Capacitive Pressure Sensors Based on MEMS, Operating in Harsh Environments

Y. Hezarjaribi[1, 3], M. N. Hamidon[3] , S. H. Keshmiri[2], A. R. Bahadorimehr[3]
[1]Golestan University, Gorgan, Iran
[2]University of Ferdowsi, Mashhad, Iran
[3]University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

Abstract **Poly-crystalline silicon carbide (poly-sic) Micro-electromechanical systems (MEMS) capacitive pressure sensors operating at harsh environments (e.g. high temperature) are proposed because of SiC owing excellent electrical stability, mechanical robustness, and chemical inertness properties. The principle of this paper is, design, simulation. The application of SiC pressure sensors are in a harsh environments such as automotive industries, aerospace, oil/logging equipments, nuclear station, power station. The sensor demonstrated a high temperature sensing capability up to 400 °C, the device achieves a linear characteristic response and consists of a circular clamped-edges poly-sic diaphragm suspended over sealed cavity on a silicon carbide substrate. The sensor is operating in touch mode capacitive pressure sensor, The advantages of a touch mode are the robust structure that make the sensor to withstand harsh environment, near linear output, and large over-range protection, operating in wide range of pressure, higher sensitivity than the near linear operation in normal mode, so in this case some of stray capacitance effects can be neglected.**

Keywords–MEMS, Touch mode Capacitive pressure sensor, high-temperature, poly-crystalline silicon carbide, PSG, harsh environment

I. INTRODUCTION

HIGH temperature pressure sensors are critical for advanced industrial, automotive, aerospace, gas turbine, oil/logging equipments, nuclear station, and power station applications [1]. Due to limitation exist for high temperature silicon's material properties; this device is not adequate to be use for designing MEMS sensor in harsh environment (high temperature). Typical temperature for these applications ranges up to 400 °C. Poly-crystalline Silicon carbide (poly-SIC) based on capacitive pressure sensors are proposed for high temperature sensing applications. Poly-SiC having excellent electrical stability, mechanical robustness, and chemical inertness is the best alternative MEMS material for harsh environment applications. Poly-SiC have the capabilities of depositing deferent material type of substrate unlike 3C-SiC, 6H-SiC [2]. We are proposed capacitive pressure sensor because of low turn-on temperature drift, having high sensitivity, wireless sensing schemes, and a minimum dependence on side stress [3].

II. DESIGN PROCESS

In this paper we demonstrate the simulation of MEMS capacitive pressure sensor in touch mode to achieve good linearity, large operating pressure range, and large overload protection at output. Fig.1a and b present a cross-sectional view of a touch mode and normal mode operation of capacitive pressure sensor.

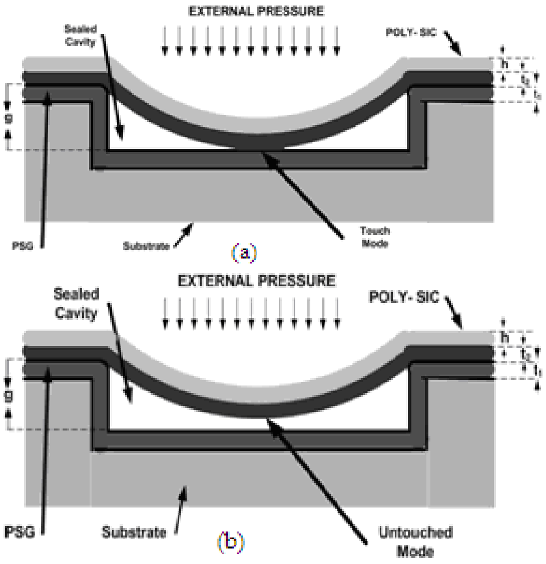

Fig. 1 Cross-section view of (a) touch mode (b) normal mode of capacitive pressure sensor.

In touch mode the top electrode is known as of diaphragm, in this case when external pressure is applied, the diaphragm will deflect toward inside, and the diaphragm start touching the bottom electrode (is know as of substrate) with a distance of insulator in between, as shown in Fig. 1a. In normal mode operation, the diaphragm is kept distance away from the substrate as shown in Fig. 1b [4].

