A HIGH-SENSITIVE ULTRA-THIN MEMS CAPACITIVE PRESSURE SENSOR

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ABSTRACT
This paper reports an ultra-thin MEMS capacitive pressure sensor with high pressure sensitivity of better than 150aF/Pa, and small die size of 1.0mm × 1.0mm × 60µm. It is able to detect ambient pressure change with a resolution of 0.025% in a pressure range +/-3.5KPa. This capacitive pressure sensor decouples the pressure sensing from its capacitance sensing by using a hermetically sealed capacitor that is electrically isolated but mechanically coupled with a pressure sensing diaphragm such that a large dynamic range and high pressure sensitivity can be readily achieved. Because the capacitor is hermetically sealed in a cavity, this capacitive pressure sensor is also immune to measurement media and EMI (Electromagnetic Interference) effects.

KEYWORDS
Capacitive pressure sensor, large dynamic range, high sensitivity, Ultra-thin, MEMS, immune to media, EMI resistance

INTRODUCTION
Capacitive pressure sensors have been designed for a variety range of applications in measuring both absolute and differential pressures because of their high pressure sensitivity, low temperature sensitivity, good dc response and low power consumption [1-5]. Typically, a capacitive pressure sensor contains a thin diaphragm and this same diaphragm is used as the pressure sensing element and the capacitive sensing element as well. In general, the high pressure sensitivity of a capacitive pressure sensor is achieved by increasing diaphragm size, reducing diaphragm thickness and decreasing sensing gap, which results in a large sensor size, non-linearity, and limited dynamic range. In addition, typical pressure sensors are sensitive to the measuring media which consists of fluidic, chemical and electromagnetic effects since their sensing diaphragms are directly exposed to measuring environment. Thus pressure sensor media protection and EMI (electromagnetic interference) resistance can be complex and also expensive.

This paper addresses above mentioned challenges by decoupling of the pressure sensing element (mechanically sensitive) from the capacitive sensing element (electrically sensitive) to achieve high sensitivity and large dynamic range. By electrically isolating the capacitive sensing element from the pressure sensing diaphragm while still being mechanically coupled and being hermetically sealed in a cavity to protect the capacitive pressure sensors from the measuring environment. Since this pressure sensor overcomes some basic problems of MEMS capacitive pressure sensors encountered, it can be deployed in industrial, consumer, military and automotive applications.

SENSOR DESIGN
Figure 1 illustrates the innovative design of the capacitive pressure sensor. Unlike conventional capacitive pressure sensor, this pressure sensor has a separate capacitor for capacitance sensing and an additional thin diaphragm for pressure sensing. As indicated in the figure, this capacitive pressure sensor consists of three main elements: a diaphragm, a capacitor made of a pair of plates (one fixed plate and one moving plate), and a mechanical coupling element (the center post). The diaphragm, the moving plate and the fixed plate are all in circular shape to maintain a radial symmetry for the stresses at the edges where the diaphragm is clamped. Square or rectangular diaphragms may also be used but there are high stress points in the corners which may affect the dynamic range.

As shown in the figure, the moving plate of the capacitor is rigidly attached to the center of the diaphragm through the center post, but is electrically isolated from pressure sensing diaphragm. The size of this center post is small enough to have a negligible effect on the diaphragm deflection. The fixed plate is placed in parallel with the moving plate to form a parallel plate capacitor. This fixed plate also caps the moving plate inside of a sealed cavity. As the diaphragm deflects under a pressure load, the moving plate of the capacitor experiences the same amount of deflection from the center of the cavity.
Thus a diaphragm deflection is readily converted to a capacitance change.

For a circular shaped pressure sensor, the capacitance sensitivity is given by

\[
\frac{\Delta C}{P} = \frac{3(1-v^2)R^4}{16ET^2} \frac{\varepsilon_0 \varepsilon_r A_{\text{sense}}}{g^2}
\]  

Where \( \Delta C \) is the change in capacitance, \( P \) is the pressure difference across the diaphragm, \( R \) and \( T \) are the radius and thickness of the diaphragm, \( E \) and \( \nu \) are Young’s modulus and Poisson’s ratio of the diaphragm material, \( A_{\text{sense}} \) is the area of the moving plate, and \( g \) is the sensing gap between the moving plate and the fixed plate. Thus the capacitance sensitivity to pressure can be increased by scaling the dimensions of both pressure sensing diaphragm and the moving plate of the capacitor independently to achieve the design objectives.

\[\text{(1)}\]

In addition, as can be seen from equation (1), for the same amount of diaphragm deflection under load, the capacitive sensitivity can be enhanced by increasing \( A_{\text{sense}} \) and reducing \( d \), while the dynamic range can be increased by scaling down the dimensions of the pressure sensing diaphragm. Thus, the pressure sensitivity and dynamic range can be scaled independently. This decoupling of the pressure sensing from the capacitance sensing enables the enhancement in both pressure sensitivity and dynamic range in a small area. By suitable selection of dimension ratio in pressure sensing diaphragms and capacitance sensors, the design window is increased tremendously. Since the moving plate is attached to the center of the diaphragm, which is the largest deflection area under the pressure load, the entire moving plate experiences this displacement. Hence further improve the sensitivity of the pressure sensor. Figure 2 shows a deflected diaphragm under a pressure load by FEM (Finite Element Method) simulations. A moving plate is attached to the center of the diaphragm. The diaphragm has a clamped boundary condition in the simulation.

