Impact of the diaphragm structure on the linearity and temperature sensitivity of low-pressure piezo-resistive MEMS pressure sensors

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Abstract: This paper presents result of a detailed simulation study aimed at optimizing the different diaphragm structures of silicon micro machined MEMS pressure sensor for operation and measurement of the low-pressure ranges (600 mbar). We first show that the conventional arrangement of the Wheatstone bridge resistors realized using the “Flat diaphragms” give rise to large temperature dependence of the offset voltage which affects the sensitivity and linearity of the pressure sensors during operation in the temperatures ranging from -40°C to +80°C, thus making the temperature compensation of the sensor output voltage rather tedious and impossible in certain instances. We further demonstrate that, this issue can be circumvented and excellent linearity with minimum dependence of the offset-voltage, sensitivity and linearity can be achieved by using “sculptured diaphragms” with optimized diaphragm dimensions. Towards this goal, in this paper, we present a set of simulation studies involving optimization of the pressure sensor diaphragm dimensions and structures with single and multiple boss structures to achieve better sensitivity, linearity, and at the same time minimize temperature drift, and to achieve better repeatability.

1. INTRODUCTION

Ever since the piezo-resistive effect has been identified in silicon and germanium, piezo-resistive pressure sensors using silicon Piezo-resistors, which are laid out on a silicon diaphragm, and connected in the form of Wheatstone bridge, have been used in applications for sensing pressures ranging from few Pascals to several hundreds of Pascals. When the monitored pressure is 10⁵ Pascals (1 Bar) and below that atmospheric pressure of 1 Bar, in the conventional pressure sensors having a thin flat diaphragm, the diaphragm thickness needs to be reduced, accompanied by an increase in the lateral dimensions to achieve good sensitivity and better output voltage span. However, this approach affects the linearity of the output voltage drastically. In addition, even when the lateral dimensions are not too high, the offset voltage and the output span of the sensor become highly temperature sensitive, and this is very difficult to compensate even with external electronics. In order to circumvent these issues and at the same time achieve high sensitivity, and stress concentration regions, “boss structured diaphragms”, also identified as “sculptured diaphragms”, have been proposed in the literature. However, Flat diaphragm structure of sensor is well known and it works very good for measuring high pressure ranges [1].

The “boss structure design” is expected to give very good sensitivity, high linearity and temperature stability. However, even though some analytical results have been reported in literature [2], a detailed quantitative analysis and comparisons with simulations or experimental results on the temperature
sensitivity of the offset voltage, linearity and output voltage span of the pressure sensors using diaphragms having boss structure with those having flat diaphragms have not been presented in the literature.

In this paper we present the results based on COMSOL multi physics simulation studies on the piezo-resistive pressure sensors having “flat diaphragms”, as well as the “sculptured diaphragms” having the boss structure. Based on these studies, we demonstrate that the temperature dependence of the “magnitude” and “polarity” of the sensor offset voltage, output voltage and its linearity can be drastically improved by using suitably designed sculptured diaphragms and by suitably laying out the resistors in the stress concentration regions. Pressure sensor are widely used for aerospace [3], biomedical, automobile and defence application [4].

2. PRESSURE SENSOR WITH FLAT DIAPHRAGM AND THE ASSOCIATED PROBLEMS

In this section Flat diaphragm structure is simulated for 600mbar pressure at different temperature -40°C, 20°C and 80°C. In each temperature the stress value on the diaphragm is obtained and the corresponding output value is calculated analytically, considering gauge factor of 100 at room temperature. The results of simulation studies aimed at determining the effects of temperature on the offset voltage, linearity and sensitivity of piezo-resistive pressure sensor are presented. Flat square diaphragm of Side length 2000µm with the square chip side length 3000µm as show in figure 1 is chosen for study.

![Figure 1. Schematic View of FLAT Diaphragm a) Cross section b) top view.](image)

The flat diaphragm structure with above dimension is simulated using COMSOL, for an applied low pressure 600mbar. The maximum stress locations on the diaphragm are shown in figure 3, at the four edges of the square diaphragm and they are chosen for placing the resistor location as shown in figure 4. Figure 2 shows the cutline where stress distribution is plotted.
Figure 2. Cutline where maximum Stress is estimated. Figure 3. Stress Plot at 600mbar.

From this stress plot figure 3 maximum stress is seen at edge centre of the diaphragm, so Wheatstone bridge resistors are kept at this maximum stress locations to finalize the resistor dimensions figure 4. The stress plot along the diaphragm are drawn and by plotting stress plot for different pressure figure 5 (0,120,240,360,480 and 600mbar) the linearity of the sensor is also obtained.

Figure 4 shows the well-known arrangement of resistors $R_1=R_2=R_3=R_4=R$, laid out on the diaphragm top surface and interconnected to realize the Wheatstone bridge. From the stress plot figure 5 the length and width of the resistor is finalized and average stress on the resistor is calculated to know the offset, linearity and temperature drift.

