 1982) presented a batch-fabricated silicon capacitive pressure transducer with low temperature sensitivity. It also reported temperature coefficients of the zero-pressure offset voltage have been equivalent to between 1 and 5 mmHg/^{o}C, while typical temperature coefficients of the pressure sensitivity have been from -1500 to - 4000 ppm/^{o}C, depending on the resistor doping level.

Therefore capacitive pressure sensor is better due to reduced temperature sensitivity and increased sensitivity.

2.3 Piezoelectric Sensor

Piezoelectric sensor is based on the principle of conversion of the deformation in the material to the voltage unlike piezoresistive which converts the deformation to resistance. Materials like single crystalline material (such as quartz), (piezoelectric semiconductor (such as ZnO_2), tourmaline, and Rochelle salt have this property to produce voltage on the application of pressure or force leading to strain in the material. This piezoelectric effect was discovered by Pierre Curie in 1880 but the manufacturers begin to use the piezoelectric effect in 1950. The piezoelectric effect was not used till early 20th century due to the development of electronic oscillator and amplifier in the early 20th century which were used to drive the piezoelectric element. Since then, this measuring principle has been increasingly used, and has become a mature technology with excellent inherent reliability as reported in [8]. There is formation of electric charge across the faces of the piezoelectric material on the application of the pressure, this electric charge can be measured as the voltage across the faces of the material. (Kim et al., 2022) a stretchable piezoelectric strain sensor was developed by introducing a kirigami pattern to achieve stretchability in a rigid PVDF film. In addition to the sensor developed a circuit was also designed to measure the output voltage generated due to the strain formation accurately and consistently. The kirigami piezoelectric sensor fabricated had a sensitivity of 9.86 V/cm^2 and stretchability of 320.8%, the highest values reported to data for kirigami piezoelectric strain sensors. (Zhang et al., 2016) developed a sensor consisting of different capacitors whose capacitances became much larger than that of the piezoelectric quartz sensor which was in parallel with the quartz sensor. With this method, the data of the sensitivity enhancement of piezoelectric sensors were obtained. Experimental results in this study showed that the sensor sensitivity was increased from 4.00 pC/N to 4.07 pC/N when the capacitance of parallel capacitors was increased from 500 to 1000 and then 5000 times of that of the sensor. The force sensor sensitivity was improved by 1.75%. This sensor also has the lowest response time.

There is also an inverse piezoelectric effect where applying a voltage to the material leads to deformation of the sensor structure.

2.4 Capacitive Pressure Sensor

The next major development in the sensors was the development of the capacitive pressure sensor. The capacitive pressure sensor is based on the principle of capacitance changing on the application of pressure.

The Capacitance of the capacitor is given by:

$$C = \frac{\varepsilon_r \times \varepsilon_o \times A}{d} \qquad (2)$$

Where

$C = Capacitance$

$\varepsilon_r = Dielectric\ constant\ of\ material\ between\ the\ plates$

$\varepsilon_o = Permittivity\ of\ free\ space\ \ (8.85\ X\ 10^{-12}\ \frac{F}{m})$

$d = distance\ between\ the\ plates$

$A = Overlap\ area\ of\ the\ plates$

(Shivaleela.G et al., 2017) proposed a MEMS based capacitive pressure sensor using 1-spring, 4-springs and 9-springs has been designed having a square diaphragm of length 10,000µm × 10,000µm and thickness of 525µm using Finite Element Method (FEM). The simulation results showed that the 9- springs capacitive pressure sensor model achieves a good and high sensitivity of 1.010e0pF/pa with displacement of 3.288e-5 µm at applied pressure of 1Pa as compared to 1- spring and 4-spring capacitive pressure sensors.

(Lee et al., 1982) The capacitance change in a capacitive sensor for temperature input is negligible. The resulting temperature coefficient of sensitivity (TCS) is -6950 ppm/°C and the temperature coefficient of offset (TCO) is - 1600 ppm/°C, which is equivalent to about -2 mmHg/°C near room temperature.

(Shaikh et al., 2008) presented a comparative study between the capacitive and piezoresistive MEMS sensors for pressure measurement. He observed that the sensitivity curve of piezoresistive is steeper than that of capacitive pressure sensor piezoresistive pressure sensor sensitivity changes up to 180 mmHg whereas capacitive pressure sensor sensitivity changes up to 335mmHg.

Therefore capacitive pressure sensor is preferred over piezoresistive sensor because it has various advantages over piezoresistive and other sensors such as less temperature dependent and have low energy consumption whereas the piezoresistive pressure sensor is temperature dependent and have large energy consumption. Another advantage of the capacitive pressure sensor is to be able to detect larger pressure changes than the piezoresistive sensor. The capacitive pressure sensor also has higher accuracy and faster response times due to small capacitances involved.

The major disadvantages of capacitive sensor are susceptible to EMI, parasitic capacitances and low sensitivity than piezoresistive sensors.