By electrically isolating the capacitive sensor from the pressure sensing diaphragm while still being mechanically coupled and being hermetically sealed in a cavity, the capacitive sensor is protected from the measuring environment. By using a conductive layer for the pressure sensitive diaphragm and holding it at a fixed potential, a Faraday cage is formed around the capacitive sensor. Since the capacitive sensor is now both hermetically sealed and incorporated into a Faraday cage, it is therefore immune to measure media and resistant to EMI effects.

**SENSOR FABRICATION**

The pressure sensors are batch fabricated and all process steps are performed at the wafer level, which results in a high-yield process and can be readily transferred to standard MEMS manufacturing facility, providing a clear cost advantage.

![Figure 3: An illustration of a fabrication process flow for an ultra-thin capacitive pressure sensor.](image)
wafers (Silicon-On-Insulator) with a 50µm-thick device layer thickness. SOI wafers are used here for achieving ultra-thin pressure sensors. Regular wafers can be used as well in this process. The top silicon nitride layer is patterned to define the shape, size, and location of the pressure sensing diaphragms. The bottom silicon oxide is served as an etch-stop for the final back-etch step.

Following nitride patterning step, the first polysilicon layer (1.0-1.5µm in thickness) is deposited, doped, and patterned to form the pressure sensing diaphragms (Fig. 3(a)). The purpose of doping here is to make the pressure sensing diaphragms conductive such that a fixed potential can be applied to these diaphragms in the use of these pressure sensor. In this way, the creation of a Faraday cage is easily incorporated into the fabrication process of pressure sensors. Complex methods for generating resistant to EMI effects are avoided.

The first sacrificial oxide layer is deposited and patterned followed by the second polysilicon (2.0-3.0µm in thickness) deposition and doping to form the moving plate of the capacitor. This moving plate is mechanically attached to the pressure sensing diaphragm at the center through a center post, but electrically isolated from the diaphragm with a thin layer of silicon nitride (Fig. 3(b)). The thickness of the first sacrificial layer can be adjusted to maximize the resistance to EMI effects.

The second sacrificial oxide layer is deposited and patterned to define the sensing gap and cavity (Fig.3(c)). The fixed plate of the pressure sensor is formed by depositing and patterning the third polysilicon layer (3.0-3.5µm in thickness) Both the moving plate and the fixed plate are perforated with small holes for release etching (Fig. 3(d)). The sacrificial oxide layers are removed from the cavity using a HF etchant through the perforated holes. The cavity is finally capped by PECVD (Plasma Enhanced Chemical Vapor Deposition) oxide to seal the perforated holes in the fixed plate in a low pressure level of ~10 Torr. The handle layer of SOI wafer is removed using DRIE (Deep Reactive Ion Etch) until the buried oxide is exposed. Other methods such as lapping and CMP (Chemical Mechanical Polishing) can be also used for this step. Both buried oxide layer and the device layer are finally pattern and etched to expose the pressure sensing diaphragm (Fig. 3(e)). At this point, the ultra-thin (60µm thick) capacitive pressure sensors are fabricated. This completes the entire sensor fabrication process.

Figure 4 shows a top view picture of the fabricated pressure sensor with an overall dimension of 1.0mm × 1.0mm × 60µm. Each sensor has six wire bonding pads where two for the pressure sensing diaphragm, two for moving plate and two for the fixed plate. These wire bonding pads are for sensor testing and characterization purpose in the development phase. They can be further reduced to minimize the sensor size. Figure 5 is a SEM picture showing the perforated moving plate inside the cavity and the perforated fixed plate above it. The diameter of the perforation hole is in the range of 2.0-2.5µm such that these perforated holes are big enough for chemical circulations during final release etching and small enough for the final sensor capping and sealing process.
SENSOR MEASUREMENTS

The fabricated pressure sensors are tested and characterized. Figure 6 and 7 demonstrate the measured results from two of the fabricated pressure sensors. Both of these two sensors have a moving plate of 150µm in radius while they have different sizes of pressure sensing diaphragms. The radius of the pressure sensing diaphragm in Fig. 6 is 90µm, and in Fig. 7 is 100µm. As can be seen from Fig. 6, the pressure sensor with a 90µm-radius diaphragm is able to provide pressure sensitivity better than 10aF/Pa in a low pressure range (<1000Pa) and much higher pressure sensitivity of 150aF/Pa in high range (>1000Pa). The overall resolution is about 0.025% in full scale range. As the radius of the pressure sensing diaphragm increases from 90µm to 100µm, the pressure sensitivity is largely increased. As can be seen from Fig. 7, in the high pressure range, the measured sensitivity is increased to 260aF/Pa (>1000Pa).

These measurements clearly demonstrate that the pressure sensitivity and dynamic range can be scaled independently with this unique sensor design.

CONCLUSION

An innovative capacitive pressure sensor that possesses high sensitivity, large dynamic range, ultra thin profile has been designed, fabricated, and tested. This pressure sensor is immune to measurement media and resistant to EMI effects. The test and measurement results also indicate that this type of pressure sensor is able to largely extend pressure sensor design space and to provide solutions for many application challenges while improve overall performance.

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REFERENCES


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