Fig. 2, consider the cross-sectional view MEMS capacitive pressure sensor, the sensor consists of two parallel plate capacitor with clamped-edges, circular poly-SiC diaphragm suspended over a sealed cavity. The concept of parallel plate capacitor is expressed as in Equation (1)

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

where ε_0 is the permittivity of the media between the two plates ε_r is the dielectric constant of the material between the plates of the capacitance. A is the area of the electrode, and d is the gap between two plates. The concept of the capacitance element of the sensor requires a change in the capacitance as a function of some applied pressure load. A realization function of this concept would be the plates of the capacitor could move under pressure load, for example if the plates move closer together, the gap height, g, would decrease, resulting an increase in capacitance of the sensor. As the external pressure applied, the poly-SiC top diaphragm will deforms up to designed area of bottom contact know as of substrate with an insulator in between, the more pressure we apply, the bigger touched radius (r_1) gets, and at the same time the untouched radius (r_2) gets smaller, and the deflection gets bigger, at the same time the value of capacitance will increases nearly linearly with pressure, before touch point, touch radius (r_1) is zero. As shown in Fig. 2. r, r_1, r_2 are defined radius, touched radius, and untouched radius respectively. t_1, t_2 are defined the thickness of dielectrics (PSG) respectively. g is the distance between the un-deformed diaphragm and the bottom of inside cavity. *h* is the thickness of diaphragm.

III. THEORY OF OPERATION

A plate defined thin plate or small deflection if the gap between two electrodes is less than 1/5 of diaphragm's thickness, and the strains and mid-plane slopes are much smaller than unity (EFunds). A plate defined as of thick plate or large deflection if its deflection is up three times larger than diaphragm's thickness [5]. Based on small deflection theory for circular plate, the deflection 'w' of any point on a circular plate under uniform pressure is expressed by the following partial equation (EFunds).

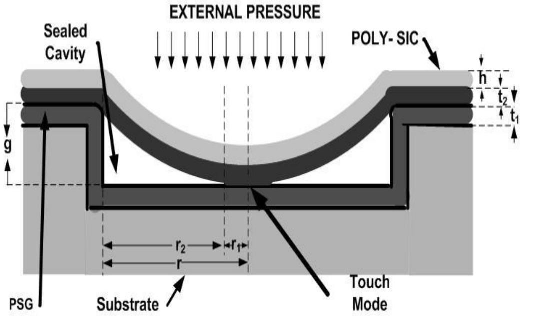

Fig. 2 Cross-section of touch and un-touch mode.

$$\nabla^2 w \nabla^2 D = p \tag{2}$$

Where P applied pressure (force per unit area) acting in the same direction as Z (w), D is the flexural rigidity of the plate is given by:

$$D = \frac{Et^3}{12\left(1 - v^2\right)} \tag{3}$$

The differential operator ∇^2 is called the Laplacian differential operator. For circular plate is simply supported classical formula and is defined by:

$$\Delta \equiv \nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2}{\partial \varphi^2} + \frac{1}{r}\frac{\partial}{\partial r} \tag{4}$$

If the bending rigidity D is constant throughout the plate, the deflection Equation (1) can be simplified to Equation shown as:

$$\nabla^4 w = \frac{p}{D} \tag{5}$$

Cylindrical coordinate (circular plates) where, Equation (5) is called the bi-harmonic differential operator.

$$\nabla^4 = \nabla^2 \nabla^2 = \Delta\Delta \tag{6}$$

The displacement for any point of the plate would be:

$$w(r) = \frac{Pa^4}{64D}\left(1-\left(\frac{r}{a}\right)^2\right)^2 \qquad (7)$$

Where, *a* is the radius of the plate, and r is the distance of the point from the center, the maximum deflection for small deflection, w0 defined by:

$$w_\circ = \frac{Pa^4}{64D} \qquad (8)$$

The maximum center deflection for large deflection, w0 for the circular diaphragm is given by equation (2) [6]

$$w_\circ = \frac{qa^4}{64D} \; \frac{1}{1+0.488\frac{w_0^2}{h2}} \qquad (9)$$

IV. SIMULATION RESULTS

Fig. 3 shows the radial distance versus the deflection of the diaphragm at different pressure load, before and after touch point for a circular plate with r=180 µm, g=0.75 µm, h=6 µm.