Table – 1: Comparison between the sensors [8] – [11]

Properties	**Type**			
	Strain Gauge	**Piezoresistive**	**Piezoelectric**	**Capacitive**
Principle	Change in Reistance	Change in Resistivity	Formation of electric charge	Change in Capacitance
Pressure range	Low	Low (21 kPa to 150	Moderate (0.7 kPa to 70	High (250 Pa to 70

		MPa)	MPa)	MPa)
Sensitivity	Moderate	High	Moderate	High
Linearity	Low	High	Low	Moderate
Power consumption	High	High	Low	Low
Temperature sensitivity	High	High	Low	Low
Susceptibility to EMI	Low	Low	Low	High
Response time	Moderate	Moderate	Lowest	High

Therefore for pressure sensing applications capacitive senor is preferred as it has widest pressure range, high sensitivity and insensitive to temperature.

3. Capacitive pressure sensor

3.1 Methods to change the capacitance

3.1.1 Changing the dielectric medium

The capacitance is directly proportional to the dielectric medium of the capacitor. Therefore by changing the dielectric constant between the electrodes the capacitance can be changed. For the application of the pressure sensor the dielectric between the electrodes needs to be displaced on the application of the pressure.

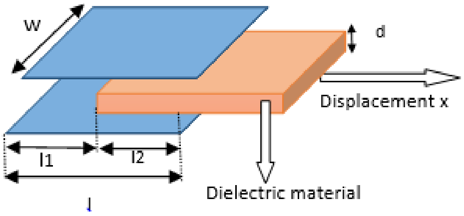


Fig. 1: Displacing the dielectric

When displacing the dielectric, change in capacitance is $\Delta C = \varepsilon_o \frac{w}{d} (\varepsilon_r - 1)\, x$. The dielectric constant of the material being displaced is ε_r. So the change in capacitance is directly proportional to the displacement.

The dielectric is an insulator that gets polarized under the application of electric field. Due to this polarization there is an electric field generated field inside the dielectric medium in the direction opposite to the external electric field. This results in increase in the capacitance of the sensor.

This method is used generally by using different geometries of the dielectric between the electrodes and changing the distance between the electrodes.

(Chaurasia et al., 2017) proposed a novel parallel plate capacitor having a droplet of dielectric in between the electrodes. On the application of the pressure the distance between the electrodes is decreased and the contact area between the electrode and the dielectric is increased. This resulted in enhanced sensitivity of 28 $\frac{\frac{\Delta C}{C}}{displacement\ (cm)}$.

(Chhetry et al., 2017) has designed a flexible and highly sensitive capacitive pressure sensor which was also fabricated by coating a microporous polydimethylsiloxane (PDMS) elastomeric dielectric onto conductive fibers. The designed capacitive pressure sensor had two microporous PDMS-coated fibers which were cross-stacked to function as a capacitive sensor. This sensor responds to compressive stress. As on applying stress due to any external agent the contact area was increased and the separation between the fiber electrodes was decreased. The developed sensor produced relatively high sensitivity of 0.278 kPa^{-1} for a low pressure region (< 2 kPa).

(Kim et al., 2022) developed a highly sensitive and flexible capacitive pressure sensor based on the porous Ecoflex, which has an aligned airgap structure and can be manufactured by simply using a mold and a micro-needle. Three different ranges: low-pressure range (1–500 Pa), middle-pressure range (500–15 kPa), and high-pressure range (15–100 kPa) were selected as per the requirements. The fabricated sensor based on the porous Ecoflex and an aligned airgap structure showed a linear response in all three pressure range. The sensitivities of the developed sensor were 1.277 kPa^{-1}, 0.045 kPa^{-1}, and 0.022 kPa^{-1}.

In this method the pressure is applied normal to the electrode surface and the distance is changing. The change in capacitance is linear but the sensitivity is lower than the method to change the distance between the electrodes.

3.1.2 Changing the overlap area

The capacitance of the sensor is directly proportional to the overlap area of the capacitor. Therefore changing the overlap area results in change in the capacitance of the sensor. This method is preferred to transduce large displacements as larger travel range is available for the capacitive plates. (Boser et al.) The change in capacitance w.r.t pressure is linear in this method but has low sensitivity.

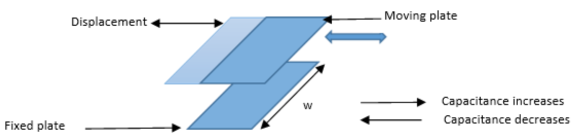


Fig. 2: Displacing the electrodes laterally

l- Length of overlapping plate

w -width of the overlapping area

d –distance between them

Therefore the nominal capacitance, $C_o = \frac{\varepsilon wl}{d}$

Now when the electrodes are displaced by any external agent, there is a change in the overlap area between the electrodes. Here if the electrodes are displaced laterally such that the width (w) remains same but length (l) changes, so the capacitance is changed which is given by:

If the electrode is moved by distance x, then the final capacitance will be:

$$C = \frac{\varepsilon w(l-x)}{d} \quad (3)$$

Now the change in the capacitance is,

$$C - C_o = \frac{\varepsilon w(l-x)}{d} - \frac{\varepsilon wl}{d} \quad (4)$$

$$\Delta C = -\frac{\varepsilon wx}{d} \quad (5)$$

So the change in capacitance will be directly proportional to the displacement due to pressure.

