The Capacitance and Temperature Effects of the SiC- and Si-Based MEMS Pressure Sensor

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Abstract. This project develops the pressure sensor for monitoring the extreme conditions inside the gas turbine engine. The capacitive-based instead of piezoresistive-based pressure sensor is employed to avoid temperature drift. The deflecting (top) plate and the fixed (bottom) plate generate the capacitance, which is proportional to the applied input pressure and temperature. Two thin film materials of four different sizes are employed for the top plate, namely cubic silicon carbide (3C-SiC) and silicon (Si). Their performances in term of the sensitivity and linearity of the capacitance versus pressure are simulated at the temperature of 27°C, 500°C, 700°C and 1000°C. The results show that both materials display linear characteristics for temperature up to 500°C, although SiC-based sensor shows higher sensitivity. However, when the temperatures are increased to 700°C and 1000°C, the Si-based pressure sensor starts to malfunction at 50 MPa. However, the SiC-based pressure sensor continues to demonstrate high sensitivity and linearity at such high temperature and pressure. This paper validates the need of employing silicon carbide instead of silicon for sensing of extreme environments.

1. Introduction

Capacitive sensor is used in many applications such as gas turbine engine sensor [1]. It parallel plate structure contains flexible diaphragm as the top plate and fixed plate in the bottom of the structure, as shown in Figure 1 [2]. The external pressure, \( P \) will deflect the top diaphragm. A sealed cavity is required in between the plates as an insulator. Two parameters namely the distance between the plate, \( d \) and the permittivity, \( \varepsilon \) play an important role in determining the value of the generated capacitance, \( C \). Capacitive sensor is also useful for measuring material properties since different materials have different values of dielectric constant as well as dielectric loss.

In the extreme environment, the selection of materials plays a very important role. The 3C-SiC material have been developed as a potential replacement to silicon due its superior thermal and electrical properties [3]. This paper will show that some of these properties, as shown in Table 1 [4] can affect the deflection values of the diaphragm. Our simulated results will demonstrate the advantages of 3C-SiC over Si diaphragms in improving the sensitivity, linearity and capacitance values of the pressure sensor at such extreme conditions [5].
Table 1. Material properties of tested materials [4].

| Material properties          | Silicon | 3C-SiC |
|------------------------------|---------|--------|
| Young’s modulus (GPa)        | 1.69    | 4.70   |
| Poisson ratio (v)            | 0.30    | 0.22   |
| Density (kg/µm³)             | 2.5 x 10^{15} | 3.2 x 10^{15} |
| TCE Integral Form (1/K)      | 2.5 x 10^{-6} | 2.3 x 10^{-6} |
| Thermal Conductivity (pW/µmK)| 1.48 x 10^{18} | 5.0 x 10^{18} |
| Specific Heat (PJ/kgK)       | 7.12 x 10^{14} | 1.34 x 10^{15} |
| Dielectric constant          | 9.72    | 11.68  |

Figure 1. Schematic of capacitive pressure sensor [2]

2. Theory

2.1. Theory of Deflection and Capacitance

2.1.1. Deflection versus differential pressure under different temperatures. The edged-clamped diaphragm is shown in Figure 2. The gap of the capacitive pressure sensor is given by \( d \), consider a length of diaphragm plate \( b \), and width, \( a \). Young modulus is denoted as \( E \), Poisson’s ratio is denoted as \( \nu \), and the elastic rigidity is denoted as \( D \). The application of a constant and uniform pressure \( P \), on the center of diaphragm surfaces at point of coordinates \((x, y)\), and thus the deflection \( W(x, y, P) \) is determined. Diaphragm bending is the elastic type and deflection \( W(x, y, P) \) remains small relative to the thickness \( h \).

Figure 2. Deflection based on center coordination

In these positions, it is shown in equation (1) that the deflection of the diaphragm is governed by the following differential system [6]:
\[
\frac{\delta^4W}{\delta x^4} + 2\alpha \frac{\delta^4W}{\delta x^2 \delta y^2} + \frac{\delta^4W}{\delta y^4} = \frac{P}{D_0h^3} \quad (1)
\]

The partial derivatives of the equilibrium position with length and width based on center coordination as shown in Figure 2 are evaluated by equation (2):

\[
W(x = \pm \frac{a}{2}; y) = 0; W(x; y = \pm \frac{b}{2}) = 0; \frac{\delta W}{\delta x}(x = \pm \frac{a}{2}; y) = 0; \frac{\delta W}{\delta y}(x; y = \pm \frac{b}{2}) = 0 \quad (2)
\]

Where,

\[
\alpha = v + \frac{2E(1 - v^2)}{E}; \quad D_0 = \frac{E}{[12(1 - v^2)]} \quad (3)
\]

To attain a general formulation independent of the diaphragm symmetrical dimensions, a new integration domain is introduced in all cases, in this study is using a square of unit side:

\[
X = \frac{2x}{a}, -1 \leq X \leq +1 \quad (4)
\]

\[
Y = \frac{2y}{b}, -1 \leq Y \leq +1 \quad (5)
\]

