Analysis of MEMS Diaphragm of Piezoresistive Intracranial Pressure Sensor

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Abstract—In the present paper, the design and simulation of square diaphragm, MEMS piezoresistive pressure sensor for intracranial application has been presented. The pressure sensor design presented in this paper consists of a carbon nanotube (CNT) suspended on a square and slotted shaped diaphragm as piezoresistor. The slot was added into the design of the square diaphragm to reduce the residual stress and stiffness of diaphragm. This kind of pressure magnifying scheme is utilized so that placement of the piezoresistor will be on the most sensitive part of the diaphragm, which is at the maximum stress locations on the diaphragm. The static analysis of the system is performed using FEM model of COMSOL Multiphysics. Two sensor designs incorporating square and slotted square diaphragm are implemented and compared to realize the pressure-sensitive components. The pressure sensor has been designed to measure pressures in the range of 0 to 10 mmHg that is in the range of intracranial pressure sensors. The change of resistance of piezoresistors placed on the maximum stress area of slotted square diaphragm was found to be linear with respect to the applied pressure.

Keywords— CNT; MEMS; Pressure sensor; Piezoresistive; Diaphragm

I. INTRODUCTION

Intracranial pressure monitoring is an important role in the management of patients with head injury and neurosurgical patients. Intracranial pressure (ICP) is measured as the difference between cerebral pressure and standard atmospheric pressure [1]. All current clinical available methods are invasive and use various transducer systems including epidural catheters, subcranoid bolt/screws, fiber optic catheters, and microchip transducers [2]. Furthermore, these measurement methods suffer relatively large error rate due to cerebrospinal fluid derivation [3], [4]. Thus, it is important to have a highly sensitive sensing device in order to carry out direct monitoring which can detect increases in ICP long before clinical signs become apparent [5].

Micro pressure sensor works on the principle of mechanical bending of a thin diaphragm caused by the contact media such as gases and liquids. Mechanical changes that occur at the diaphragm are usually detected by a piezoresistive or capacitive methods. Although capacitive sensors have greater pressure sensitivity and decreased temperature sensitivity, they still have disadvantage of non-linearity and excessive signal loss from parasitic capacitance [6]. On the other hand, piezoresistive sensors were widely used as they are able to overcome the limitations observed in other sensing technologies such as the non-linearity, relatively large size, low sensitivity, output drift with temperature and age [7], [8].

A successful realization of a MEMS pressure sensor requires development of high performance diaphragm structure, provided the parameters such as diaphragm thickness are adjusted according to the pressure range applied. Thus, choosing the suitable structural parameter will assist the optimization of diaphragm sensitivity [9]. To produce a highly sensitive pressure sensor, a pressure magnification designed diaphragm is needed so that the sensor might detect even a small pressure change. This can be achieved by carefully designing the diaphragm shape to utilize the pressure magnification scheme. Due to the fact that rectangular or square diaphragms possess the easier lithography and fabrication techniques and occupied lesser area, this type of main sensing element are most commonly used instead of circular ones [6].

The excellent strain of CNTs produces a highly piezoresistive network, which benefits pressure sensors and microscale/nanoscale strains with fine resolution. Many studies have examined the fabrication of highly sensitive pressure sensors by depositing piezoresistive CNTs onto the fixed silicon substrate in which single-walled and multi-walled carbon nanotubes (SWNTs and MWCNTs, respectively) are utilized as active sensing elements [4]–[6].

In this paper a few slotted has been introduced onto the typical square diaphragm of pressure sensor to measure pressures in the range of intracranial pressure. FEA analysis of piezoresistive pressure sensor with the slotted square diaphragm is analyzed and the performance is compared with the square one.
II. DESIGN OF DIAPHRAGM

Fig 1. Square (a) and (b) slotted square diaphragm dimension.

Fig 2. Cross sectional view of square diaphragm (a) and slotted square diaphragm (b).

A. Square Diaphragm

The square diaphragm is preferred because it produce the highest induced stress for a given pressure which mean it can provide a pressure sensor with better sensitivity. Also it is easy to dice the diaphragm from standard wafers. There were also a few mask design techniques available to avoid convex corner undercutting phenomenon that always occur in realizing a perfect square diaphragm [10]. To obtain the maximum sensitivity, resistors should be placed near the edges of the silicon diaphragm, which are the high stress regions when there is a pressure load [3].

