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Design and Optimization of Sculptured Diaphragm with Deflection, Stress Analysis and Sensitivity Enhancement

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ABSTRACT: In this paper, studies were initiated to design the special geometry diaphragms such as sculptured diaphragms with supports or rigids. These sculptured diaphragms (single boss sculptured, double boss sculptured) with support increase the stiffness which limits the maximum deflection and concentrate the stress in centered region. These specialized geometries with square shape is analyzed for simultaneous improvement of sensitivity and linearity. The load deflection analysis is carried out to ensure high linearity to ensure Small Scale Deflection (SSD) for less than 40%. The percentage of deflection is considered as small as possible to ensure higher linearity. Stress analysis is performed to identify the maximum stress regions for the proper placement of piezoresistors. The proposed diaphragm with four piezoresistors in wheat stone bridge arrangement used to estimate electrical output and analyzed for its voltage sensitivity. Further sensitivity enhancement is tested with Silicon-On-Insulator (SOI) which is a special micro machining method for the proposed diaphragms.

I. INTRODUCTION

Pressure measurement is certainly one of the most mature applications of Micro Electro Mechanical Systems (MEMS). This is made possible by the advantage of batch fabrication micromachining technologies capable of manufacturing sensors at very low unit cost. Silicon micromachined pressure sensors are inherently smaller, lighter and faster than their macroscopic counterparts and are often more precise. Low pressure measurement is essential and need to be highly accurate. Flash flood level measurement is the one which requires pressure to be measured in the range of 10cm to 100cm which is equivalent to 1000Pa which is in the low pressure range. Any type of level measurement which is below the 10kPa is considered as low pressure measurement. The intracranial pressure is also in the range of 1000Pa. So, the low range pressure is chosen as 0Pa to 1000Pa. The objective is to design a Micro Electro Mechanical Piezoresistive Pressure sensor to measure low pressure in the range of 0-1000Pa with good voltage sensitivity and acceptable linearity.

Many of the silicon micromachined pressure sensors use diaphragm as the major sensing element and piezoresistive transduction mechanism is used to convert the small deflection from the diaphragm into electrical output. The most common square shapes considered due to their ease of fabrication and higher deflection sensitivity. Very thin diaphragms are required for sensing low pressure. In MEMS pressure sensors, diaphragm material with lower young’s modulus with higher breaking stress, square diaphragm rather than circular diaphragm, materials with high gauge factor for piezoresistors, single crystal silicon for diaphragm and piezoresistive property of silicon or polycrystalline silicon [Sivakumar,2006] as transduction mechanism is used to improve sensitivity [Bhat,2013]. Not only in different range of pressure, but also MEMS sensors need to be rugged, reliable, sensitive, biocompatible and to survive in harsh and corrosive environments [Bhat,2007&Vidhya Balaji,2012].

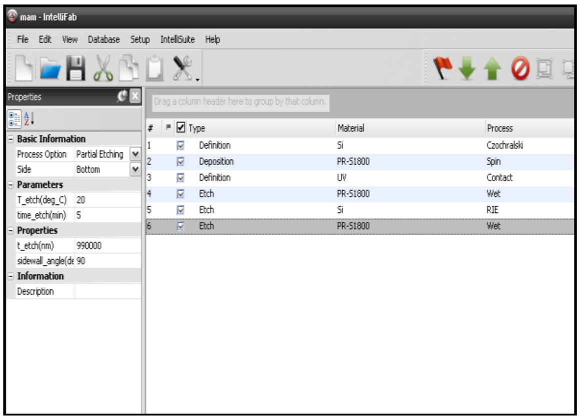
As the diaphragm is the major key for this pressure sensor, it should be designed with acceptable linearity, high sensitivity, withstand the maximum pressure and should not break [Narayanaswamy,2011]. So design of diaphragm is more critical to sense this low pressure. The diaphragm structure created using Intellisuite MEMS CAD tool using Bulk Micromachining [Xiadong Wang,2006] method including Reactive Ion Etching [Vidhya Balaji,2012].

