Design and optimization of piezo resistors for a graphene based MEMS ICP sensor

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Abstract. Modeling and simulation of MEMS Intracranial pressure sensor using Graphene as the structural layer is defined. At normal health condition, the ICP pressure is in the range of 10-15 mmHg. Any variation from this range will signify the abnormalities such as neural system malfunction, nausea, vomiting, paralysis, brain tumor rupturing, and excitement. For Intracranial pressure sensing applications, to measure this slight variation of pressure a sensor having high sensitivity need to be employed and is solely depends on membrane used. Properties of high young’s modulus, high thermal stability and electrical conductivity, inertness and zero band gap made it biocompatible to fabricate Intracranial piezoresistive pressure (ICP) sensor with membrane as graphene. COMSOL Multiphysics tool which is a finite element analysis (FEA) is deployed to optimize the dimensions and parameters for using graphene as a structural layer for pressure sensor diaphragm. A variability study of piezo resistors with three different meander shape are designed and simulated in COMSOL. The optimum design is further analyzed for three different type of pressure sensor specifications as conventional, with n-type dopant and graphene as a structural layer. The design with three meander resistance and graphene as a structural layer provides a strain induced of 0.14 with the pressure input of 10 mmHg.

Keywords: Piezo resistors, MEMS pressure sensor, Graphene

1. Introduction

ICP monitoring for patients with head injury or neurosurgical procedures utilize the conventional invasive and transduction systems of epidural catheters, sub coronoid screws and fiber optic catheter.[1][2]. A requirement of highly super sensitive device to work on direct monitoring that can detect and monitor the significant increment in ICP pressure before the occurrence of clinical signals is the need of the time.[3] Graphene as a structural material with electromechanical properties [4] is used as a potential materials for ultra high sensitive devices Piezo resistive graphene as a strain sensor with sensitivity 16.3 ± 0.8 N/Hz and a minimum detectable mass of 1.41 ± 0.02 zeptograms (10⁻²¹ g) at ambient temperature[5] Methods to enhance the sensitivity along with selection of structural materials include extensive optimization of diaphragm geometry.[6] Atomic thickness of graphene coupled with very high mechanical strength proves it to be an apt material as a nanoscale pressure transducer[7] Graphene based MEMS devices for biomedical application is safely subjected to human biological cell and implanted for long term monitoring to 30 days as per the recent study.[8] The typical specifications for an intracranial nano pressure sensor is tabulated in Table 1, with a designed framework as shown in figure.1 for introducing strain of graphene over the cavity providing a
MEMS/NEMS pressure sensor for patients suffering from head trauma and Hydrocephalus, a condition with water in brain. Early detection of elevated ICP helps in reducing the risk of permanent damage and to mitigate the Hydrocephalus symptoms.

![Graphene Membrane](Image)

**Figure 1.** General Model of ICP Sensors [1]

| S.No | Performance         | Value (SI units) |
|------|---------------------|-----------------|
| 1    | Measurement range   | 57.2kpa         |
| 2    | Sensitivity         | 43.51mV/kPa     |
| 3    | Maximum pressure    | 690kPa          |
| 4    | Resolution          | 0.00069kPa      |
| 5    | Nonlinearity        | <1.0%FS         |

2. Materials and methods

Intracranial pressure (ICP) measures pressure inside skull between the cerebral spinal fluid (CSF). The brain diseases are treated and diagnosed with the help of ICP monitoring; many neurological deterioration or brain damage can be avoided by continuous monitoring of ICP. The age and body posture are the parameter which defines normal ICP. Normal ICP for adults is between 5 and 15 mmHg. If ICP is increases above 15 – 20 mmHg then it is called ICP hypertensive. ICP is measured in mmHg that is millimeter mercury as ICP increases there is restriction in flow of fluid and causes various symptoms like headache, confusion, increased blood pressure, shallow breathing, and nausea etc.

To monitor ICP there several invasive and noninvasive method, compared to noninvasive method invasive method are more accurate but there is a risk of hemorrhage and infection. Hence it is desirable to use wireless implantable ICP monitoring which avoids risk of infection. The battery powered in which ICP’s level is monitored wirelessly. But the life cycle of these implant are minimal, battery free wireless monitor can be implemented whereas a hole has to be driven on the skull to place a small sensors and rest are implanted outside the skull.