FEA analysis of piezoresistive pressure sensor with square diaphragm is investigated and proposed by Zanhang and co-workers [3], [11]. A square 50 $\mu$m x 50 $\mu$m diaphragm with thickness of 2 $\mu$m is clamped at the age, showed in Fig 1 (a) above is analyzed. The cross sectional view of the square pressure sensor is shown in Fig. 2 (a).

B. Slotted Diaphragm

For achieving more sensitive device and reducing the effect of residual stress and stiffness of the diaphragm, slotted diaphragm is proposed. Eight slots with the same dimension and geometry was formed on the square diaphragm. The dimension of eight slots are depicted in Figure 1 (b). The ratio of slot size with the size of square diaphragm is adopted from [11]. The cross sectional view of the slotted square pressure sensor is shown in Fig. 2 (b). Table 1 lists the parameter of these diaphragms.

Table 1. Parameter of diaphragm

<table>
<thead>
<tr>
<th>Diaphragm Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>silicon</td>
</tr>
<tr>
<td>Size</td>
<td>50 X 50 $\mu$m</td>
</tr>
<tr>
<td>Thickness</td>
<td>2 $\mu$m</td>
</tr>
<tr>
<td>Slot dimension</td>
<td>6.94 X 3.33 $\mu$m</td>
</tr>
</tbody>
</table>

III. COMSOL ANALYSIS

The simulation of the stress distribution and deflection on the surface of the diaphragm due to pressure applied on its surface are both accomplished with the finite element analysis software COMSOL Multiphysics. The main steps of the simulation include modeling (building geometry), material selection, setting the boundary condition (fix support and load), initial condition, meshing and finally running the model and viewing the result.

The objectives of the simulation are first to verify the value and location of maximum stress induced on the surface of the diaphragm due to the mechanically applied force between the diaphragm and back chamber. Secondly is to verify the displacement and strains value where the value obtained are assume to be acting on the piezoresistor placed on the diaphragm.

Fig. 3 (a) illustrates the simulation set up of the piezoresistive pressure sensor with square diaphragm. Four faces of the square silicon diaphragm are fixed. Force in the range of minimum 2 mmHg and maximum 10 mmHg are applied on Z direction while the forces in x and y direction are zero.

Fig. 3 (b) shows the simulation set up of the piezoresistive pressure sensor with slotted square diaphragm. Twelve faces of the square silicon diaphragm are fixed. The same force range and direction as square diaphragm are applied onto the slotted diaphragm.

Fig 3. Simulation set up for a (a) square and (b) slotted square diaphragm pressure sensors
IV. SIMULATION RESULT AND DISCUSSION

This section presents the simulation results of both the clamped and slotted square diaphragm. The maximum stress in the z axis of diaphragm with a thickness of 2 μm at maximum applied pressure of 10mmHg (1333 Mpa) is investigated. Fig. 5 shows the contour plot of the stress difference on the surface of the square diaphragm from the simulation. It is obvious that the maximum stress (2.1 x 10^5 pa) occur at the center edges of the diaphragm where the piezoresistor can be placed in order to obtain maximum sensitivity.

When eight slots were introduced in the design of square diaphragm, the maximum stress region was found to be the same with the square diaphragm, which is at the center edges of the diaphragm. However it is important to note that the value for maximum stress is increased by almost 70% (3.54 x 10^5 pa) as compared to the square diaphragm. This is shown in the of the stress difference on the surface of slotted square diaphragm in Fig 6.

The deformation in the Z axis of the diaphragm with thickness of 2 μm at a maximum applied pressure of 10mmHg is also analyzed. Fig 7 (a) and (b) show the maximum central deflection of both square and slotted square diaphragm. The value for maximum deflection of silicon square diaphragm is 9.42 x 10^-5 μm while for slotted square diaphragm is 11.6 x 10^-5 μm. It is obvious that the slotted diaphragm has more deflection than the square one under the same load.

As depicted in Fig 8, for the range of intracranial pressures applied, the deflection at the center of the diaphragms has been found to vary linearly with pressures. The center deflection is increasing when the applied pressure increased. With the introduction of slots in the square diaphragm design, the effect of residual stress and stiffness of diaphragm reduce. So for the maximum applied pressure, the center deflection of the slotted diaphragm was increased by 20%. The slope of the curves are equal to the mechanical sensitivity (S_m = \( \frac{d\omega}{dp} \)) of the diaphragm [12]. From this result, mechanical sensitivity of the slotted square diaphragm would be higher as compared to the square diaphragm.