Paper is organized as follows. Section II describes diaphragm design for sensing low pressure using thin diaphragms which concentrate stress in relatively localized thin area by sculptured diaphragm [Mallon,1990 & Sandmier,1991]. After diaphragm design , dimension of the diaphragm is optimized based on small scale deflection to ensure linearity. Next, maximum stress regions are identified for the placement of piezoresistors and output estimated by wheat stone bridge arrangement in section III using four piezoresistors. Section IV presents sensitivity enhancement of designed sensor using SOI technique. Finally, Section V presents conclusion.

II. DIAPHRAGM DESIGN

A. Area of Study

The diaphragm is designed with single rigid and two rigid or support at the bottom in the center. The dimension of the diaphragm is (Lμm× Wμm× hμm) 500μm× 500μm ×1μm where L is the length, W is the width and h is the thickness of the diaphragm. The shape of the diaphragm is selected as square shape [Zhao Linlin, 2006]. The structure is created with single crystal silicon by czochrolski [Smith,1954] substrate process using proper mask with suitable photo resist, reactive ion etching, wet etching and UV exposing. The following steps are used to create the structure using Intellisuite is shown in Fig. 2.1.



Basic Information
Process Option: Partial Etching
Side: Bottom
Parameters
T_etch(deg_C): 20
time_etch(min): 5
Properties
t_etch(nm): 990000
sidewall_angle(de: 90
Information
Description:

#	☑ Type	Material	Process
1	☑ Definition	Si	Czochralski
2	☑ Deposition	PR-S1800	Spin
3	☑ Definition	UV	Contact
4	☑ Etch	PR-S1800	Wet
5	☑ Etch	Si	RIE
6	☑ Etch	PR-S1800	Wet

Fig.2.1. Steps involved in creating the single boss and double boss sculptured diaphragm

The square diaphragm of thickness h and side length =2a, subjected to a uniform pressure P. from the theory of plates [Sandmier, 1991], the maximum deflection at the center of the diaphragm is given by the equation (1)

$$P = E\frac{h4}{a4}\left(g1\frac{w0}{h} + g2\frac{w0}{h}\right) \qquad (1)$$

where E is Young’s modulus and g1 and g2 are constants related to Poisson ratio ν, by the relation

$$g1 = 4.13/1\text{-}v^2 \quad \text{and} \quad g2=1.98(1-0.585)/1-v =2.33 \qquad (2)$$

Substituting ν=0.3for silicon g1 and g2 turn out to be 4.54 and 2.33 respectively. Thus the maximum deflection $w_0$is linearly related to pressure P till w_0<<h. The second term inside the bracket is about 0.5% of the first term when w_0 = 0.1h. The first term is Small Scale Deflection (SSD) region and second term is Large Scale Deflection (LSD) region [Timoshenko,1959 & Zhao Linlin, 2006]. The deflection w_0 in the linear region of operation can be expressed as follows for a square diaphragm.

$$\frac{w0}{h} = \frac{pa4}{E\,h4\,g1} \qquad (3)$$

The structure is created using silicon with the following material properties given in Table 2.1.

Table 2.1 Material Properties of Silicon

S/N	Material property	Value
1	Yield Strength	7 Gpa
2	Hardness	850 Kg/mm^2
3	Young's Modulus	170 GPa
4	Melting point	1410°C
5	Gauge Factor	100-200
6	Poisson's ratio	0.3
7	Temperature	20°C

The top view of single boss sculptured diaphragm and double boss sculpture diaphragm is shown in Fig. 2.2 and Fig.2.3.

