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A Simulation Based Geometrical Analysis Of MEMS Capacitive Pressure Sensors for High Absolute Pressure Measurement

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***Abstract*— In this paper two MEMS capacitive pressure sensors with varying geometries are analyzed in FEM based Multiphysics simulation platform. The geometries are very common having parallel plates with spring loaded. In first stage the shape of the parallel plates is circular and in second case of the parallel plate is square. During modeling of these two diffident shaped sensors, the area of parallel plates in both cases is considered as equal. Once the geometries are formed, the electromechanical analyses have been performed. It is observed that these types of pressure sensors can withstand a wide range of absolute pressure from kilo Pascals to several order of mega Pascals. Mechanical, electromechanical as well as material studies were performed in the Finite Element Method based Multiphysics simulation platform. In this paper two same area different shape micro sensors are designed and their comparative study is analyzed with different silicon compound (like Silicon, PolySi and SiC). This type of absolute pressure measuring sensor can be used for pulse rate measurement.**

***Keywords*— Capacitive pressure sensor; MEMS; absolute pressure; PolySi; SiC; Finite Element Method (FEM).**

I. INTRODUCTION

The microfabricated pressure sensor is one of the most useful, developed MEMS device used in a wide range of applications. In MEMS technology, piezoresistive pressure sensors are very common. However, in the past years capacitive pressure sensors have received attention due to several advantages in comparison to piezoresistive pressure sensors. The main disadvantage of the piezoresistive pressure sensor is the inherent temperature dependence of piezoresistive coefficients [1]. Moreover, capacitive pressure sensor has lower power consumption than piezoresistive pressure sensor [2].

But piezoresistive pressure sensor most widely used than capacitive pressure sensor because of two reason; capacitive structure is more complicated to fabricate and the capacitive sensing principle is sensitive to parasitic capacitances. The structure of the capacitive pressure sensor is more complicated, because it involves formation of a cavity that separates the two sensing electrodes from each other. Formation of such a cavity is done in two different ways. For first case multiple film depositions and etch of a buried sacrificial layer [3–6] or in second case bonding after the cavity has been etched into one of the wafer. Wafer bonding is done by fusion bonding of two silicon wafers [7–9] or anodic bonding of a silicon wafer and a glass wafer [10, 11]. Capacitive pressure sensors are required in applications including bio-medical systems, environmental monitoring and industrial process control. Capacitive pressure sensors provide low noise, high sensitivity, have low temperature sensitivity and are preferred in many emerging high performance applications and can withstand a lot of vibration. Micromachined capacitive pressure sensors have typically used an elastic diaphragm with springs and a sealed cavity in between the diaphragm and the substrate below. There is a pair of parallel plate which forms capacitor. Lower plate is fixed and upper plate acts as movable plate which is attach with spring and four boundaries are fixed. Pressure is applied on upper plate; it deforms which changes the distance between two plates due to this capacitance changes. The change of capacitance is used for measuring pressure.

This paper explores the design parameters of MEMS based diaphragm type capacitive pressure sensor using FEM (Finite Element Modeling) [12] based Multiphysics software. Here, two different shaped diaphragms with same area are designed for sensing high absolute pressure.

Mechanical and electromechanical studies are performed. The analyzed results are in the form of 2-D plots in section III as results and discussion. The outcome of this designed sensors are discussed and compared against their efficiencies. The concluding remarks from these analyses are described in section IV.

II. Methods And Materials

A. Mathematical modeling

The maximum stress for circular diaphragm is given by

$$\sigma_{max} = \frac{3\gamma W}{8\pi h^2} \quad (1)$$

And the maximum deflection of the circular plate occurs at the centre position of the plate [13]

$$W_{max} = \frac{3W(m^2-1)a^2}{16\pi m^2 h^2} \quad (2)$$

The maximum stress at the middle of each edge for square diaphragm is given by

$$\sigma_{max} = \frac{0.309Pa^2}{h^2} \quad (3)$$

The maximum deflection for square diaphragm is given as [14]

$$W_{max} = -\frac{0.0138Pa^4}{Eh^3} \quad (4)$$

Where, W = total force acting on the plate, h is the diaphragm thickness, 'a' is the radius of the circle, 'E' is the Young's Modulus, 'γ' is the Poisson's ratio and 'm' is the reciprocal of the Poisson's ratio [13]. Eq. 1, Eq.2, Eq. 3 and Eq. 4 are describing for performing the analytical analysis of the proposed MEMS based capacitive pressure sensor.