Considering the situation when all the resistors (R), are exactly equal to each other, the offset voltage, offset is calibrated to be 0 at room temperature $T=20^\circ C$ and pressure=0. With this initial condition, we have studied the effect of temperature on the stress components along the longitudinal and transverse directions of the resistors $R_1=R_2=R_3=R_4=R$ by carrying out the stress analysis on the top surface of the diaphragm using the commercially available COMSOL multi physics simulation tool. The corresponding changes $\Delta R$ in the resistors are determined using the standard Piezo-resistive coefficients for silicon in the longitudinal and transverse directions. The estimated output voltages, $V_o=(\Delta R/R)*V_{in}$ of the bridge as a function of Pressure varied from 0 to 600 mbar at three different temperatures taking $V_{in}$ as 5V. The plots of estimated values of stress at different pressure versus diaphragm length at different temperature are presented in figure 6 (a) and (b).
At different temperature stress values is taken and its corresponding output voltage is calculated for input voltage $V_{in}=5V$, Young’s Modulus=170Gpa and taking gauge factor 100 at 20°C for nominal doping and for -40°C is 125 and 80°C is 75 [5]. The output is calculated using the below equation 1.

$$V_o = V_{in} \times \left( \frac{\Delta R}{R} \right) \text{where} \frac{\Delta R}{R} = \frac{\text{Stress} \times \text{gauge factor}}{\text{Youngs modulus}}$$

(1)

The figure 7 shows the Pressure(mbar) vs Voltage output(mV) plot where we can see output is linear with pressure but as temperature changes zero offset voltage shifting which makes difficult to compensate the sensor for wide temperature range.

| Temp(°C) | Offset $V_{off}$ (mV) | Full scale offset FSO (at 600mbar) | Span(mV) (FSO – offset) | NL+Hys in % FSO | Change in Offset In % w.r.t span at 20°C |
|----------|------------------------|-------------------------------------|--------------------------|-----------------|----------------------------------------|
| -40      | 143.48                 | 421.33                              | 277.85                   | 0.134           | 53.06                                  |
| 20       | 0                      | 270.38                              | 270.38                   | 0.116           | 0                                      |
| 80       | -90.16                 | 173.04                              | 263.20                   | 0.196           | 33.34                                  |
The corresponding offset voltage $V_{\text{off}}$, full scale output voltage $V_{\text{FSO}}$ at 600mbar and the output voltage Span = ($V_{\text{FSO}}$ – $V_{\text{off}}$), etc are presented in the Table. Excellent sensitivity may be noted at all the three temperatures. However, it is interesting to note that the offset voltage $V_{\text{off}}$ which is zero at 20°C increases to +143mV when the temperature $T$ = -40°C. However, at +80°C the $V_{\text{off}}$ becomes negative and takes a value -90mV as shown in table 1. If we calculate the change in offset voltage with respect to span it shows 50% value, which is undesirable. In addition, linearity is around 0.2% which is high. In order to overcome these issues, and improve the pressure sensor performance parameters, we have chosen the sculptured structure with single and double boss structures, as detailed in the following sections.

3. PRESSURE SENSORS WITH SCULPTURED DIAPHRAGM OR BOSSED DIAPHRAGM

Pressure sensors having flat-diagram are not suitable in the low-pressure range for wide temperature ranges (e.g., about 500Pa), because the sensitivity will have to be increased considerably by making the lateral width to thickness ($a/h$) ratio extremely large, resulting in high degree of nonlinearity. As discussed before, the nonlinearity is the result of stretching of the middle plane which becomes significant when the deflection becomes comparable to thickness of the diaphragm. In order to improve the sensitivity and the linearity simultaneously, specialized geometries such as diaphragms with a rigid centre or boss have been introduced for increasing the stiffness to limit the maximum deflection of the diaphragm, for enhancing the linearity. Such a structure has also been known as the sculptured structure. Typical schematic cross sections of such structures are shown in Figure 8. In the structure only at some regions where diaphragm is formed so this type of diaphragm is rigid compared to flat diaphragm, which in terms increases the burst pressure of the sensor.

![Figure 8. Schematic View of Sculptured Diaphragm Structure.](image)

3.1 Boss Structure Simulation Result

In this structure only certain region of the 2mm*2mm diaphragm area is etched so that it forms double boss silicon(800µm*800µm) and Single boss silicon(1200µm) as shown in figure 9 (a) and (b). Maintaining SOI wafer thickness(25µm) and diaphragm dimension same as FLAT structure boss structure is studied. Figure 9 shows the different region where diaphragm is formed at stress due to this diaphragm is studied for 600mbar pressure. Region is chosen such that resistor can be placed in that area without any difficulties.

![Figure 9. Schematic diagram of a) Double boss b) Single boss.](image)
The stress is plotted on the diaphragm to fix the resistor location and its dimension. The figure 10 shows the stress plot along the centre of the diaphragm at 20°C for 600mbar pressure.

From this stress plot maximum stress is seen at region 1,2 be kept at this maximum stress locations to finalize the resistor dimensions. The stress plot along the diaphragm is drawn and by plotting stress plot for different pressure figure 11. (0,120,240,360,480 and 600mbar) the linearity of the sensor is also obtained.