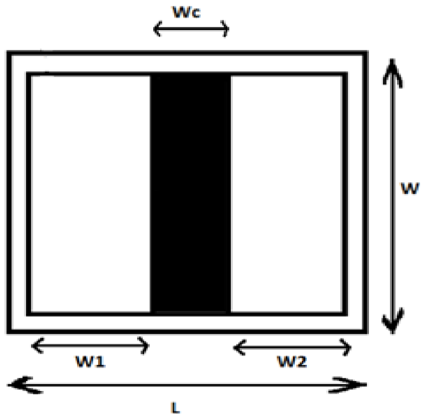


Fig.2.2. Top View of single Boss Sculptured Diaphragm

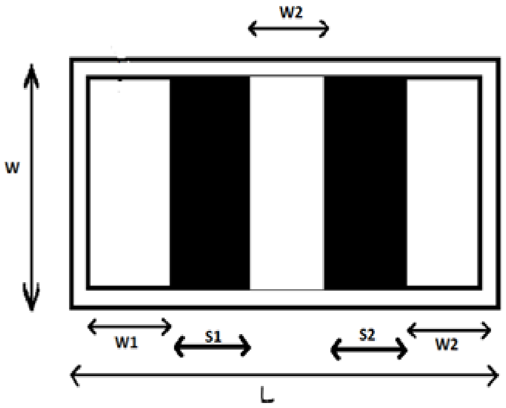


Fig.2.3. Top View of double Boss Sculptured Diaphragm

The optimized diaphragm is selected for the stress analysis and piezoresistive analysis to estimate the electrical output. The selected diaphragm satisfies the deflection within 20% of thickness of the diaphragm is given in Table 2.2 and Table 2.3.

Table 2.2 Single Boss Sculptured Diaphragm

h (µm)	G_1 (µm)	G_2 (µm)	S (µm)	Y (µm)	y_p (%)
0.9	170	170	160	0.1525	17

Table 2.3 Double Boss Sculptured Diaphragm

h (µm)	G_1= G_2 (µm)	S_1= S_2 (µm)	G_c (µm)	Y (µm)	y_p (%)
1	20	160	140	0.1892	18

From the load deflection analysis carried out for the single sculptured diaphragm with G_1 = 170µm, G_2 = 170µm, S =160µm and h= 0.9µm and for the double support diaphragm reveals that center support width G_c = 180 µm, G_1 and G_2 = 20µm and S_1 and S_2 = 160 µm and h= 1µm gives the center deflection 15% of h, and these structures are considered where the rigid boss to limit the nonlinear deflection due to balloon effect [Bhat,2013] for further analysis. The optimized diaphragm is selected for the stress analysis and piezoresistive analysis to estimate the electrical output in next section.

III. STRESS ANALYSIS AND ELECTRICAL OUTPUT

The next important step is to analyze the maximum stress regions in the longitudinal and transverse directions which are essential for placing the piezoresistors on top of the diaphragm [Wisitsoraat,2007]. The stress relation is given in equation (4),

$$\sigma_{yy} = \beta_1 P \left[\frac{G}{h}\right]^2 \quad and \quad \sigma_{xx} = \beta_2 P \left[\frac{G}{h}\right]^2 \qquad (4)$$

The maximum longitudinal and transverse stress values for the different structures 'C_1', 'C_2', 'C_3', 'C_4', 'C_5' , 'C_6' and 'C_7'of single boss sculptured diaphragm at 1000Pa are given in Table 3.1.

The stress results in Table 3.1, show that the optimized structure 'C_7' gives the highest stress and highest deflection (20%) within SSD than 'C_5' and 'C_6'. Though, structures 'C_1', 'C_2', 'C_3' and 'C_4' yield the higher stress than 'C_5', 'C_6' and 'C_7', it is not satisfying the required SSD condition. To estimate the electrical output, the square diaphragm 'C_7' is selected for further analysis as it is within the limits of SSD and safe to realize [Milon jevti,2008]. The maximum longitudinal stress regions of the simulated single boss sculptured diaphragm are highlighted in red colour as shown in Fig.3.1. The maximum transverse stress regions of the simulated single boss sculptured diaphragm are highlighted in red colour as shown in Fig.3.2

Table.3.1 Comparison of maximum longitudinal stress and transverse stress of the different single boss sculptured diaphragms

Stress estimated at Pressure 1000 (Pa)	C_1	C_2	C_3	C_4	C_5	C_6	C_7
	G_1=G_2 =230µm	G_1=G_2 =220µm	G_1=G_2 =210µm	G_1=G_2 =200µm	G_1=G_2 =190µm	G_1=G_2 =180µm	G_1=G_2 =170µm
	S=40µm	S=60µm	S=80µm	S=100µm	S=120µm	S=140µm	S=160µm
S_{xx}(MPa)	16.539	14.125	11.8802	11.8802	9.796	7.891	6.1808
S_{yy}(MPa)	10.1046	8.4543	7.0839	7.083	5.7184	4.6164	3.529