So this method does not have the pull in effect on the application of the voltage. This method has low sensitivity than the other two methods. It also has low nonlinearity than the other two methods.

3.1.3 Changing the distance between the plates

The capacitance in a parallel plate configuration is inversely proportional to the distance between the plates. In this method the pressure is applied perpendicular to the surface of the plates. This pressure leads to the displacement of the plates to decrease the distance between the plates. The change in the capacitance has a hyperbolic relation to the change in the distance between the plates i.e. $C = \frac{\varepsilon A}{d_o \pm d}$.

However if two capacitors are considered, out of these one has a constant capacitance and the capacitance of the second capacitor's capacitance changes with pressure. Then it has the relation as described below.

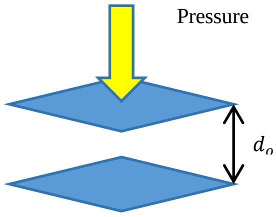


Fig. 3: Application of pressure perpendicular to the surface of the plates

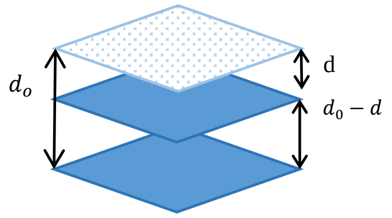


Fig. 4: Displacement of the movable plate on the application of the pressure

Initial (Nominal) Capacitance: $C_o = \frac{\varepsilon A}{d_o}$ (6)

Final Capacitance: $C = \frac{\varepsilon A}{d_o - d}$ (7)

Assumption: $d \lll d_o$

(d_o Approximately 3 order larger than d)

Change in capacitance:

$$\Delta C = \frac{-\varepsilon A d}{d_o^2} \quad (8)$$

(Boser et al.) Change in capacitance in this method is 10 times more than the overlap area method. This method is preferred to transduce small displacements than the overlap area method. This method has higher sensitivity but travel range is limited to the small distance between the plates. The major disadvantages of this method are nonlinear characteristic curve and pull in effect.

(Young et al., 2004) proposed a single-crystal 3C-SiC capacitive pressure sensor. The fabricated sensor in this paper showed a high-temperature sensing capability up to 400 °C, which was limited by the test setup. At 400 °C, the device achieves a linear characteristic response between 1100 and 1760 torr with a sensitivity of 7.7 fF/torr, a linearity of 2.1%, and a hysteresis of 3.7% with a sensing repeatability of 39 torr (52 mbar)

(Saleh et al., 2006) performed modelling and analysis of a fabricated sensor. This sensor was a fully integrated Double-Ring Capacitive Pressure Sensor. The fabricated sensor showed sensitivity of 150μV/V-mmHg, which was the major advantage of the fabricated sensor. Also the sensor showed higher sensitivity (150µV/V-mmHg) than the piezoelectric or piezoresistive pressure sensors.

(Chang et al., 2004) stainless steel was studied as a potential robust substrate and a diaphragm material for micromachined devices. The pressure was applied to normally to the diaphragm resulting in bending the diaphragm. The sensitivity of the device fabricated was 9.03 ppm kPa−1 with a net capacitance change of 0.14 pF over a range 0–178 kPa.

The sensors developed by using this method has high sensitivity and highest nonlinearity compared to other methods.

Table – 2: Comparison between the methods [12], [13], [29],[30]

Parameter	**Method**		
	Overlap area of the plates	**Distance between the plates**	**Dielectric**
Transduce displacement	Large	Small	Large
Sensitivity	Low	High	High
Travel Range	Large	Limited	Large
Pull-in	No	Yes	No
Linearity	Highest	Low	Moderate
Change in Capacitance	Low	High (10 times)	Moderate

Therefore for small displacements and high sensitivity the method preferred is changing the distance between the electrodes of the capacitor on the application of pressure.

3.2 Different diaphragms structures available

There are different diaphragm structures available. The square, circular and the rectangular diaphragms are the commonly used structures. This paper compares three different diaphragm structures which are square, circular and rectangular.

(Balavalad et al., 2015) performed simulations for the designed pressure sensor whose top electrode was free, whereas the bottom electrode was fixed. The different diaphragm were compared keeping the area of the diaphragm and electrode same. The conclusion of the simulation were as shown in table below.

Table – 3: Results of the simulation

Properties	**Diaphragms**		
	Square	**Circular**	**Rectangular**
Capacitive Readout	Average	Better	Average
Linear Output	Moderate	Least	High
Percentage Relative Change in Capacitance	Moderate	Highest	Lowest

The Circular diaphragm showed best PRCC (percentage relative change) compared to the square and rectangular models. But it also showed highest nonlinearity as compared to the other two diaphragms.