(a)  
(b)

Figure 10. Stress Plot at 600mbara) Double boss b) Single boss.

(a)  
(b)

Figure 11. Stress plot along the cutline for different pressure (0 to 600mbar) at 20 °C a) Double boss b) Single boss.

(a)  
(b)

Figure 12. Whetstone bridge resistor location a)Double boss b)Single boss.

In this structure all the four resistors (R1, R2 R3 and R4) are subjected to transverse stress when the
pressure is applied from the top side of the diaphragm as shown in the above Figure 12. In double boss the resistors R1 and R3 (located in Regions-1 and -3) experience identical transverse-tensile stress and are connected to the opposite arms of a Wheatstone bridge. The resistors R2 and R4 (located in the region-2) experience identical transverse compressive stress and are connected in the other opposite arms of the bridge. Similarly, in single boss the resistors R1 and R3 (located in Regions-4) experience identical transverse-tensile stress and are connected to the opposite arms of a Wheatstone bridge. The resistors R2 and R4 (located in the region-5) experience identical transverse compressive stress and are connected in the other opposite arms of the bridge. In this structure, the presence of the rigid island enhances the linearity because the stresses in the different regions are quite balanced. At the same time this structure ensures high sensitivity due to the stress concentration in the regions where the piezo resistors are located.

![Figure 13](image)

**Figure 13.** Pressure Vs Output Plot at -40, 20 and 80˚C a) Double Boss b) Single Boss.

Figure 13 shows temperature effect on sensitivity and offset drift for -40, 20 and 80˚C. In boss structured diaphragm as temperature changes the TCS effect on the diaphragm is very less due to its rigid silicon boss. So offset drift due to temperature is very less compared to its span values. If we plot characteristic table of both the difference is clearly visible.

| Temp(˚C) | Offset(mV) | Full scale offset FSO (at 600mbar) | Span(mV) (FSO - offset) | NL+Hys in %FSO | Change in Offset In % w.r.t span at 20˚C |
|----------|------------|------------------------------------|-------------------------|----------------|----------------------------------------|
| -40      | -14.66     | 166.96                             | 181.62                  | 0.081          | 8.63                                   |
| 20       | 0          | 169.72                             | 169.72                  | 0.108          | 0                                      |
| 80       | 6.20       | 163.10                             | 156.90                  | 0.164          | 3.66                                   |

Double-boss structure it has better sensitivity along with less offset drift due to temperature as shown in table 2. But non linearity is little high 0.16%FSO and also it has 100um feature size where we have to etch to form a diaphragm which is little critical using DRIE (Deep Reactive Ion Etching) [6].

| Temp(˚C) | Offset(mV) | Full scale offset FSO (at 600mbar) | Span(mV) (FSO – offset) | NL+Hys in % FSO | Change in Offset In % w.r.t span at 20˚C |
|----------|------------|------------------------------------|-------------------------|----------------|----------------------------------------|
| -40      | -8.19      | 120.16                             | 128.35                  | 0.002          | 7.57                                   |
| 20       | 0          | 108.15                             | 108.15                  | 0.014          | 0                                      |
| 80       | 4.73       | 92.16                              | 87.43                   | 0.009          | 4.37                                   |

From the characteristic table 3 of single boss, we can see that it has better linearity and offset drift due
to temperature compared to double boss but with less sensitivity. This structure has enough place for keeping the resistor compared to double boss structure. This will ease out the sensor fabrication.

4. RESULTS AND CONCLUSIONS

From this simulated result for measuring low pressure ranges we can conclude that sculptured structure will improves the linearity and offset drift due to temperature with better sensitivity. Flat diaphragm pressure sensor provides very good sensitivity. However, linearity and offset drift values are high. In situation where the pressure sensor has to work over a wide range of temperatures, sculptured structure is a better choice. In point of view of fabrication Resistor dimensions can easily be decided in boss structure because here all the resistor experience only transverse stress. This will also reduce the DRIE (Deep Reactive Ion Etching) error. However, if the use boss structure is required for Absolute pressure sensing, we have to etch the Glass wafer for anodic bonding which requires extra step of fabrication. Table 4 gives the comparison of three different diaphragm structures.

| Characteristics                  | Flat Diaphragm | Double Boss | Single Boss |
|----------------------------------|----------------|-------------|-------------|
| Span (mV) (At 600mbar, 5V supply) | 270.38         | 169.72      | 108.15      |
| Linearity (% FSO)                | 0.196          | 0.164       | 0.014       |
| Offset Drift (% Span)            | 53.06          | 8.63        | 7.57        |
| Fabrication feasibility for      |                |             |             |
| Resistor dimension               | Small          | Large       | Large       |
| Fabrication feasibility for      |                |             |             |
| DRIE                             | Difficult      | Easier      | Easier      |
| Fabrication feasibility for      |                |             |             |
| Anodic bonding                   | Direct Bonding | Need an extra step For Glass etching | Need an extra step For Glass etching |

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