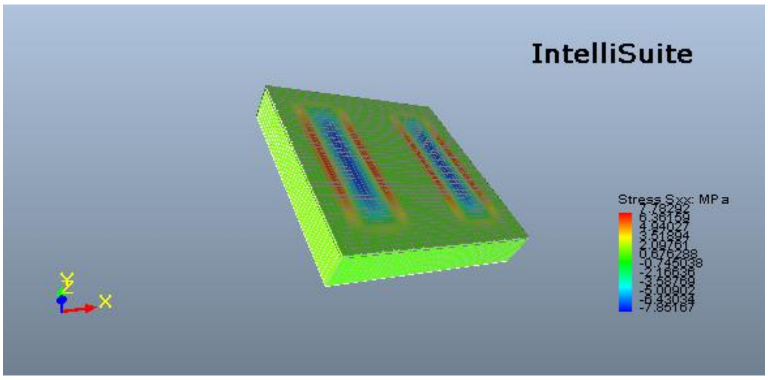


Fig.3.1 Simulated single boss sculptured diaphragm with longitudinal stress distribution at 1000Pa

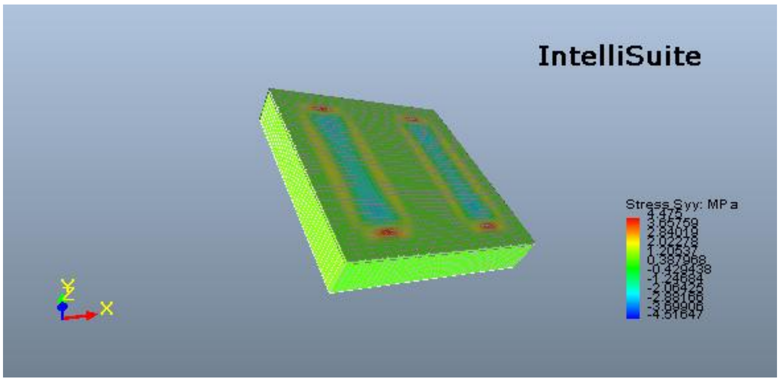


Fig.3.2 Simulated single boss sculptured diaphragm with transverse stress distribution at 1000Pa

The maximum longitudinal and transverse stress values for the different structures ‘T_1’, ‘T_2’, ‘T_3’, ‘T_4’, ‘T_5’ and ‘T_6’of double boss sculptured diaphragm at 1000Pa are given in Table 3.2. The structures ‘T_1’, ‘T_2’, and ‘T_3’ that do not satisfy SSD though their stress values are very high and are not considered. The longitudinal stress and transverse stress are found higher for the ‘T_4’ structure, but it gives 28% percentage of deflection which is greater than the limits of small scale deflection. ‘T_5’ structure gives a very poor deflection of 8% which creates the balloon effect. Therefore, ‘T_6’ structure with 15% percentage deflection with the moderate stress value is considered for further analysis. The ‘T_6’ structure satisfies both SSD and ensures linearity. The maximum longitudinal stress regions of the simulated double boss sculptured diaphragm are highlighted in red colour as shown in Fig.3.3. The maximum transverse stress regions of the simulated double boss sculptured diaphragm are highlighted in red colour as shown in Fig.3.4.

Table 3.2 Comparison of maximum longitudinal stress and transverse stress at 1000Pa for double boss sculptured diaphragm

Stress estimated at Pressure 1000 (Pa)	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**T_6**
	G_1=G_2=20μm	**G_1=G_2 =20μm**	**G_1=G_2=20μm**	**G_1=G_2 =20μm**	**G_1 =G_2=20μm**	**G_1=G_2=20μm**
	G_c =360μm	**G_c =300μm**	**G_c =240μm**	**G_c =200μm**	**G_c =180μm**	**G_c =140μm**
	S_1=S_2=50μm	**S_1=S_2=80μm**	**S_1=S_2=110μm**	**S_1=S_2=130μm**	**S_1=S_2=140μm**	**S_1=S_2=160μm**
S_{xx}(MPa)	37.0411	28.8078	16.5012	11.98	7.891	4.9424
S_{yy}(MPa)	27.5034	17.8073	10.1026	7.08397	4.6164	2.6975