(Lahreche et al., 2022) paper presents the design, simulation and analysis of capacitive pressure sensor based on MEMS technology. The square and circular shape diaphragm were compared for same overlapping area between the plates. The results in this paper showed that the membrane deflection is linearly related to the applied pressure. The results obtained showed that the circular membrane structure had a high capacitance of 1.325 pF at applied pressure of 25000 Pa. Additionally, in case of increasing temperature, the results showed that the capacitance for circular shape was also higher than that for square shape diaphragm.

(Roy et al., 2014) MEMS capacitive pressure sensor of with two different geometries were designed for measurement of absolute pressure. Both of these sensors were designed with parallel plate configuration where one was movable and the other plate was fixed. The only difference with common parallel plate structure was that one of the movable plates was supported by four anchors with respect to the fixed plate. Two such structures, one having circular shaped parallel plates whereas the other having square shaped were analysed. Both the sensors had equal diaphragm area. Detailed simulation and analysis on the electromechanical, mechanical as well as material studies were also performed. The pressure sensors were designed for measuring a particular range of pressure 10KPa to 100KPa. Circular shaped sensor was more sensitive than square one.

Therefore as a tradeoff between the sensitivity and nonlinearity the square diaphragm is the best option. As it has lower nonlinearity than circular diaphragm and higher sensitivity than rectangular diaphragm.

3.3 Bossed diaphragm structure

The linear square diaphragm has large nonlinearity as the central area of the diaphragm has the highest displacement on the application of pressure and therefore there is nonuniform displacement across the diaphragm. So for having uniform displacement across the diaphragm a new structure was proposed. This structure had a proof mass in the center of the diaphragm. This proof mass can be situated above the diaphragm or below the diaphragm inside the cavity or vacuum. When using this proof mass in the diaphragm then there is a parallel motion between the electrodes of the capacitor. This parallel motion reduces the nonlinearity to a great extent.

(Ettouhami et al., 2004) proposed a new structure to improve the contribution of edges and hence the sensor sensitivity, by decreasing the thickness of diaphragm edges. The resulting diaphragm has a square boss at the center (Fig. 8). He also proposed an optimal size leading to a maximum contribution of the all points of the diaphragm. He proposed that for the maximum sensitivity the ratio of the boss side length to the diaphragm side length should be between 0.4 and 0.5. So in this case the square central boss occupies from 16 % to 25 % of the diaphragm area. The value of the ratio of the boss thickness to the diaphragm thickness for maximum central displacement was stated as 2. The sensitivity was increased and nonlinearity was decreased from 6.4 % to 2.7 % for differential structure with bossed diaphragm.

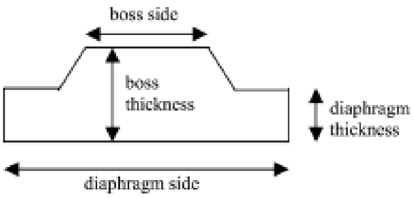


Figure 5: Cross section of square diaphragm with a square central boss [5]

(Ramesh et al., 2015) performed an analysis using Multiphysics tool and the results showed that the capacitance sensitivity of normal diaphragm was 0.011pF/kPa and that of bossed diaphragm is 0.012pF/kPa.

(Yongtai He et al., 2012) presented a novel capacitive pressure sensor with the island-notch structure. The results showed that the linearity of the capacitive pressure sensor with island-notch structure reached up 0.9941 in the linear measurement zone, the sensitivity reached up 0.0019 pF/kPa, and the measurement range of the sensor is also increased.

Therefore for increased sensitivity and low nonlinearity bossed diaphragm should be preferred.

3.4 Single and Differential Sensing Structure

There are two types of sensing structures available single and differential sensing structures.

In single sensing structures there is only one capacitor involved in the sensing structure whereas in differential sensing structure there are two capacitances involved. (Ettouhami et al., 2004) The differential sensing structure has higher sensitivity when compared to single sided structure. The nonlinearity error reduces from 6.4 % to 3.8 % for differential structure.

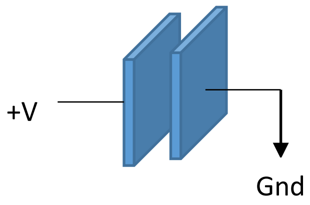


Figure 6: Single Sensing Structure

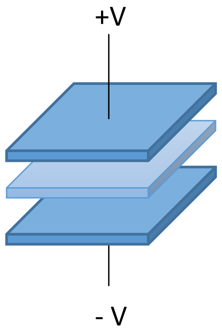


Figure 7: Differential Sensing Structure

(Achouch et al., 2020) designed a capacitive pressure sensor for large deflections. This work stated that the sensitivity was increased from a minimum of 9.98 x 10^{-2} pF/hPa to a minimum of 3.4 x 10^{-1} pF/hPa for differential structure. The linearity was also improved.