The systems obtained using the Galerkin method indicates to the following approximately analytical solution [7]:

\[
W(x, y, P) = W(0, 0, P) \cdot F(X, Y, r) \quad (6)
\]

Where F is given in equation (8). The analytical solutions substituting equation (3) into equation (1) associated equation (6) response for diaphragm center deflection \(W(x = 0, y = 0)\) calculated by:

\[
W(0, 0, P) = \frac{k(r)S^2}{16D_0h^3}P \quad (7)
\]

Where:

\[
F(X, Y, r) = \left[(1 - X^2)(1 - Y^2)\right]^2 \times \sum_{i=0}^{n} \sum_{j=0}^{n} k_{ij}X^iY^j \quad (8)
\]

\(n,\) is an even positive integer
\(i, j = 0, 2, 4, 6, \ldots, n\)
\(S = \) area of the plate = ab
\(r = b/a, k(r)\) and \(k_{ij}(r)\) are shape factors

Therefore, as the response for center deflection of diaphragm \(W(0, 0, P)\) approaches the area, \(S,\) shape factor, \(k(r),\) thickness of diaphragm, \(h\) and elastic rigidity, \(D_0\) material of the diaphragm under various pressure load, \(P,\) thus the entire top plate experience this displacement towards. Changes in the dimensional of the diaphragm plate and fixed plate, thus also affect the deflection value.
2.1.2. Capacitance between two parallel plates. A variable capacitor is recognized with the diaphragm (flexible plate) and a fixed plate. In the absence of applied pressure \( P = 0 \), the distance between plates equals \( d \). Capacitance calculation is given by the following equation:

\[
C = \int \mathfrak{e}_0 \frac{\mathfrak{e} dxdy}{h - W(X,Y)}
\]

\[
C = \frac{\mathfrak{e}_0 \mathfrak{e} S}{d}
\]

Where, \( \mathfrak{e}_0 \) stands for vacuum permittivity, \( \mathfrak{e} \) stands for materials permittivity and \( S = ab \) is the plate area.

It has been seen in Figure 3 that the application of a uniform pressure \( P \neq 0 \) on diaphragm surfaces, at point \( (X,Y) \) causes a deflection \( W(X,Y,P) \). At this point, the distance between plates becomes \( d - W(X,Y,P) \). Capacitive pressure sensor response is then given by [8]:

\[
C(P) = C(0) \int_0^1 \int_0^1 \frac{dXdY}{1 - \left( \frac{W(X,Y,P)}{d} \right)}
\]

Where, \( W(X,Y,P) < d \)

![Figure 3. Diaphragm under applied pressure \( P \neq 0 \)](image)

Given the axial symmetry of the diaphragm, condition \( W(0,0,P) < d \) is equivalent to \( W(0,0,P) = d \). For \( W(0,0,P) = d \), a short circuit occurs between plates. The sensor becomes inoperative. In the following, the specific value of \( P \), for which \( W(0,0,P) = d \) is noted \( P_{sc} \). The analytical expression of \( P_{sc} \) is easily deduced from:

\[
P_{sc}(r) = 16D_0 \frac{d h^3}{S^2} \frac{1}{k(r)}
\]

From (6), (7) and (12), expression (11) can be written under the following normalized form:

\[
C(P) = C(0) \int_0^1 \int_0^1 \frac{dXdY}{1 - \frac{P}{P_{sc}(r)} F(X,Y,r)}
\]

Therefore, as the deflection \( W(X,Y,P) \) approaches the gap distance, \( d \), the capacitance, \( C \) and therefore the capacitance change \( \Delta C \) increases drastically. Changes in the deflection of the diaphragm affects the distance of the diaphragm plate and fixed plate, thus also affects the capacitance value.
2.1.3. Effects of capacitance – temperatures. The capacitances are affected with differential temperature measurement has been performed based in temperature efficient offset (TCO) by using this equation [9]:

\[
TCO = \frac{\Delta C_{\text{offset,max}}}{C_{\text{max}} - C_{\text{min}}} \times \frac{10^6}{T_{\text{max}} - T_{\text{min}}} \text{ ppm/}°\text{C}
\] (14)

Where,
- \(\Delta C_{\text{offset,max}}\) maximum offset capacitance for all temperatures;
- \(C_{\text{max}}\) and \(C_{\text{min}}\) maximum and minimum capacitances at the minimum temperature after offset compensation
- \(T_{\text{max}}\) and \(T_{\text{min}}\) maximum and minimum temperatures

In this case, TCO is the value of the output signal at a reference capacitance and the offset at the reference temperature.

2.2. Simulation model design

The diaphragm of capacitive pressure sensor can be modelled as a square plate that is deflected by a differential pressures and temperatures, as shown in Figure 4. CoventorWare ver.2008 simulation software is used to design, simulate and modify the performance of MEMS capacitive pressure sensor. It has three main components: Architect, Designer and Analyzer [10]. Architect is used to design the schematic of the capacitive pressure sensor. Designer is used to build the 3D design of the diaphragm. Analyzer is used to analyze the diaphragm deflection with given pressure and temperature.