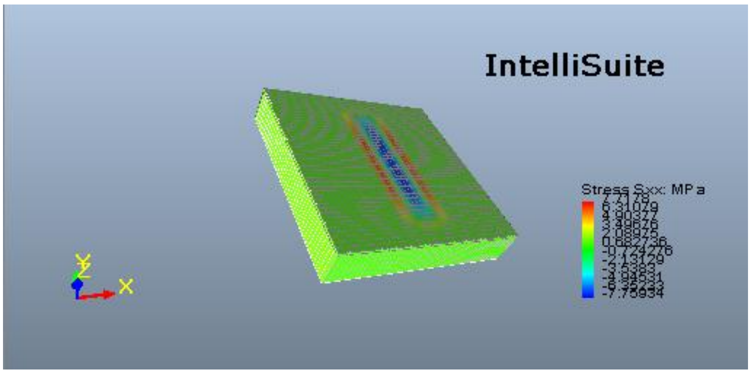


Fig.3.3 Simulated double boss sculptured diaphragm with longitudinal stress distribution at 1000Pa

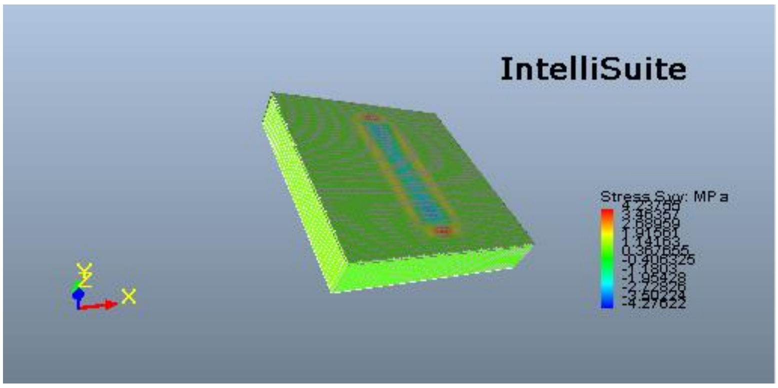


Fig.3.4 Simulated double boss sculptured diaphragm with transverse stress distribution at 1000Pa

The stress obtained is to be converted into electrical output by piezoresistive analysis. The polysilicon with suitable properties [Ingelin Clausen,2007 & Shyam Aravamudhan,2008] has been considered in this work to realize the piezoresistors using surface micromachining on the top of the diaphragm. Improvement of the voltage sensitivity, requires placing the four piezoresistors in such a way that two resistors (R_2, R_4) experience tensile stress and exihibit increase in their resistance and the remaining two resistors (R_1, R_3) experience compressive stress and exihibit decrease in their resistance from the resistance value measured at no stress condition [Zhao Linlin, 2006].

Hence resistors (R_2, R_4) are palced at 80µm from the center of the diaphragm in the XX direction and resistors (R_1, R_3) are placed at 220µm from the center of the diaphragm in the YY direction as shown in Fig. 3.5 for single boss sculptured diaphragm and in Fig. 3.6 for double boss sculptured diaphragm.

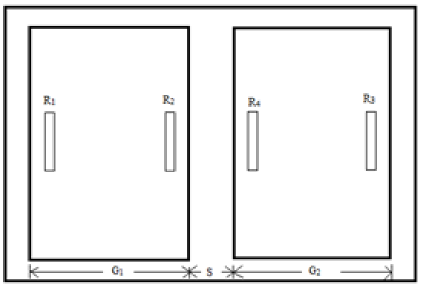


Fig.3.5 Piezoresistor placement on the optimized single boss diaphragm ‘C_7’

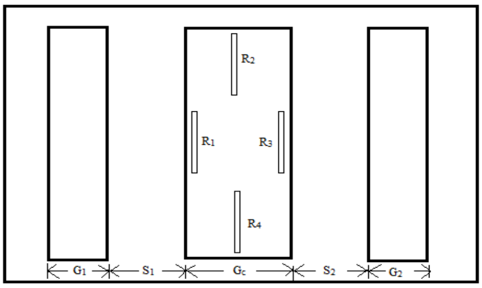


Fig.3.6 Piezoresistor placement on the optimized double boss diaphragm 'T_6'

The smith piezoresistive coefficients [Smith,1954] used in the simulation are as follows: $\pi_{11} = 6.6\times10^{-11}$ Pa^{-1}; $\pi_{12} = 1.1\times10^{-11}$ Pa^{-1}; $\pi_{44} = 138\times10^{-11}$ Pa^{-1}, sheet resitance of the p-type silicon resistor is 1000 Ω per square cm and temperature = 20°C. The size of polysilicon piezoresistor is 40µm×20µm×1µm. The voltage sensitivity has been estimated using wheat stone bridge assembly for the "C_7" and "T_6" type sculptured diaphragm. The bridge excitation voltage'V_b' is 5V. The estimated electrical output is in the range of 64.99µV/Pa.