From the viewpoint of stress, Fig 9 illustrated the analytical result of stress-pressure curves. We can find that the square diaphragm has lower stress on its edges than the slotted square diaphragm when applying the same pressure.
V. PIEZORESISTIVE ANALYSIS

The study of the stress profile enables the strategic placement of CNT piezoresistors and it is prime importance in order to obtain maximum sensitivity. From the stress profile in Fig 5, it is proven that the maximum stress is induced at the center of the edges of the diaphragm so that the piezoresistors are placed here. In general, the piezoresistors are arranged in the form of a Wheatstone’s network over the diaphragm to obtain an electrical output as shown in Fig. 10. In this section the analysis is continue with the slotted square diaphragm only as it was already proven to produce higher stress.

![Diagram of Wheatstone’s bridge](image)

Fig 10. Schematic of the piezoresistors connected in a Wheatstone’s bridge

Volumetric strain computed from COMSOL analysis is utilized to calculate the strain band gap. The strains obtained are assumed to be acting on the CNT placed on the diaphragm, and then used to estimate change in resistance of the CNT \( \frac{\Delta R}{R_0} \). The strain dependent band gap of an ideal ballistic SWCNT is expressed by \[7\], \[13\]–\[15\].

\[
E_g = E_g^o + \frac{\hbar q^2}{2m^*} \varepsilon
\]

(1)

Where,

\[
E_g^o = \frac{\hbar q^2 \gamma \alpha_o}{2m^*}
\]

(2)

And,

\[
\frac{dE_g}{2d\varepsilon} = \text{sgn}(2p+1) \frac{\gamma}{2} \frac{1 + \rho \cos 2\theta}{\cos 2\theta} \left[1 + \rho \cos 2\theta\right]
\]

(3)

Where \( \varepsilon \) is the applied strain, \( \gamma \) is the tight banding overlap or the hoping integral (\( \sim 2.6eV \)), \( \alpha_o \sim 2.049 \text{ Å} \) is the graphene lattice unit vector length, \( \rho \) is the Poisson’s ratio of the CNT, \( \theta \) is the chiral angle, and \( p = 0, \pm 1 \) labels the nanotube family. In this study the CNT in the \( p=+1 \) familiy was considered as it is proven to have higher sensitivity that the CNT in \( p=-1 \) family [16]. The resistance of a CNT depends on its energy band gap is given as [13]:

\[
R(x) = \frac{1}{R_0} \frac{\hbar}{e^2} e \left[1 \pm \exp \left( \frac{E_g - \Delta E}{kT} \right) \right]
\]

(4)

Where \( |\varphi| \) is the transmission coefficient, \( h \) is the Planck’s constant, \( e \) is the electron charge, \( k \) is the Boltzmann’s constant and \( T \) is the absolute temperature. The evaluation of piezoresistance of CNT is done using the above strain dependent energy band gap equations in MATLAB solver.

The plot of the change in resistance of the piezoresistive CNT for intracranial pressure range of 0-10 mmHg is given in the graph below (Fig 11). From the plotted graph, the linear change in in resistance of the piezoresistive CNT can be observed which is implored for a sensor.

![Plot of change in resistance](image)

Fig 11. Plot of change in resistance (\( \Delta R/R_0 \)) of CNT with respect to applied pressure.

This result also indicates that the high sensitivity of CNT piezoresitors to be applied in low pressure range application. As the proposed sensing material in this study is a very small CNT, and not much affected by thermal effects, chances of maintaining the linearity is very high [7].

VI. CONCLUSION

The relationship between the different clamped and slotted square diaphragm have been analyzed using COMSOL Multiphysics for a pressure range of 0-10mmHg. This piezoresistive pressure is suitable for measuring intracranial pressure that is designed in the range of 0 to 10 mmHg. The pressure sensor uses silicon diaphragm with thickness of 2 \( \mu \text{m} \) and a 50 x 50 \( \mu \text{m} \) diaphragm. By introducing slots in the square diaphragm, improvement in sensitivity of the slotted pressure sensor has been achieved by the increment of the slope of maximum pressure. This result is also important in order to determine the location of CNT piezoresistors for covering the high stress region. The values of volumetric strain from COMSOL analysis were utilized to estimate the change in resistance of CNT piezoresistor. The change of resistance is linear with respect to the applied pressure which is good for sensor.
ACKNOWLEDGMENT
This research is funded by the University Malaya Research Grant (UMRG)-AET (Grant Number RP009B-13AET). The authors would also like to express their gratitude to the Micro Electronic laboratory, Faculty of Engineering for allowing the facilities to be used.

REFERENCES