The capacitance between two parallel electric conductive plates can be written as,

$$C=\varepsilon_0 \varepsilon_r \frac{A}{d} \quad (5)$$

Where C is capacitance, ε_0 is dielectric constant of vacuum ε_r is the dielectric constant of material. 'A' is area of electrode plate and d is the gap between two electrode plate.

Based on Hooke's Law, the change in thickness in the dielectric layer is the proportional to the pressure and original thickness (Eq. 6).

Therefore, the relationship between the applied pressure and the capacitance change can be expressed as Eq. 6 and Eq. 7.

$$\Delta d = d_0 \frac{\Delta P}{E} \quad (6)$$

$$\Delta C = C_0 \frac{\Delta P}{E-\Delta P} \quad (7)$$

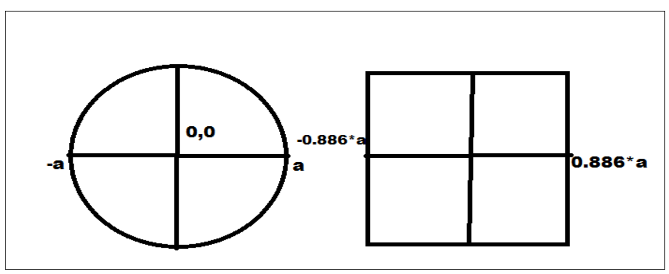
Where Δd is thickness change of dielectric layer, d_0 is original thickness of dielectric layer. ΔP is applied external pressure, c_0 is original capacitance when pressure is not applied and ΔC is capacitance change when pressure is applied.

B. FEM modeling

Finite Element Method (FEM) is used to predict mechanical response to a load, such as force or moment applied to a part of the constructed model. This part is to be simulated is broken down into small discrete element – this procedure is called meshing. Each element has a no. of nodes and its corners at which it interacts with neighboring element. Thus the system Partial Differential Equation (PDEs) is assumed to be linear element within the nodes and is solved in FEM based Multiphysics computation platform.

C. Sensor layout

For design purpose, the two different geometries (circular and square) of the diaphragm are designed in FEM based Multiphysics simulation platform in such a way that their area between the plates is made similar. Both cases there are two plates. Lower one is fixed and upper one is movable. Pressure is applied on upper plate. Distance between two plate changes when pressure is applied and due to these capacitance changes. The dimensions of both the square and circular shaped capacitive pressure sensor is provided below:



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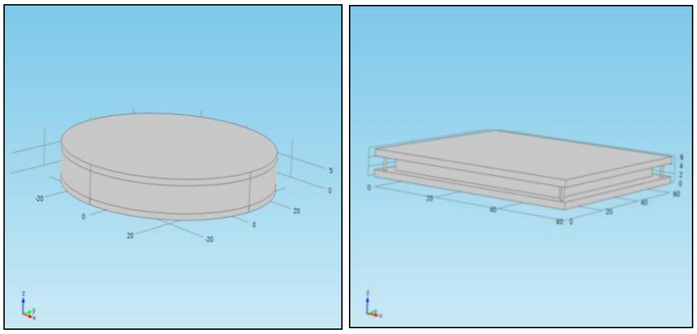

Fig. 1.Cross-section and 3D view of the sensor geometries

- Side length of square diaphragm= 60 µm
- Radius of circular diaphragm= 33.84 µm
- Thickness of diaphragm= 1.5 µm
- Separation gap between the plates=3.0 µm

I. *Material Analysis*

The physical properties of silicon, PolySilicon and Silicon Carbide are noted in Table I. These properties are used in performing the analysis of the two designed MEMS based capacitive pressure sensor model in FEM based Multiphysics software.