IV. ENHANCEMENT OF SENSITIVITY

The simulated output is 64.99µVPa for the optimized 'T6' double boss sculptured disphragm. Further reduction of thickness to 0.2µm with Silicon-On-Insulator (SOI) has been done to improve the voltage sensitivity. The SOI layer improves electrical performance [Dimitropoulos,2005, Narayanaswamy, 2011,2013] and is helpful for the electrical integration of the piezoresistor on the diaphragm. The SiO2 layer also gives higher deflection sensitivity, reduces the thickness of the diaphragm and improves the performance by reducing power consumption. The optimized 'T6' sensor with SOI gives a voltage sensitivity of 104.9 µV/Pa. The sensitivity further improves to 154 µV/Pa by the use of polycrystalline silicon material for both diaphragm and piezoresistor. Also, the thickness of diaphragm is reduced from 1µm to 0.5 µm which is shown in Fig.4.1.

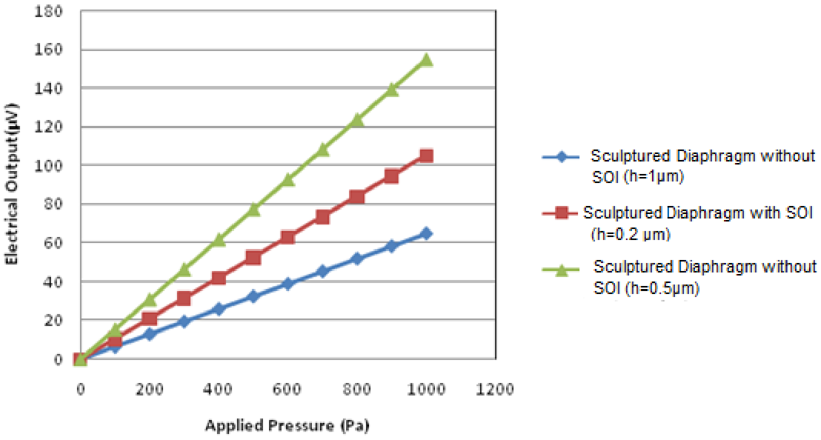


Fig.4.1 Applied pressure versus electrical output of sculptured diaphragm 'T_6'

V. CONCLUSION/RECOMMENDAIONS

Conclusively, it has been observed that the single support and double support diaphragm with dimensions 500µm×500µm×1µm is constructed with reactive ion etching. The diaphragms were analysed for deflection sensitivity through variation of the support width in the range from 120µm to 160µm to achieve small scale deflection within 20% of h. The four piezoresistors are wired by wheatstone bridge arrangement which estimates the electrical output. The output is in the order of 64.99µV at 1000Pa. The sensitivity is improved through use of silicon-on-insulator (SOI) technology by which integration of piezoresistors is easily achieved. The output using SOI method is around 104.9µV at 1000Pa. The longitudinal stress S_{xx} is 7.89MPa and transverse stress is 4.61MPa. The voltage sensitivity improves through use of polysilicon piezoresistors with thickness reduced from 1µm to 0.5µm is about 154µV at 1000Pa. It can therefore be recommended that

1. The sculptured diaphragms were analyzed for the maximum stress regions to place two resistors (R_1, R_3) to undergo increase in resistance and two resistors (R_2, R_4) to undergo decrease in resistance in the longitudinal and transverse directions.
2. The sensitivity is improved through use of silicon-on-insulator (SOI) technology by which integration of piezoresistors is easily achieved.
3. The sensitivity of the diaphragm is enhanced through the reduction of diaphragm thickness.
4. The same material for diaphragm and piezoresistor gives output more than twice the conventional voltage.

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