SPLIT-BOSS DESIGN FOR IMPROVED PERFORMANCE OF MEMS PIEZORESISTIVE PRESSURE SENSOR

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Abstract—This paper proposes a novel split-boss design of piezoresistive pressure sensor for low pressure range (0-1.1bar). This design improves both sensitivity and non-linearity of the pressure sensor. The square diaphragm of pressure sensor is proposed to be fabricated by wet bulk micromachining using TMAH, undercutting the structure with an angle of 54.74°. Corner compensation structures are proposed to be used for avoiding convex undercutting. The size of diaphragm is optimized to have high sensitivity and then a boss is added to improve the linearity. Further a split is introduced in the boss to improve the performance. Conventional design, bossed design and novel design are simulated in COMSOL® and the sensitivity and non-linearity are compared. The novel split-boss design proposed is found to be improving both non-linearity and sensitivity and thus enhancing the performance of pressure sensor.

Keywords—Piezoresistive pressure sensor, bossed diaphragm, TMAH, COMSOL®.

I. INTRODUCTION

Pressure Sensors are by far the leading type of MEMS devices in terms of revenues and although they were the first commercialized MEMS based sensors, there is scope of innovation and development in this field. There are various sensing principles which can be employed for measurement of pressure [1]. These include piezoresistive, capacitive, resonant and piezoelectric sensing. Out of these different sensing principles, the piezoresistive sensing is preferred in pressure sensors because of ease of fabrication, high reliability, high linearity in output of sensor and simple compensation circuitry. Hence micro-fabricated piezoresistive pressure sensor is one of the better developed MEMS devices in use [2]. Since it involves simple and direct transduction mechanism between mechanical and electrical domain, it has been employed in a wide variety of applications [3-5]. Especially in low pressure range applications, micro pressure sensors are employed which require very high sensitivity. Thin diaphragms can be used to attain high sensitivity but this will in turn deteriorate the linearity. Hence improving both sensitivity and linearity simultaneously is a challenge.

The first piezoresistive pressure sensor was developed in 1962 and since then, various designs are proposed to improve the performance of pressure sensor [6]. The first low pressure sensor based on the bossed diaphragm structure was proposed in 1980 [7]. After 1980s, continued improvements in sensing configuration design allowed further reduction in size, increase in sensitivity, higher yield, and better performance. Further, sensor with a centre boss on the diaphragm and an annular groove formed in the back surface of the diaphragm was proposed in 1982 [8].

The boss structure improves the nonlinearity but deteriorates the sensitivity considerably. We propose a split boss structure which helps to achieve a good linearity without losing much sensitivity.

This work is organized as section 2 discusses the theory. Section 3 and 4 describes the conventional boss-less design and bossed-diaphragm designs respectively including simulation results. Finally, section 5 presents the novel split-boss design and comparison with former designs showing the improvement in performance. Conclusions are given in Section 6.

II. THEORY OF PIEZORESISTIVE PRESSURE SENSOR

A. Working Principle

A piezoresistive pressure sensor typically consists of a silicon chip with an etched diaphragm [9] fixed over glass. This Pyrex glass is fixed since absolute pressure is measured and hence vacuum is created between glass and diaphragm. Schematic of a typical pressure sensor is shown in figure 1.

![Figure 1. Typical etched Diaphragm](image)

The resistors are located close to the edges of the silicon diaphragm and metal paths provide electrical connections between the resistors. A voltage input is provided between two opposite nodes of the Wheatstone bridge and the output is sensed at the...
other two nodes as shown in figure 2. When a pressure is applied, the diaphragm deflects and the piezoresistive effect causes change in resistance of the piezoresistors under stress [7]. So the output of the Wheatstone bridge varies according to pressure applied.