Si and 3C-SiC materials with their respected electrical and mechanical properties are used to simulate the movable diaphragm (top plate). The capacitive pressure sensor is simulated at the initial voltage of 10 volts. Four diaphragm sizes are employed, namely 200 µm\(^2\), 250 µm\(^2\), 300 µm\(^2\) and 350µm\(^2\). The separation between the diaphragm and fixed plate is 10 µm with the diaphragm thickness of 1.0 µm, and the range of applied pressures is between 0 to 100 MPa. The design steps include selecting the substrate layer and wet etching of the backside of the substrate to create the membrane. The next process is mesh creation for the device that is essential to allow the Analyzer to do the pressure and temperature analysis. Both are performed using CoventorWare mechanical solver MemMech. Figure 5 and Figure 6 shows the diaphragm deformation and maximum stress under a series of different pressures, respectively. In addition, the mechanical tool in MemMech module is employed to perform the deflections at various pressures, and the output of the capacitance changes between the diaphragm and the fixed plate, as shown in Figure 7.
Figure 6. Maximum stress of diaphragm by applied pressure

Figure 7. Capacitance results by CoventorWare vers.2008 software

Figure 8 shows the 3D model of the diaphragm using mapped bricks mesh generated by Designer [11]. There are three steps involved. Firstly is the substrate step, secondly is the silicon planar fill with an anistropic front side wet etch, and thirdly Si/SiC top diaphragm by using stack material modelling action. The MemCap solver produces an elastic electrostatic solution by solving for the charge and capacitance interaction between two plates. It computes the total number of charges and presents the final solution with charge distribution calculated for all the panels in the model as proposed by equation (13).

3. Results and discussion
Figure 9 and Figure 10 show the capacitance versus pressure plots of 3C-SiC- and Si-based pressure sensor at room temperature and 500 °C, respectively. Square diaphragms of four different sizes are used. Three main observations are recorded. First, both 3C-SiC- and Si-based sensors display linear
relationship between the capacitance and the pressure. In addition, SiC-based sensor produces higher capacitances and thus is more sensitive towards the change in pressure. Second, the diaphragm with the largest area produces the largest capacitance value, as expected from equation (10). Third, it is interesting to note that starting at 40 MPa, the capacitance versus pressure curve of SiC-based sensor demonstrate slightly different path from the Si-based sensor.

In this work, the linearity is represented by the R square value. At room temperature, the 350 um² square shape diaphragms produce maximum capacitance value of 52.126 pF with linearity of 0.957 for 3C-SiC, compare to Si that produces 51.067 pF with linearity of 0.949. At 500°C, the superior performance of SiC-based material is noticeable. The SiC-based sensor achieves the linearity of 0.985 with maximum capacitance value of 55.99 pF, while the Si-based sensor has the linearity of 0.985 with the maximum capacitance value of 54.46 pF.

In general, it can be concluded that both 3C-SiC and Si0based pressure sensor maintain their expected performance at the applied pressure of 100 MPa and the temperature of up to 500 °C. Both have enough mechanical strength to withstand the external load without failure [12].

![Figure 9. Capacitance versus pressure of 3C-SiC and Si at room temperature (27 °C)](image1)

![Figure 10. Capacitance versus pressure of 3C-SiC and Si at 500 °C](image2)

Figure 11 and Figure 12 shows the capacitance versus pressure plots of both SiC- and Si-based pressure sensor at 700 °C and 1000 °C, with four sizes of diaphragm. One important observation is the fact that the SiC- based pressure sensors continue its linear operation at such high temperature, while the Si-based pressure sensor start to fail at 50 MPa. In addition, the SiC-based pressure sensors continue its excellent linear behaviour. At 700 °C, the 200 μm² diaphragm has a linearity of 0.994 while Si-based sensor has a linearity of 0.814. At 1000°C, the 350 μm² diaphragm produces the linearity of 0.996 for SiC, while achieving the linearity of 0.393 for the Si. Based on the data from Figure 11 and Figure 12, SiC-based pressure sensor could sustain its performances at the higher temperature of 700 °C and 1000 °C, while SI-based pressure sensor fails to operate at these extreme temperatures. It is possible that this is due to the fragile properties of Si material due higher load and thermal cyclic on the diaphragm, which aggravate the cracks initiated by defects or scratches through the [13]-[14].

Based on these data, there seemed to be an effect of capacitance due to influence the alpha (α) based in the equation $\alpha = v + 2E(1 - v^2)/E$, which is the parameter that is linked to Young Modulus, shear modulus and poison ratio that make the distinction in the capacitive performance between Si and 3C-SiC based pressure sensor. More work needs to be performed to confirm this relationship.
4. Conclusion

This paper studies the capacitance and temperature effects of the capacitive pressure sensor when two thin film materials are employed, namely cubic silicon carbide (3C-SiC) and silicon (Si). SiC has been known to supersede Si in both electrical and mechanical properties at extreme environment, and the results from this paper supports this prevailing theory. The simulation data shows that the SiC-based pressure sensor shows higher sensitivity and linearity compares to Si-based sensor.

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