TABLE I.
Some Properties of Silicon, Polysilicon and Silicon carbide

Materials	**Properties**		
	Silicon	***Polysilicon***	***Silicon Carbide***
Young's Modulus	170e9[Pa]	160e9[Pa]	748e9[Pa]
Poission's Ratio	0.28	0.22	0.45
Density	2329[kg/m^3]	2320[kg/m^3]	3216[kg/m^3]
Thermal Expansion Coefficient	2.6e-6[K^{-1}]	2.6e-6[K^{-1}]	4.3e-6[K^{-1}]
Thermal Conductivity	130[W/(m*K)]	34[W/(m*K)]	490[W/(m*K)]
Relative Permitivity	11.7	4.5	9.7

III. Result And Discussion

A wide range of mechanical and electromechanical studies and also materials studies of the proposed two geometrical structures have been performed in the FEM Multiphysics Software platform. In this paper effect of various parameters for designing sensor is analyzed and discuss below.

A. *Design sensor layout*

Two types of geometrics are designed. Sensor layouts are given on fig.2 and fig.3. Deflection is maximum at center of the diaphragm and minimum at side of the diaphragm.

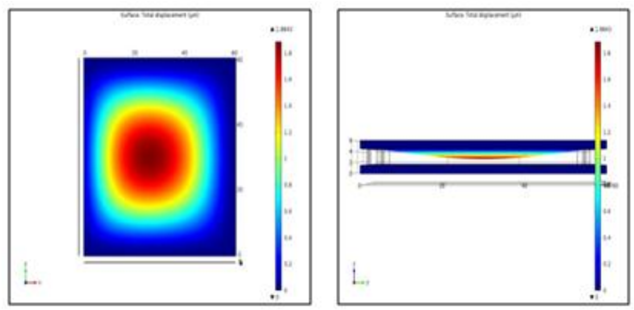

Fig.2. Square sensor layout (a) top view (b) side view

Applied pressure vs. deflection is measured and change in capacitance is measured. In fig. 2(a, b) and 3(a, b) red colure shows maximum deflection at center of the diaphragm and blue colure shows minimum deflection at side of the diaphragm.

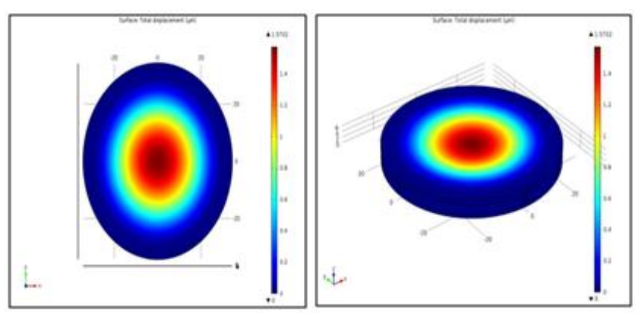

Fig.3. Circular sensor layout (a) top view (b) side view

B. Square and circular diaphragm

Mechanical Analysis: Diaphragm deflection is measured for square and circular diaphragm and graph is plotted in fig.4 and their comparative performance is analyzed. d Square diaphragm is more suitable than circular one for measuring small changes.

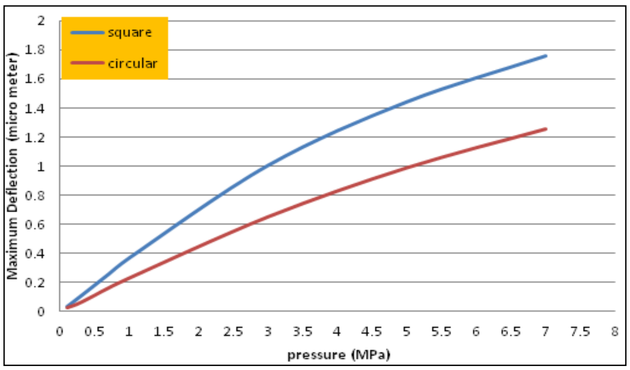

Fig. 4.Plot of maximum deflection vs. applied pressure (0.1 MPa-7 MPa) for both square and circular shaped diaphragm

Electromechanical Analysis:

The change in capacitance due to applied pressure having same range is more for square diaphragm than that of circular diaphragm. Thus, Square diaphragm shows significant changes in capacitance in measuring range of pressure 1 MPa to7 MPa.