The piezo resistive pressure sensors consists of various layer such as substrate which is called bulk, a sacrificial layer like SiO2 which used for cavity formation, a diaphragm which is also called as a membrane which should be sensitive to pressure usually in conventional piezo resistive n type layer
are used as a membrane, in this project the diaphragm is placed by a graphene and resistor which can be implanted or diffused on the membrane usually it of p type material. The piezoresistive pressure sensors are of 200×200 µm in size. The project utilize a tool COMSOL Multiphysics to model graphene based ICP sensor, in which the deflection and strain induced in graphene due to applied pressure are calculated. The project shows the feasibility of utilizing the thickness of graphene membrane in ICP sensor to monitor intracranial pressure.

A silicon technology for the fabrication of MEMS pressure sensor includes SOI wafers, SOS silicon on insulator, silicon on sapphire, silicon carbide, steel, carbon nanotubes that provides improved performance. The various signal transduction methods for a typical ultrasensitive pressure sensor include piezoresistance, capacitive, acoustic transduction, optical and resonance with a conventional gauge factor of 0.27% per °C of temperature coefficient of Piezo resistivity (TCP). The piezoresistive effect in poly Silicon is due to its atomic level crystallographic orientation, as the stress applied, the average effective mass of the silicon carrier alters and in turn effects the silicon carrier mobility resulting in change of resistivity. A piezoresistive element placed in a Wheatstone bridge format onto the diaphragm changes the resistance and hence the voltage which is directly proportional to the pressure applied. As shown in figure 2. The fabrication and Characterization of Piezoresistive MEMS Pressure Sensors on double side polished p-type (100) silicon 2 inch wafers. Membrane structures of dimensions 200 micron X200 micron and thickness of 3.45 nm are realized using anisotropic wet chemical etching technique of bulk silicon. N-type single crystal piezoresistors are fabricated by phosphorous diffusion. The fabricated sensors are characterized for nominal resistance and offset voltage. Temperature compensation and signal conditioning using MAX1452 is also demonstrated.

The resistance of the silicon piezo resistor is a function of stress in the material and the orientation of the piezo resistors. The variation of resistance due to stress is given in Eqn. 1

\[
\frac{\Delta R}{R} = \pi l \sigma_t + \pi l \sigma_l \quad \text{..........................(1)}
\]

2.1. Pressure Sensor Design

The pressure sensor is realized using four piezo resistors arranged along <110> axis on a membrane in Wheatstone bridge configuration as shown in Figure 2. The sensitivity depends on the orientation of piezo resistor and the location, the locations of piezo resistors on the membrane as shown in Figure 2. The maximum stress on a piezo resistor for a square membrane of width 2a, thickness h and uniform applied pressure P is given by Eqn.(2).

\[
\sigma_{\text{edge}} = P \left( \frac{a}{h} \right)^2 \quad \text{..........................(2)}
\]

For a 3.45 micron thick membrane of a=100 micron and pressure of 10 bar gives \( \sigma_{\text{edge}} \) of 625 MPa which is lesser than yield strength of silicon (7 GPa). Using Eqn. 2 and Eqn. 1 gives.

\[
\Delta R/R = \pi l \left( \frac{a}{h} \right)^2 (1 - \nu) P \quad \text{..........................(3)}
\]

Where \( \nu \) is the Poissons ratio which is \( \approx 0.3 \) for silicon. This gives \( \Delta R/R = 0.13825 \). Referring to Fig. 1 and assuming that all the resistors are equal the output voltage is given by Eqn. 4.

\[
V_{\text{out}} = \Delta R/R \cdot V_s \quad \text{..........................(4)}
\]
2.2. Materials of Piezoresistive Pressure Sensor

The structural materials to design the diaphragm and the piezo resistors are the two important crucial parameters of study for the application of developing an ultrasensitive intracranial pressure sensor using graphene and polysilicon as piezo resistors. The properties of materials like Polysilicon for piezo resistance include density of 2320 Kg/m³, young’s modulus of 169 and a poisons ratio of 0.22. The properties of single crystalline Silicon include a density of 2270 Kg/m³, density of 70 and poisons ratio of 0.17. The signal transduction element is the piezoresistor and is from the Wheatstone bridge. The change in pressure is distributed in directions. The output signal of the transducer at nano level \( V_{out} = V_{in} \frac{\Delta R}{R} \), where \( \Delta R \) is the change in resistance with the change in input pressure. The amount of change in overall voltage sensitivity is

\[
\Delta R/R = \pi_l \sigma_l + \pi_t \sigma_t
\]

Where \( \sigma_l \) is the longitudinal stress which is parallel to the current direction, \( \sigma_t \) is the transverse stress perpendicular to the current direction. \( \Pi_l \) is the longitudinal piezoresistive coefficient of silicon, in the same direction as of longitudinal stress, \( \pi_t \) is the transverse piezoresistive coefficient of silicon within the same direction as the transverse stress. The p-type silicon has a value of -31.6 for \( \Pi_l \) value and -17.16 for \( \pi_t \) value in an orientation of <110>.