Table – 4: Single v/s Differential Structure

Parameter	**Type**	
	Single	**Differential**
Sensitivity	Lower	Higher
Nonlinearity	Higher	Lower
Power Consumption	Lower	Higher
Complexity & Cost	Lower	Higher
Manufacturing Challenges	Lower	Higher
Sensor Footprint	Lower	Higher

The preference of the two structures depends on the application. For applications requiring higher sensitivity and where accurate pressure measurements are crucial the differential structure is generally preferred. Whereas applications with moderate pressure ranges, where high precision or sensitivity is not critical but manufacturing cost is important then single sided structure is preferred.

3.4 Single sided and double sided excitation

(Bao et al., 2000) Electric excitation is necessary for sensing the capacitance. The excitation voltage generates an electrostatic force between electrodes of the capacitive sensor and which leads to the movement of the movable electrode. As a result the accuracy of the measurement of the pressure or even the normal operation of the capacitive sensor is affected by the excitation voltage. The discussion till 3.3 was based on single excitation mechanism. In single sided excitation the excitation voltage generates a force on the movable electrode. As a result this mechanism has a fixed offset displacement on the application of the electric excitation.

(Bao et al., 2000) On the other hand the double sided driving is used in differential capacitance structure. In this excitation mechanism both the sides generate equal force on the movable electrode in opposite direction so there is no fixed offset. The linearity is better and the driving voltages can be larger without causing the pull-in effect.

Therefore in applications requiring higher sensitivity and lower nonlinearity with no offset displacement on the application of the excitation voltage, the differential structure is preferred.

3.5 Pull in effect during anodic bonding

In manufacturing of the capacitive pressure sensor anodic bonding is generally used. (Kárpáti et al., 2013) During this bonding 1000 V voltage is used for the bonding of the edges of the diaphragm to the substrate edges. (Bao et el., 2005) on the application of the voltage, there is Force applied by the stationary electrode to the movable electrode given by:

$$F_N = -\frac{A\varepsilon\varepsilon_o}{2x^2}V^2 \text{ Or } F_N = -\frac{Q_c^2}{2A\varepsilon\varepsilon_o} \qquad (9)$$

Where F_N *is the normal force*

Q_c = *charge stored in the capacitor*

ε_o = *Permittivity of free space* $(8.85\ X\ 10^{-12}\ \frac{F}{m})$

A = *Overlap area of the plates*

x is the distance between the plates

V is the volatge applied

(Wei et al., 2018) Pull-in effect is a common during anodic bonding. Anodic bonding is a key step in the fabrication process of capacitive sensors and actuators. So if the deformable electrode of the capacitor is forced by an electrostatic force due to the bonding voltage beyond the upper limit which is balanced by the mechanical restoring force, it will come into contact with a fixed electrode and remain attached even after the voltage is switched off (see Figure 8).

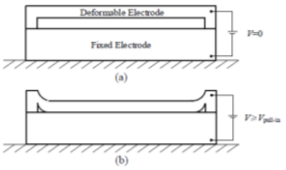


Figure 8: Pull in effect (a) Initial Structure without voltage bias and (b) attached structure with a voltage bias beyond pull-in voltage.

This is known as the pull-in effect and the critical voltage is called pull-in voltage. The pull in voltage is given by equation (10) as in [1], [7]:

$$V_{pull\ in} = \sqrt{\frac{8kd^3}{27\varepsilon_o A}} \qquad (10)$$

Where k is the mechanical elastic coefficient, d is the distance between the plates, A is the overlap area, ε_o is the permittivity of free space. For manufacturing process using anodic bonded for the capacitive sensors and actuators the pull-in effect frequently occurs. This pull-in effect occurs due to small gaps and large areas of capacitor plates with deformable features and extremely high bonding voltages being used during anodic bonding. To eliminate the pull in effect a capacitor is inserted in series with the mechanical capacitor.

As per mathematical calculations the pull in voltage is dependent on *d* and the mechanical elastic coefficient k so the value of *d* should be selected such that the

($V_{pull\ in}$) > (Voltage used in anodic bonding) (1000 V generally). Also the stable displacement of the movable electrode in the normal direction by an external agent is limited to one third of the original distance between the two plates.

3.6 Capacitive Sensing Scheme

After the manufacturing of the sensor die the readout circuit has to be designed. The change in the capacitance has to be measured and converted into a quantity which can be used for further processing. Therefore the change in capacitance is converted to voltage. Different sensing mechanisms used for this conversion of the capacitance to voltage are as follows:

(i) DC Bias sensing method

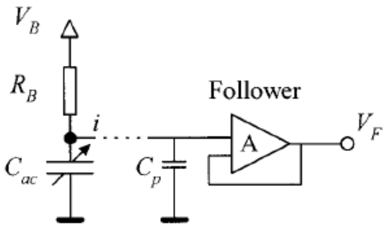


Figure 9: DC bias sensing method [1]

The DC bias sensing method has a DC voltage for biasing the sensing capacitor. The DC bias sensing method is relatively simple to implement and does not require complex circuitry.