Figure 2. Transduction mechanism of a typical piezoresistive pressure sensor

B. Mechanical Properties of Silicon
Silicon is the most commonly used material in Microelectromechanical systems (MEMS). Generally, Silicon is considered as an isotropic material for easy analysis and calculations. But in this work, the stiffness matrix corresponding to anisotropic behaviour of silicon is used to have more accurate results. In the case of isotropic materials, stress and strain are related in the familiar form \( \sigma = E \varepsilon \). But in an anisotropic material, stress, strain are expressed by a second rank tensor and they are related by a fourth rank tensor. Because of cubic symmetry of silicon, the fourth rank tensor can be specified with only three independent components. So the tensor can be written as,

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6
\end{bmatrix} =
\begin{bmatrix}
c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\
c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\
c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & c_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & c_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & c_{44}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{12} \\
\gamma_{13} \\
\gamma_{23}
\end{bmatrix}
\]

(1)

The elasticity values in the frame of reference of a standard (100) silicon wafer is used as given stiffness matrix (in GPa)[10].

These values were used for the simulation in COMSOL.

C. Piezoresistive coefficient of silicon
The change in resistance of a piezoresistive material under stress in given by [11],

\[
\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{2 \Delta r}{r} + \frac{\Delta \rho}{\rho}
\]

where \( \Delta R, \Delta l, \Delta r, \Delta \rho \) is change in resistance, length, width and resistivity respectively and \( R, l, r, \rho \) are the initial resistance, length, width and resistivity respectively.
The first two terms corresponds to geometrical deformation and is negligible in case of piezoresistors. Hence the equation reduces to [11],

\[
\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} = \pi_1 \sigma_1 + \pi_t \sigma_t
\]

(3)

where \( \pi_1, \pi_t \) corresponds to piezoresistive coefficients of the material along longitudinal and transverse directions respectively. \( \sigma_1, \sigma_t \) are resultant stresses along longitudinal and transverse directions respectively. In the present design, considering the resistors are oriented along [110] directions in (100) wafers in order to maximize the piezoresistivity effects. We have [12],

\[
\begin{align*}
\pi_{1110} &= -1.1 \times 10^{-11} \text{ Pa}^{-1} \\
\pi_{1111} &= -6.6 \times 10^{-11} \text{ Pa}^{-1} \\
\pi_{1112} &= -1.381 \times 10^{-9} \text{ Pa}^{-1}
\end{align*}
\]


D. Sensitivity
The relative change in the output voltage per unit of applied pressure is defined as the sensitivity of pressure sensor [13]. For calculation of sensitivity from observations, the calibration curve is developed into a straight line. This straight line, known as an "end-point straight line" is formed by connecting the two end points [14] as shown in figure 3.

Figure 3. Illustration for calculation of sensitivity

\[
V_{out} = V_{out,\text{max}} \frac{P}{P_{\text{max}}}
\]

\[
V_{out,\text{max}} = V_{in} \text{ for } P = 0
\]

\[
V_{in} = \text{ constant (e.g. 5 V)}
\]

\[
P_{\text{max}} = 1 \text{ bar}
\]
The sensitivity is given by slope/input voltage.

**E. Non-linearity**

Nonlinearity is defined as the deviation of calibrated point from the end-point straight line. So for each observation, there is a specific deviation and corresponding non-linearity. Generally nonlinearity is expressed as a percentage. By using the formula for nonlinearity [11],

$$ NL = \left( \frac{V_o(p_i) - V_o(p_{\text{max}})}{V_o(p_{\text{max}})} \right) \times 100\% $$

where, $p_i$ is pressure at calibrated points, $p_{\text{max}}$ is maximum pressure of range, and $V_o$ is corresponding voltage. Non-linearity of each calibrated point is found and the maximum among them is defined as the non-linearity of the sensor. The nonlinearity of a piezoresistive pressure sensor is typically in the range of 0.5%–0.05% [15].

**III. CONVENTIONAL DESIGN**

**A. Boss-less Design**

To achieve the expected sensing range, a chip size of 3.5mm×3.5mm was chosen. Since the sensor is for low pressure range a thin diaphragm of 20µm is chosen. Thin diaphragms have a better sensitivity but poor linearity whereas the reverse is true for thick diaphragms. The boss-less design for these dimensions is shown in figure 4.

For good linearity, the maximum deflection of the diaphragm (at the midpoint) must be five times lesser than the thickness of the diaphragm [16]. The maximum deflections for diaphragms of different dimensions were simulated by applying a pressure of 1.1 bar. The results obtained by simulating in COMSOL is given in Table I.