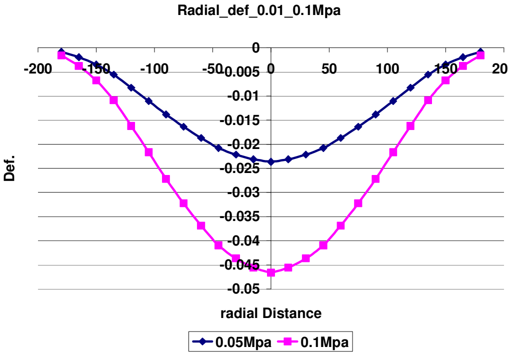

Fig. 3a Radial distance vs. deflection for r=180 µm, g=0.75 µm, h=6 µm

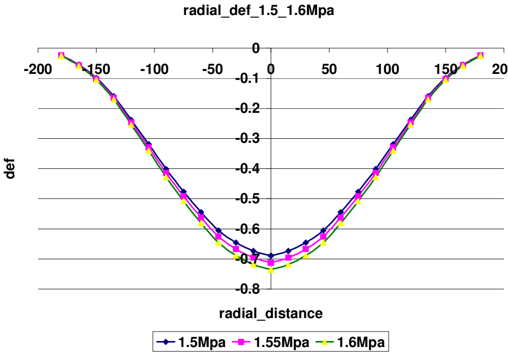

Fig. 3b Radial distance vs. deflection for r=180 µm, g=0.75 µm, h=6 µm

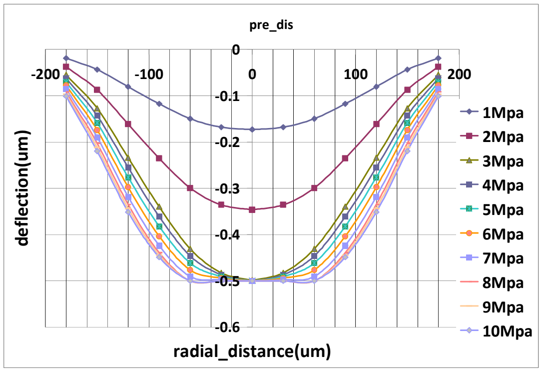

Fig. 3c Radial distance vs. deflection for r=180 µm, g=0. 5 µm, h=7.75 µm

Fig. 4 shows the characteristic of pressure versus capacitance, as the pressure load increases the value of capacitor increases linearly, we can define four mode operation as of normal mode, transition mode, touch mode, and saturated mode. The characteristic of operations in Fig. 4 is defined as: 1- *normal area*, due to small pressure load, that causes small deflection, 2- *transition area*, in this area the top diaphragm start touching the inside bottom cavity. 3-*linear or touch area*, defines that the top diaphragm touches the inside bottom cavity, as the load increases the touch area is more linear and the value of capacitance increases. 4-*saturation area*, in this area as the pressure keeps increases, the capacitance value will saturate [6].

Fig. 5 shows as the pressure load increases to designated contact point, as far as we get maximum deflection equal to depth of gap (cavity depth). Fig. 6, 7, 8 shows the 3D_views of pressure vs. deflection.

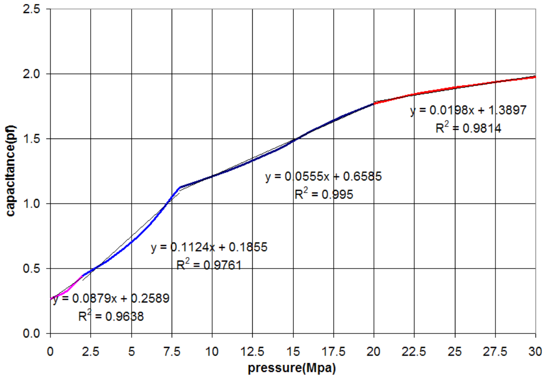

Fig. 4 Typical characteristic of a capacitive pressure sensor with four modes: normal, transition, touch and Saturated modes r=180 µm, g=2 µm, h=5 µm.