2.3 Graphene

Graphene is a two dimensional sheet of carbon atoms that are densely packed in a honey comb crystal lattice structure, stiffer than diamond, 100 times stronger than steel providing us with an excellent materials from the carbon age as shown in figure.3. Graphene, first exfoliated from graphite, a low cost technique demonstrated with flakes later grown by chemical vapor deposition with properties as shown in Table.2. The early approaches of cleaving multilayer graphite into single layers or growing it epitaxial by deposition of a layer of carbon onto another materials is supplemented by methods that include Wedge based and other reduction methods.[9-10]
In a wedge based method, a strong sharp single crystal diamond wedge that penetrates graphite exfoliates the layers producing highly ordered for pyrolytic graphite HOPG. A Graphite oxide reduction (Reduction of graphite into monolayers) yields graphene films by annealing hydrazine in argon/Hydrogen gas. The oxidation process is enhanced to produce graphene oxide with an intact carbon framework allowing efficient removal of functional groups. Graphene is also obtained by heating silicon carbide to elevated temperatures at 1100°C and reduces it to graphene. Another method of obtaining graphene using epitaxial growth on metal surfaces of Iridium and Ruthenium. A modified technique in cutting open the carbon nanotubes produces graphene ribbons.

Table 2. Properties of Graphene

| S. No | Properties                       | Values                                    |
|-------|----------------------------------|-------------------------------------------|
| 1     | Elasticity matrix                | \{368[GPa], 120[GPa], 288.8[GPa], 108.4[GPa], 74.8[GPa], 288.8[GPa], 0[GPa], 0[GPa], 0[GPa], 107.7[GPa], 0[GPa], 0[GPa], 0[GPa], 0[GPa], 124[GPa], 0[GPa], 0[GPa], 0[GPa], 0[GPa], 124[GPa]\} |
| 2     | Electrical conductivity          | 3.3 * 10^5 S/m                            |
| 3     | Density                          | 300 kg/m^3                                |
| 4     | Coefficient of thermal expansion | 3.5x10^-6 /k                              |
| 5     | Heat capacity                    | 2500 J/kg.k                               |
| 6     | Relative permittivity            | 10 -15                                    |
| 7     | Thermal conductivity             | (2-4) KW/m.k                              |
| 8     | Tensile strength                 | 130G Pa                                   |
| 9     | Young’s modulus                  | 1TPa                                      |
| 10    | Elastic constant                 | 354 Nm-1                                  |
| 11    | Elastic stiffness                | 340 Nm-1                                  |
| 12    | Current density                  | 10^8 A/cm^2                               |
| 13    | Intrinsic capacitance            | 21uF/cm^2                                 |
3. Results and discussion

3.1. Design modelling in COMSOL Multiphysics

The project mainly consists of designing of piezoresistive pressure sensors. Here the pressure sensors used must be very much sensitive compared to conventional piezoresistive pressure sensors. The sensors should have the capacity to sense low pressure as well as moderate pressure as it is placed on the most sensitive part of human body that is brain the pressure will be in mmHg. The piezoresistive pressure sensors consists of substrate which is also called as bulk, a sacrificial layer like SiO\(_2\) which used for cavity formation, a diaphragm which is also called as a membrane which should be sensitive to pressure usually in conventional piezoresistive n type layer are used as a membrane, in this project the diaphragm is replaced by a graphene which is also called miracle material and the resistor which can be implanted or diffused on the membrane usually it of p type material. The piezoresistive pressure sensors are of 200×200 µm in size. The project is analyzed using a tool COMSOL Multiphysics to model graphene based ICP sensor, in which the deflection and strain induced in graphene due to applied pressure are calculated.