(ii) Diode quad sensing method

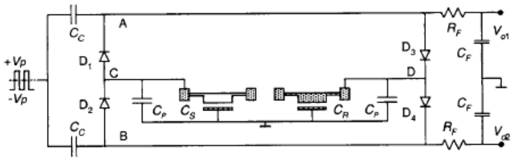


Figure 10: Diode quad sensing method [1]

In the diode quad sensing method, four diodes are arranged in a quad configuration. These diodes are typically connected in a bridge or diamond configuration, forming a network that interfaces with the capacitive sensor. The biasing voltage used in this is generally rectangular pulse. (Harrison et al., 1973) This method helps to isolate the sensor capacitance from the stray and cable capacitance.

(iii) Opposite driving sensing method

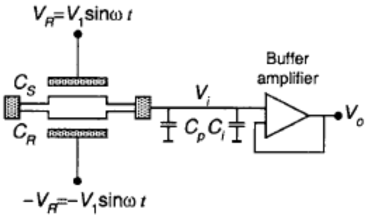


Figure 11: Opposite driving sensing method [1]

The opposite driving sensing method is an effective technique for capacitive touch sensing systems, offering improved SNR, reduced parasitic effects, and enhanced sensitivity for reliable and accurate touch detection. The sensing electrodes measure the differential capacitance changes induced by the application of the pressure. (Mohamed et al., 2015) By driving the electrodes in an opposite manner, common-mode noise and interference are minimized, improving the SNR of the measured signals. Opposite driving helps mitigate the effects of parasitic capacitance, stray capacitance, and environmental noise, leading to more accurate touch sensing.

(iv) Force Balancing Effect

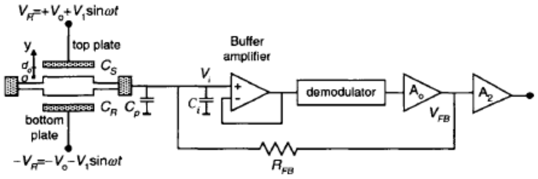


Figure 12: Force balancing sensing technique [1]

(Bao et al., 2005) In force balancing method the measurand is measured by the feedback voltage which creates an electrostatic force to balance the external force. This electrostatic force is in opposite direction to the external force and therefore keeps the central plate at the balanced position.

(v) Switched capacitor sensing method

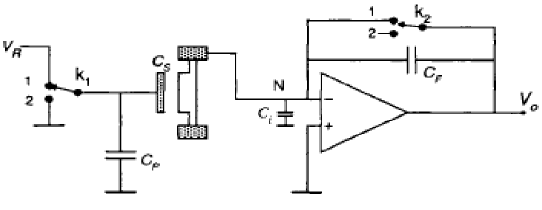


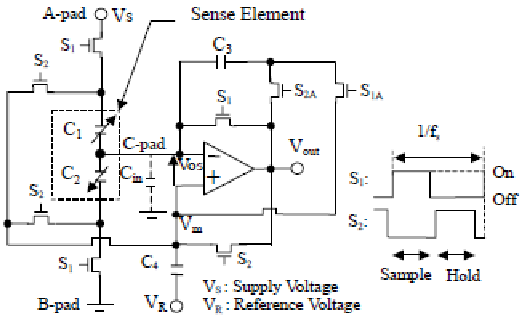
Fig. 4.30. Switched capacitor method

Figure 13: Switched capacitor sensing method [1]

(Masahiro et al., 2003) The switched capacitor is based on the charge balance principle. The major advantages of this method are immunity to stray capacitance. This method can also be used for offset correction.

Therefore due to reduced active and passive components in the circuit and immunity to stray capacitances the switched capacitor sensing method is preferred.

(Tsugai et al., 2003) developed a charge balanced capacitance to voltage converter for differential capacitor. In this the circuit was developed using opamp and switches using a new configuration for a switched capacitor type capacitance to voltage converter. The ideal results in this had 3.5 V and 4.5 V for the acceleration of 4G and 8G respectively.



(a) Circuit configuration (b) Clock timing diagram

Figure 14: Charge balanced C-V converter

(Alam et al., 2010) proposed a design of capacitance to voltage circuit for pressure transducer as shown in Figure 19. In this the design was able to measure a wide range of capacitance variations for the capacitive transducer. The designed circuit showed required performance parameters in terms of low power consumption, response and a linear output voltage. The circuit worked for a wide range of capacitance variation with a power supply voltage of 1.2 V. The capacitance was changed with 20fF steps in the simulation and the results showed linear output voltage within the range of 0.02-0.59V for the variation of the capacitance from 100-1640fF, respectively.