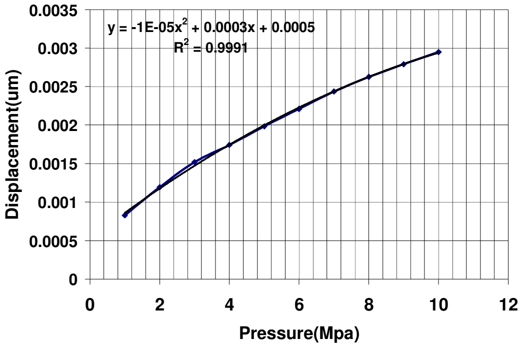

Fig. 5 Pressure vs. Z displacement r=180 µm, g=0.5 µm, h=7.75 µm.

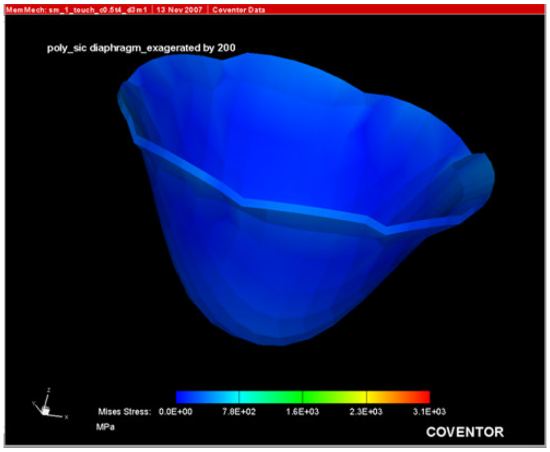

Fig. 6 3D-Pressure vs. deflection without clamp, using COVENTOR.

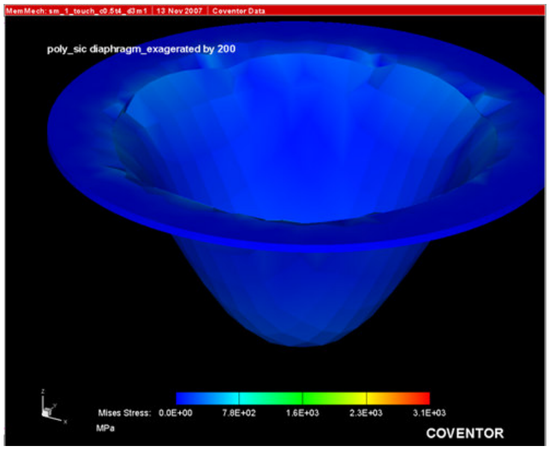

Fig. 7 3D-Pressure vs. deflection with clamp, using COVENTOR.

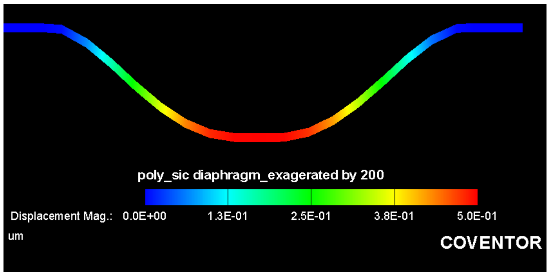

Fig. 8 3D_visulize side view touch-mode Contact point_1Mpa

VI. CONCLUSION

The results of analytical and finite element method (FEM) are presented to evaluate before and after touch mode circular diaphragm at different applied pressure load. These methods is widely used to model MEMS pressure sensors, but simulating in FEM is time consuming to optimize sensor's parameters such as: radius, cavity depth, diaphragm and dielectric thickness, Young's modulus, thermal coefficient expansion (TCE) and etc. theories for before and after touch-point proposed by Timoshenko's theories .The results by using FEM based on simulation was very promising results. It has shown exact contact deformation, pressure vs. deflection, pressure vs. capacitive, and pressure vs. Z displacement.

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