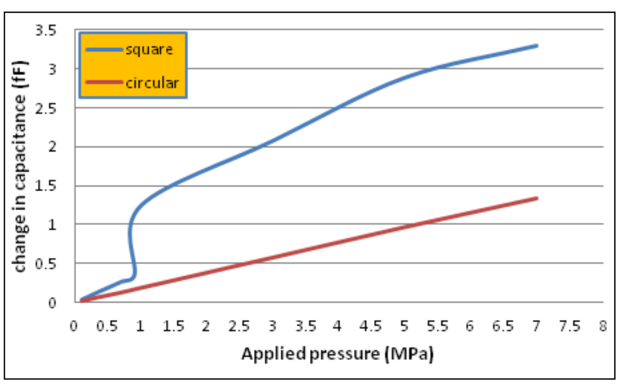

Fig.5. Plot of the change in capacitance with the applied pressure (1-7 MPa) for circular and square shaped geometries

C. Effect of Distance Between two Diaphragm

Distance between two diaphragms is very important parameter for designing diaphragm type capacitive pressure sensor. If distance between two plates increases then capacitance decreases. In fig.6, the change in capacitance due to varying distance between two diaphragms is plotted. This study we have done only with square shaped diaphragm.

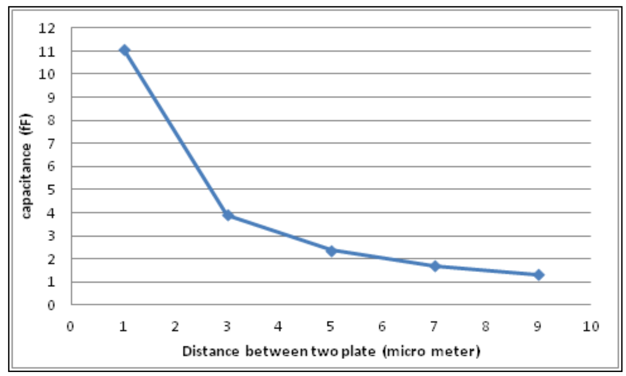

Fig. 6.Plot of capacitance with the variation of the distance between the plates

D. Effect of thickness of diaphragm on sensor performance

Thickness is very important parameter for diaphragm deflection. If diaphragm thickness is increased, deflection decreases. Diaphragm deflection is inversely proportional to diaphragm thickness as shown in eqn. 5. Fig.7 (circular diaphragm) and fig.8 (square diaphragm) are showing how the deflection for different diaphragm thickness varying with applied pressure. If diaphragm thickness increases then pressure withstand capability also increases.

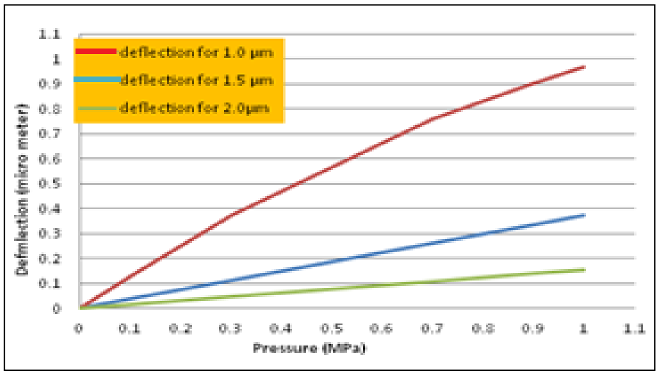

Fig.7. Plot of the deflection with diaphragm thickness (1.0, 1.5, 2µm), with the range of applied pressure from (0.1-1) MPa for circular shaped diaphragm