![Model of Conventional Pressure Sensors](image)

Figure 4. Model of Conventional Pressure Sensors

The model consists of a square membrane of 1mm× 1mm die with a thickness of 20 µm as shown in figure 4. The edges of the diagonal membrane has cross shaped piezo resistors with part of its interconnections along the piezo resistors to have a p type density of 1.32 ×10\(^{19}\) cm\(^{-3}\) and thickness of 400 nm. The interconnect with same thickness and density of 1.45 ×10\(^{20}\) cm\(^{-3}\). The edges of the die are aligned with {110} directions of the substrate SOI. The piezo resistors are oriented at an angle of 45° to the edge of the die.

The Figure 5 shown below is a block substrate obtained by using a block in geometry and defining necessary width height and depth upon that a graphene membrane is placed. The n type substrate 200 µm × 200 µm n type substrate with thickness of 1 µm later SiO\(_2\) is placed and a cavity is formed above the substrate.
Figure 5. Model 1 of pressure transducer (b) Model 2 of pressure transducer (c). Model 3 of pressure transducer

The p type resistor which can be implanted or diffused. The meander resistance as shown Figure 6 are used to increase sensitivity there are three type zero turn, one turn and three turn. The one and two turn are formed by dividing the zero turn by two and three respectively and the properties as depicted in Table 3.

Figure 6. Specification of Meander Resistance

| S. No | Geometric Parameter | Zero Turn in µm | One turn in µm | Three turns in µm |
|-------|---------------------|-----------------|----------------|-------------------|
| 1.    | I_{pb}              | 80              | 40             | 20                |
| 2.    | W_{pb}              | 5               | 5              | 5                 |
| 3.    | W_{cb}              | -               | 10             | 10                |
| 4.    | g_{ap}              | -               | 5              | 5                 |

3.2. Model 1

The model 1 proposed is the design of a conventional pressure sensor with polysilicon piezo resistors implanted onto the diaphragm in the Wheatstone bridge to provide an appropriate signal transduction to convert the change in stress to change in voltage as a readout circuitry.
The Figure 7 above shows the simulation of conventional pressure sensor in COMSOL Multiphysics 5.1. The intensity of the color goes on increases. The dark blue color region indicates no deviation from original distance hence the total displacement that is strain is zero. In the yellow region the strain is of the range 0.6 to 0.8 and at red region the strain ranges from 1 to 1.2. The strain is high at the center of the membrane, thus we can calculate stress as follows

\[
\text{Strain} = \frac{\text{Change in length}}{\text{Total length}}
\]

The stress can be calculated using this equation below

\[
\text{Stress} = \text{Young’s Modulus} \times \text{Strain}
\]

The Young’s Modulus of silicon is 150 GPa

\[
\text{Stress} = 150 \text{ GPa} \times 1.2 = 180 \text{ GN/m}^2
\]

The stress is directly proportional to sensitivity. Hence conventional pressure sensor gives high sensitivity but they are sensitive for high pressure. Here pressure applied is 100 K Pa which is very much high and in ICP low pressure are available in terms of mm Hg. From the above Figure 7 shows the plot of conventional pressure sensor with x-axis arc length in m and y-axis total displacement in µm. With the applied pressure of 1 KPa the surface displacement is high at the center and diminishes at the edges.

3.3. Model 2 with n-type as membrane

The Figure 8 above shows the simulation of N type Membrane ICP sensor in COMSOL Multiphysics 5.1. The intensity of the color goes on increases. The dark blue color region indicates no deviation from original distance hence the total displacement that is strain is zero. In the yellow region the strain is of the range 0.04 to 0.06 and at red region the strain
ranges from 0.07 to 0.08. The strain is high at the center of the membrane, thus we can calculate stress as follows
\[
\text{Strain} = \frac{\text{change in length}}{\text{Total length}} 
\]
\[\text{...................... (9)}\]

The stress can be calculated using this equation below
\[
\text{Stress} = \text{Young’s Modulus} \times \text{Strain} 
\]
\[\text{...................... (10)}\]

The Young’s Modulus of silicon is 150 GPa
\[
\text{Stress} = 150 \text{ GPa} \times 0.08 = 12 \text{ GN/m}^2 \text{ (for 10mmHg of pressure applied)} 
\]

The plot of n type based ICP with x-axis arc length in m and y-axis total displacement in µm. With the applied pressure of 10mmHg the surface displacement is high at the center and diminishes at the edges.