From Table 1, the diaphragm size of 1300µm have maximum possible deflection and therefore was found to be more appropriate.

**B. Piezoresistors and Their Placement**

The junction depth of the resistors is assumed to be 1µm. Regions where high stresses are developed were found and piezoresistors of dimensions 240µm×10µm and are placed in these regions. This structure designed in COMSOL is given in figure 5.

Pure silicon is used as the base structure including diaphragm. Aluminium is used as conductors joining the piezoresistors as well the metal pads at corners. Conductivity of aluminium is taken at as 3.774×10⁷ S/m. Input as well as output voltages are taken from the corners of conductors. All conductors are placed in symmetry. Values of other physical parameters are taken as discussed in section 2.3 and 2.4. The sensitivity and non-linearity of this structure is found to be 20.474mV/MPa.V and 0.981% respectively.

**IV. BOSED DIAPHRAGM DESIGN**

**A. Bossed Design**

Conventional Pressure sensors are based on the principles discussed above. Since the design goal is for low pressure ranges, thin diaphragms are more desirable to have better sensitivity. But thin diaphragms results in more nonlinearity which is also a crucial parameter. In these conventional diaphragms, the diaphragm can be considered as spring which has deflection proportional to force applied. In case of thin diaphragms this deflection has a nonlinear proportionality which results in increase in nonlinearity of pressure sensor [17]. To improve linearity bossed structures are proposed because they locally increase the stiffness of diaphragms [18]. Since the design is proposed to fabricate by wet bulk micromachining using TMAH, the structure is undercut with an angle of 54.74°. Schematic of a typical bossed diaphragm structure is given in figure 6.
The structure designed is COMSOL is shown in figure 7.

Figure 7. Bossed diaphragm designed in COMSOL

B. Corner compensation technique for TMAH etching

We need to achieve a structure as discussed above, which is generally called as mesa structure, will give a bottom view as shown in figure 8(a) but without proper corner compensation technique a distorted structure will be resulted due to convex under cutting as shown in figure 8(b). [19]

Figure 8(a) Ideal mesa structure. 8(b) Convex corner undercutting of mesa structure.

Corner compensation technique is used to avoid this convex undercutting and thus achieve ideal mesa structure. Different types of compensation structures are proposed [19-20] to avoid this and thus achieve perfect mesa structure. Such three compensation structures are shown in figure 9.

Figure 9. Corner compensation structures.

As the boss size is reduced sensitivity is increased accordingly. But there is no particular trend for nonlinearity as observed.

V. SPLIT-BOSS DESIGN

The According to equation (6) placing the piezoresistors in maximum stress region should increase the change in resistance and thus improves both sensitivity and non-linearity. So a novel split boss was proposed expecting that high stress regions will be formed where lateral piezoresistors are placed and thus improving both sensitivity and non-linearity. Schematic of proposed design is given in figure 10.

Figure 10. Proposed split boss structure

Split distance of 100 µm is taken and the structure designed in COMSOL as shown in figure 11.

Figure 11. Split boss structure designed in comsol

Sensitivity and nonlinearity for proposed split-boss design is found and compared with split-less bossed diaphragm design as given in Table III and Table IV.

Table II. Sensitivity and nonlinearity

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Boss size (µm)</th>
<th>Sensitivity (mV/MPa.V)</th>
<th>Nonlinearity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without boss</td>
<td>--</td>
<td>20.474</td>
<td>0.981</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>5.172</td>
<td>0.475</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>7.710</td>
<td>0.339</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>10.213</td>
<td>0.449</td>
</tr>
</tbody>
</table>

Table III. Sensitivity of split-less boss and split-boss designs

Split-Boss Design For Improved Performance Of MEMS Piezoresistive Pressure Sensor
It is observed that introducing the split significantly improve both sensitivity and non-linearity.

CONCLUSION

A conventional piezoresistive pressure sensor is designed with optimized performance. A boss is added to this basic design and its performance is analysed. Finally a split is introduced in the boss structure and sensitivity and non-linearity are found. Comparing the results it is found that proposed novel split-boss design has improved both sensitivity and non-linearity.

REFERENCES