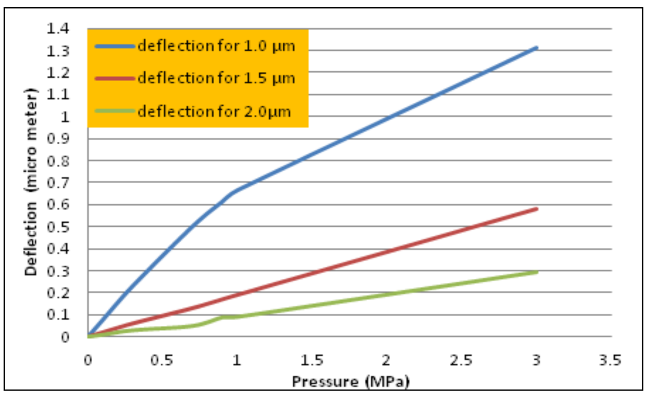

Fig.8. Plot of the deflection with diaphragm thickness (1.0, 1.5, 2µm), with the range of applied pressure from (0.1-3) MPa for square shaped diaphragm

E. Effect of thickness of diaphragm on capacitance and change in capacitance

Circular diaphragm: Capacitance and change in capacitance is measured with respect to applied pressure for circular diaphragm is shown in fig.9 and fig.10. It is observed that applied pressure vs. change in capacitance is maximum for thin diaphragm. As a result, low thickness diaphragm is more sensitive than high thickness diaphragm.

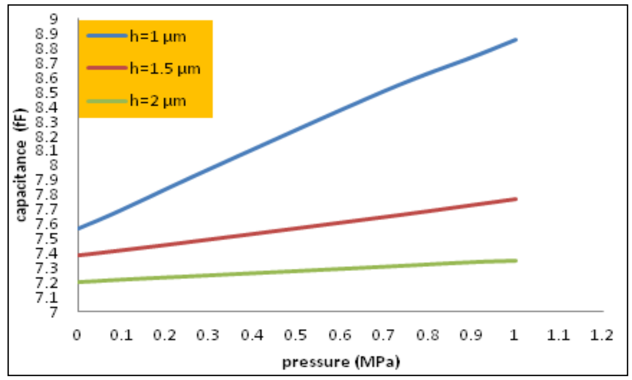

Fig.9. Plot of capacitance with the applied pressure (0.1-1 MPa) for circular shaped diaphragm of different thickness

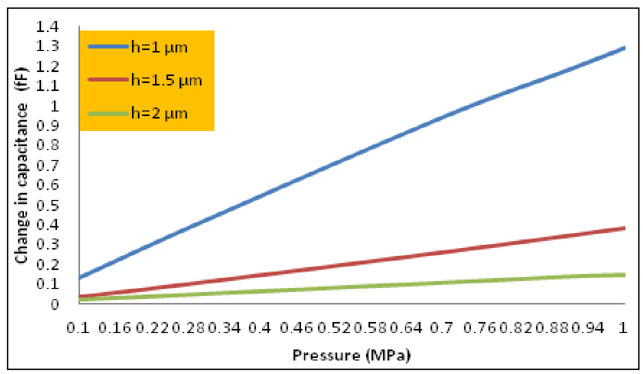

Fig.10. Plot of change in capacitance with the applied pressure (0.1-1 MPa) for circular shaped diaphragm of different thickness

Square diaphragm: Applied pressure vs. capacitance and change in capacitance is measured for circular diaphragm in fig.11 and fig.12. Applied pressure vs. change in capacitance is better for square diaphragm than circular diaphragm.