3.4. Model 3 - ICP Sensor with Graphene as a Membrane

The Figure 8 above shows the simulation of Graphene Membrane ICP sensor in COMSOL Multiphysics 5.1. The intensity of the color goes on increases. The dark blue color region indicates no deviation from original distance hence the total displacement that is strain is zero. In the yellow region the strain is of the range 0.08 to 0.1 and at red region the strain ranges from 0.12 to 0.14.

The strain is high at the center of the membrane, thus we can calculate stress as follows
\[
\text{Strain} = \frac{\text{change in length}}{\text{Total length}} 
\]
\[\text{...................... (11)}\]

The stress can be calculated using this equation below
\[
\text{Stress} = \text{Young’s Modulus} \times \text{Strain} 
\]
\[\text{...................... (12)}\]

The Young’s Modulus of graphene is 1 TPa
\[
\text{Stress} = 1 \text{ TPa} \times 0.14 = 140 \text{ GN/m}^2 \text{ (for 10mmHg of pressure applied)} 
\]

The plot of graphene based ICP with x-axis arc length in m and y-axis total displacement in µm. With the applied pressure of 10mmHg the surface displacement is high at the center and diminishes at the edges.

### Table 4. Comparison of different type of sensor

| Type of Sensors   | Pressure Applied | Strain Induced |
|-------------------|------------------|----------------|
| Conventional      | 100KPa           | 1.2            |
| Pressure Sensor   |                  |                |
| N Type Based ICP  | 10mmHg           | 0.08           |
| Graphene Based    | 10mmHg           | 0.14           |
The Table 4 above infers that Graphene is highly sensitivity at low pressure; hence it can be used in ICP invasive monitoring. Graphene based ICP have much flexibility and lighter weight compare to other pressure sensors

4. Conclusion
The inference drawn from the results shows that conventional pressure has high stress which increases sensitivity has stress is directly proportional to sensitivity but the pressure applied is high and hence cannot be used in ICP. In N type ICP sensor the sensitivity is moderate for low pressure whereas Graphene ICP sensor high sensitivity due to young’s modulus is high compare to other two sensors. A MEMS intracranial pressure sensor for low pressure sensing using graphene is studied and the results conclude that the design and optimization are feasible to proceed towards fabrication of the designed device with all the parameters.

References

[1] Yanhang Zhang, Zhaohua Zhang, Bo Pang, Li Yuan, & Tianling Ren 2014 Tiny MEMS-based pressure sensors in the measurement of Intracranial Pressure Tsinghua Science and Technology 19 p161
[2] Ma J, Jin W, Ho H L, & Dai J Y 2012 High-sensitivity fiber-tip pressure sensor with graphene diaphragm Optics Letters 37 p2493
[3] Rahman SHA, Soin N & Ibrahim F 2018 Load deflection analysis of rectangular graphene diaphragm for MEMS intracranial pressure sensor applications. Microsyst Technol 24 p1147
[4] Yagya Gera 2017 Application of graphene in medicine and electronics IOSR Journal of Applied Physics 9 p19
[5] Akinwande D, Brennan C J, Bunch J S, Egberts P, Felts J R, Gao H Zhu Y 2017 A review on mechanics and mechanical properties of 2D materials—Graphene and beyond Extreme Mechanics Letters 13 p42
[6] Rajat Subhra Karmakar, Jer-Chyi Wang, Yu-Ting Huang, Kun-Ju Lin, Kuo-Chen Wei, Yung-Hsin Hsu, Ying-Cheng Huang, and Yu-Jen Lu 2020 Real-Time Intraoperative Pressure Monitoring to Avoid Surgically Induced Localized Brain Injury Using a Miniaturized Piezoresistive Pressure Sensor American Chemical Society Omegan 5 p29342
[7] Nag A, Mitra A, Mukhopadhyay S C 2018Graphene and its sensor-based applications: A review Sensors and Actuators A: Physical 270 p177
[8] Lou, Z, Chen S, Wang L, Jiang K, & Shen G 2016 An ultra-sensitive and rapid response speed graphene pressure sensors for electronic skin and health monitoring. Nano Energy 23 p7
[9] Ma J, Jin W, Ho,HL, & Dai J Y 2012 High-sensitivity fiber-tip pressure sensor with graphene diaphragm Optics Letters 37 p2493
[10] Ali A, Khan A, KarimovKS, Ali A, & Daud Khan A 2018Pressure Sensitive Sensors based on Carbon Nanotubes, Graphene, and Its Composites Journal of Nanomaterials 5p1