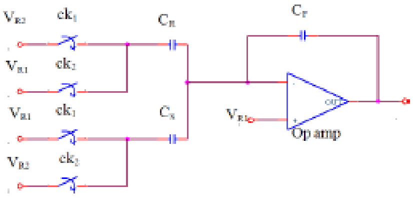


Figure 15: Capacitance to Voltage Converter (CVC)

3.7 Parasitic Capacitances

In the sensor various capacitances are introduced due to the die and the readout circuit. In practical situations for MEMS sensors the dimensions of the electrode are comparable to the distance between the electrodes. Therefore the capacitances cannot be approximated accurately as the edges of the electrodes have nonuniform electric field. As the electric field is present outside the sensor structure. This electric field leads to change in the capacitance. This effect is known as the fringe effect. Due to this effect the capacitance between the electrodes is larger than the nominal capacitance. Some examples are shown below.

Figure 16: Cross section of some typical capacitive sensors [1]

At electrostatic level, the fringing phenomenon acts when an uneven charge distribution is present and the resulted effect is an exterior electrical field with bent field lines. Due to this fringe effect the capacitance between the electrodes is larger than the nominal capacitance due to the fringe capacitances.

The parasitic capacitance are also generated between the bonding area of the diaphragm and the substrate. This bonding area usually has an insulator layer deposited.

The parasitic capacitance are also introduced by the PCB linking traces.

The parasitic capacitance are also generated between the top electrode and the ground and the bottom electrode and the ground. The readout circuit used also contribute to the parasitic capacitance.

3.7.1 Methods to avoid parasitic capacitances

(Daul et al., 2021), (Islam et al., 2017) To avoid the inaccuracy in the calculation of the parallel plate capacitor due to the fringing fields at the edges of the electrodes, the guarding is necessary. Due to this guarding electrodes the electric field is inside the electrode area and therefore no fringe capacitance in included in the nominal capacitance.

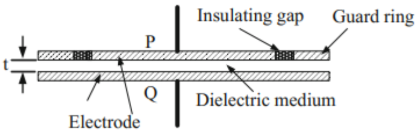


Figure 17: Parallel plate capacitor with guard ring [17]

To avoid the parasitic capacitance introduced by the PCB linking traces two traces one in front of the other can be positioned at the farther distance to avoid the mutual capacitance between the traces.

The readout circuit has intrinsic parasitic capacitance tolerance to avoid the parasitic capacitance due to the readout circuit.

(Nagatomo et al., 2018) Inserting low dielectric constant materials between the electrodes was reported to be effective to reduce the parasitic capacitance.

(Pedersen et al., 2009) An on-chip CMOS ASIC for signal conditioning helps in avoiding wire bonds that otherwise will induce parasitic capacitances.

(Pedersen et al., 2009) Another solution is to create a larger capacitive signal by fabricating an array of sensing elements that are coupled in parallel, such that the total capacitance is the sum of all the single elements, thus making the parasitic capacitance negligible.

3.8 Noise

Undesired signals that do not carry any information is called noise. The noise plays a crucial part in designing of a capacitive pressure sensor as the capacitive signals are very small in magnitude. The noise interferes with the capacitance signal and distort the output. The different types of noise present in a capacitive pressure sensor are Thermal noise, Flicker noise and shot noise.

Mechanical noise: (Utz et al., 2017) There is noise in the die due to the Brownian motion of the particles inside the packaged sensor. Due to the thermal motion of the air atoms inside the MEMS package there is collision of the atoms with the sensor structure leading to noise.

(Leland et al., 2005) derived the effect of the thermal noise on the MEMS gyroscopes. Therefore mechanical thermal noise is main source of noise other than the electrical noise.

Imperfections in the semiconductor: Imperfections in the semiconductor used for manufacturing the sensor can also lead to noise.

Thermal noise: The thermal noise is generally present at higher frequencies in the capacitive pressure sensor. (AlHinai et al., 2020) Thermal noise is one of the major sources of the noise that can affect the capacitive signals with low amplitude and comparable with the noise. The thermal noise is always present in the electrical equipment used in the circuit. The vibration of charge carriers within an electrical conductor causes the thermal noise and it is directly proportional to the temperature, regardless of the applied voltage.

Flicker noise or 1/f noise: (AlHinai et al., 2020) Flicker noise or 1/f noise is a function of frequency, and its effects are often observed at low frequencies in electronic components used in the circuit. The random motion of the charge carriers leading to the charge carriers being randomly trapped and released between the interfaces of two materials results in flicker noise. Instrumentation amplifiers used to record electrical signals generally have flicker noise due to this phenomenon.

Noise due to Power lines: (AlHinai et al., 2020) Power lines also introduces noise in the circuit. Power-line interference introduces 50–60 Hz frequency. This effect is due to the stray effect present in cables carrying signals from the sensor to the output.

EMI: There is also EMI (Electromagnetic Interference) present inside a capacitive pressure sensor due to the electric field of the electrodes of the sensor. This electric field can be changed by any external electric field and this could lead to change in the capacitance of the sensor.

Drift: Over time, capacitive pressure sensors may exhibit drift, where the baseline capacitance or output signal gradually changes even in the absence of pressure variations. Drift can be caused by factors such as aging of components, material properties changes, or temperature variations.