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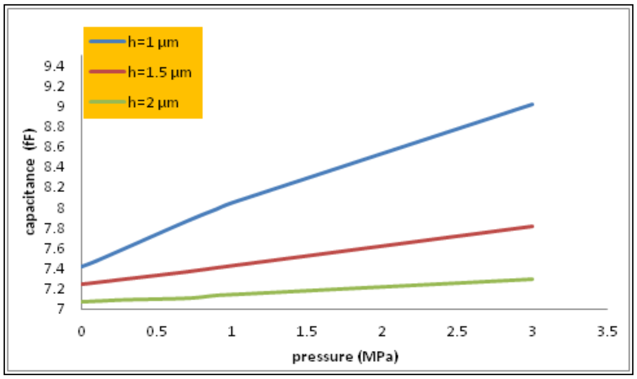

Fig.11. Plot of the capacitance with the applied pressure (0.1-1 MPa) for square shaped diaphragm of different thickness.

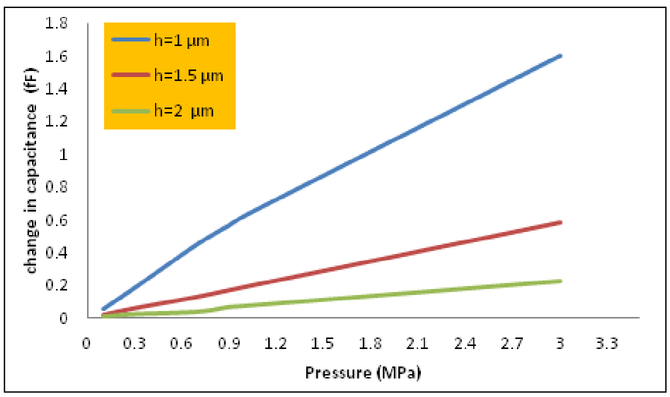

Fig.12. Plot of the change capacitance with the applied pressure (0.1-1 MPa) for square shaped diaphragm of different thickness

IV. MATERIAL STUDY

Three materials are chosen for diaphragm material, Silicon, Polysilicon and Silicon Carbide. For these three materials, diaphragm maximum deflection and change in capacitance with respect to applied pressure is measured.

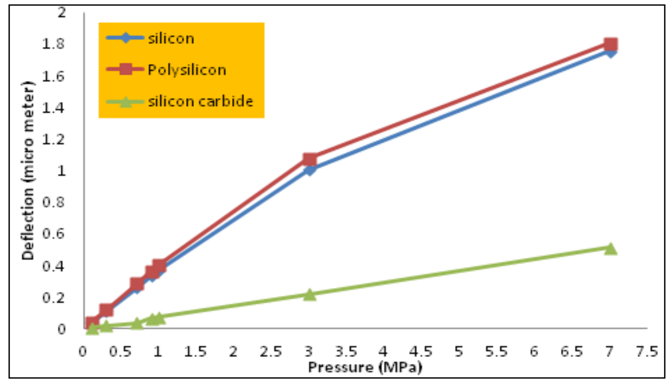

Fig.13. Deflection of the diaphragm (Circular and squared shaped) for a particular pressure range 0.1 -7 MPa with silicon, polysilicon and silicon carbide as diaphragm material.

Fig. 13 and Fig. 14 show for a particular pressure the deflection as well as the change in capacitance of Polysilicon type diaphragm is greater compared to the Silicon and Silicon Carbide type diaphragm. Thus, Polysilicon provides a higher sensitivity in various applications when chosen as a diaphragm material. Silicon is more preferable than Silicon Carbide. When young's modulus increases, the deflection of diaphragm decreases. Due to this changes in capacitance also low for high young's modulus materials.

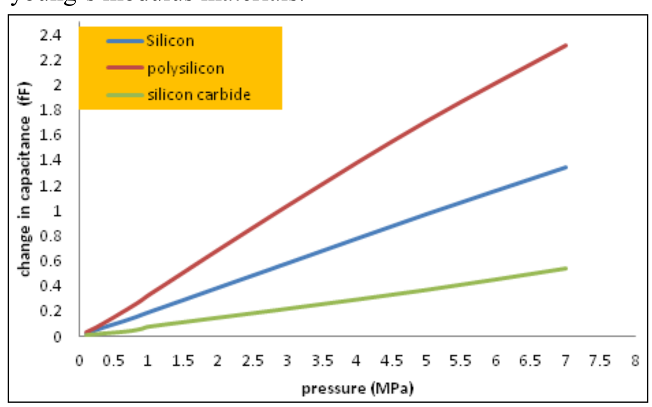

Fig.14. Change in capacitance (Circular and squared shaped) for a particular pressure range 0.1-7 MPa with silicon, polysilicon and silicon carbide as diaphragm material.

V. CONCLUSIONS

In this paper we have analyzed two different models of MEMS based capacitive pressure sensor. One having circular shaped whereas other having square shaped diaphragm. Square diaphragm is more preferable than circular diaphragm. Detailed simulation based analyses on the mechanical, electromechanical as well as material studies were performed. As analyzed from the mechanical analysis that designed model can withstand a high absolute pressure range extends to several of mega Pascals. This design technology allows for simple and inexpensive batch fabrication and integration of this type of sensors with dedicated signal detection circuits. Thus, the practical implementation of these designed sensors will cater wide range of applications over a varied field (biomedical, robotics etc.

REFERENCES

[1] Y. Kanda, A graphical representation of the piezoresistance coefficients in silicon,IEEE Transactions on Electron Devices ED-29 (1982) 64–70

[2] J.-S. Park, Y.B. Gianchandani, A servo-controlled capacitive pressure sensor using a capped-cylinder structure microfabricated by a three-mask process, Journal of Microelectromechanical Systems 12 (2003) 209–220.

[3] K. Kasten, J. Amelung, W. Mokwa, CMOS-compatible capacitive high temperature pressure sensors, Sensors and Actuators 85 (2000) 147–152.

[4] C.Kolle,W. Scherr, D. Hammerschmidt, G. Pichler,M.Motz, B. Schaffer, B. Forster, U. Ausserlechner, Ultra low-power monolithically integrated capacitive pressure sensor for tirepressuremonitoring, in: Proceedings of IEEE Sensors, Vienna, Austria, 24–27 October 2004, 2004, pp. 244–247.

[5] M. Habibi, E. Lueder, T. Kallfass, D. Horst, A surface micromachined capacitive absolute pressure sensor array on a glass substrate, Sensors and Actuators A 46–47 (1995) 125–128.

[6] U. Paschen, M. Leineweber, J. Amelung, M. Schmidt, G. Zimmer, A novel tactile sensor system for heavy-load applications based on an integrated capacitive pressure sensor, Sensors and Actuators A 68 (1998) 294–298.

[7] W.H.Ko,Q.Wang, Touchmode capacitive pressure sensor, Sensors andActuators 75 (1999) 242–251.

[8] P. Dimitropoulos, C. Kachris, D. Karampatzakis, G. Stamoulis, A new SOI monolithic capacitive sensor for absolute and differential pressure measurements, Sensors and Actuators A 123–124 (2005) 36–43.

[9] S.T. Moe, K. Schjølberg-Henriksen, D.T.Wand, E. Lund, J. Nysæther, L. Furuberg,M. Visser, T. Fallet, R.W. Bernstein, Capacitive differential pressure sensors for harsh environments, Sensors and Actuators A 83 (2000) 30–33.

[10] R. Puers, Capacitive sensors: when and howto use them, Sensors and Actuators A 37–38 (1993) 93–105.

[11] A.V. Chavan, K.D. Wise, Batch-processed vacuum-sealed capacitive pressure sensors, Journal of Microelectromechanical Systems 4 (10) (2001) 580–588.

[12] B. Puers, E. Peeters, A. van den Bossche,W. Sansen, A capacitive pressure sensor with low impedance output and active suppression of parasitic effects, Sensors and Actuators A 21–23 (1990) 108–114.

W.C. Young and R. G.Budynas “Roark’s formulas for stress and strain” by (Mc Graw Hill)

[13] Tai Ran Hsu “Mems and Microsystems” Tata McGraw-Hill 2002)