Quantization noise: (Utz et al., 2017) Some ASICs use direct conversion of capacitance change to digital signals. The direct conversion to digital signals from the capacitance leads to additional electrical and quantization noise.

3.8.1 Methods to reduce noise

The mechanical noise due to the air atoms inside the MEMS package can be reduced by vacuum sealing or electrostatic feedback.

(AlHinai et al., 2020) Elimination of thermal noise is impossible; however, it can be reduced by reducing the temperature of operation or reducing the value of the resistance in electrical circuits.

(AlHinai et al., 2020) Flicker noise can be effectively reduced by a technique called chopper stabilization or chopper, where the amplifier offset voltage is reduced. In this chopper stabilization technique the signal is modulated twice using a square wave, first at the input and then at the output stage. So the signal is chopped twice in this technique.

Different filtering techniques can be used to reduce the effect of PLI corrupting the signal.

The EMI sources can affect the capacitance of the sensor. So the sensor should be kept from EMI sources such as motors, power lines, and radio transmitters as far away as possible.

To prevent EMI the sensor is also generally shielded so that the external electric fields cannot change the capacitance of the sensor.

Grounding provides a path for the unwanted noise signal to safely discharge to the ground. So it's essential to ground the sensor and the shield at one point. Grounding will prevent creation of ground loops, which could inadvertently introduce more noise.

Choose components for the readout circuit with low noise and susceptibility to EMI. For example using opamp with in-built offset and noise cancellation.

(Eastsensor et al., 2024) Use shielded cables to connect the pressure sensor, and avoid running these cables parallel to power lines or near other sources of EMI. The shield should also be grounded at one end to provide an additional path for unwanted signals to be discharged.

3.9 ASICs

There are different developed Application Specific Integrated Circuits available for the readout of the sensors developed. These ASICs can be used according to the application requirements. Most of these ASICs also convert the sensed parameter to a quantity which can be used for further processing.

Table – 5: Different ASICs available [22 – 28]

Parameter	**MS3110**	**AD7745/46**	**FDC1004**	**CAV444**	**AD7152/53**	**FDC2214**	**ZSSC3123**
Type	Universal Capacitive readout	Capacitance to Digital Converter	Capacitance to Digital Converter	Capacitance to Voltage Converter	Capacitance to Digital Converter	Capacitance to Digital Converter	Capacitance to Digital Converter
Configuration	Single or Differential	Single or Differential	Single or Differential	Single	Single or Differential	Single or Differential	Single or Differential
Input Capacitance Range	0.25 – 10 pF	± 4 pF	± 15 pF	10 pF upto 10 nF	± 0.25 pF to ± 2 pF in differential 0.5 pF to 4 pF in single	250 nF	2 -260 pF
CAPDAC	10 pF	21 pF	100 pF	---	5 pF	---	---
Voltage Supply	+ 5 V	2.7 V to 5.25 V	3.3 V	5 V	2.7 V to 3.6 V Typical- 3.3 V	2.7 V to 3.6 V Typical- 3.3 V	2.3 to 5.5 V
Parasitic Capacitance Tolerance	---	60 pF	400 pF (Shield for EMI also present)	---	50 pF	4 pF (EMI resistance architecture)	10 – 80 pF
Noise	$4aF/\sqrt{Hz}$	$2aF/\sqrt{Hz}$	$33.2aF/\sqrt{Hz}$	---	---	System noise floor: 0.3 pF at 100 sps (samples per second)	---
Resolution	$4aF/\sqrt{Hz}$	4aF	0.5 fF	---	0.25 fF	---	125 aF
Resolution (bits)	---	21 bits	---	---	12 bits	28 bits	8 – 14 bits
Interface	---	I2C	I2C	---	I2C	I2C	I2C or SPI
Excitation frequency	100 kHz	32 kHz	25 kHz	3.5 kHz	32 kHz	10 kHz to 10 MHz	$(f_{sys}/2 - f_{sys}/16)$ kHz
Bandwidth	0.5 – 8 kHz	8 – 87.2 Hz	---	0 – 4 kHz Oscillator Frequency(1 – 240 kHz)	---	External master clock input: 2 – 40 MHz	---

4. CONCLUSION

This paper presents a review of the capacitive pressure sensor. Different type of sensors available are compared and analysed based on various properties showing that the capacitive pressure sensor should be preferred in applications requiring high sensitivity. This study also showed that the method involving application of the pressure normally and resulting in the displacement of the movable electrode normal to the fixed electrode and decreasing the distance between the electrodes should be preferred for higher change in capacitance. The diaphragm having a square bossed structures has the lowest nonlinearity. After the structural analysis the pull in effect was also analysed and the results showed that the diaphragm thickness and dimension of the sensor should be chosen such that the electrodes do not stick during the anodic bonding. Different capacitive sensing schemes are also shown in this paper. The parasitic capacitances introduced in the sensor due to various factors and the methods to avoid such capacitances are also explained in detail. The noise sources are also reviewed. A comparative analysis of the ASICs available for the conversion of the capacitance to voltage or digital output is also presented.

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