Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 4, 2021, Pages. 609 - 617
Received 05 March 2021; Accepted 01 April 2021.

Design and Simulation Analysis of Membrane Based Mems Piezoresistive Pressure Sensor for Intracranial Pressure Measurements

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ABSTRACT

In this paper, need to achieve high sensible pressure measurements by designing and analyzing a piezoresistive sensor with different materials. Bio-MEMS are being used for biomedical applications by their scaling mechanisms. This structure mainly focuses on systematic analysis of measuring intracranial pressure (ICP), rectangular membrane based piezoresistive pressure sensor is simple and very precise for measuring pressure. The diaphragm thickness and different material properties are important in analyzing the sensitivity performance of the sensor. The designed pressure sensor for measuring pressures in the range of 1 to 40 mmHg range of intracranial pressure sensors. The piezoresistor is placed on maximum stress area of the rectangular membrane, which gives very sensitive linear results to applied pressure. The simulation results of rectangular membrane structure were obtained in a high sensitivity of 4.49(μV/kPa). The sensing outputs of the design and displacement of the membrane were determined through simulations using COMSOL Multiphysics.

Keywords: Bio-MEMS, intracranial pressure(ICP), piezoresistive pressure sensor, COMSOL.

1. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) is a technology, defined as miniaturized mechanical & electro-mechanical elements. It's made by using micro fabrication techniques. The ability of create unambiguous structures ranging from few micrometers to few millimeters. MEMS devices to be used for *in vivo* monitoring of physiological phenomena and it's used to measure the pressure in human body with high sensitivity [6]. These sensors have considerable advantages over other sensors, such as high sensitivity, low nonlinearity error, low cost, high efficiency and small size, and they can also be easily manufactured. These attributes are very important for the use of the piezoresistive pressure sensors in a variety of applications [8]. Intracranial pressure (ICP) is mainly induced by the cerebrospinal fluid in the brain and it is not easy to measure directly [7]. This could be done by lumbar puncture surgery which is the most widely used clinical invasive approach for intracranial pressure monitoring. This pressure is measured in millimeter of mercury (mmHg) [2]. The normal range for ICP varies with age. Normal adult ICP is defined as 5 to 15 mmHg [13], 3 to 7 mmHg for young children, and 1.5 to 6 mmHg for term infants. ICP can be sub atmospheric in newborns [12]. However, ICP values greater than 20 mmHg require treatment in most circumstances. Sustained ICP values of greater than 40 mmHg indicate severe, life-threatening intracranial hypertension [9]. Intracranial pressure monitoring is an important role in the management of patients with head injury and neurosurgical patients [5]. An injury due to traffic accidents, blasts, sport injuries or physical assaults exert strong external forces on the brain and damages the brain. Such damages are called Traumatic Brain Injuries (TBI) and are a major cause of death and disability for patients subjected to closed head injuries. Traumatic brain injury (TBI) is a worldwide phenomenon that has highly destructive consequences for both the patient and society. The key to TBI management is the control of intracranial pressure to prevent secondary brain injury [9]. Intracranial pressure (ICP) is measured as the difference between cerebral pressure and standard atmospheric pressure [5]. Increased ICP: Most damaging aspect of brain trauma, directly related with poor outcome, is raised intracranial pressure. Increase in pressure, commonly due to head injury. Its leading to intracranial hematoma, can crush brain tissue, and restrict blood supply to the brain. Decreased ICP: *Spontaneous* intracranial hypotension may occur as a result of an occult leak of CSF into another body cavity. More commonly, decreased ICP is the result of lumbar puncture or other medical procedures involving the brain or spinal cord. The advancement in MEMS technology has made intracranial micro sensors more reliable and pleasant to patients, albeit remaining invasive [3].

MEMS pressure sensor is a device that measure change in pressure by means of a change in resistivity of a piezoresistor [14]. Piezoresistive pressure sensors were some of the first MEMS devices to be commercialized. Compared to capacitive pressure sensors, they are simpler to integrate with electronics, their response is more linear, and they are inherently shielded from RF noise [1]. Capacitive-based pressure sensors are associated with high sensitivity to pressure and a low response to changes in temperature. Although they are known for their robustness, their output signal is nonlinearly related to the input, except in the limited ranges where the output signal is highly affected by parasitic capacitances. Piezoresistive-based pressure sensors, on the other hand, exhibit less sensitivity to temperature and lifetime and produce an output signal that is linearly correlated to the input [11]. Graphite sheet have been demonstrated to possess excellent electromechanical properties and have been used in piezoresistive sensors designs because of their high sensitivity [6]. Although the piezoresistive output is sensitive to temperature changes, it could be corrected easily by using a simple compensation circuit, namely Wheatstone bridge [10].

Geometry of the membrane, selection of the membrane materials, and improving the piezoresistive properties can be manipulated. So, that the sensitivity of a piezoresistive pressure sensor could be enhanced. There is a need to establish ultra-small micro pressure sensors in dynamic performance for intracranial monitoring and other mechanical movements in biomedical applications. Graphite sheet that consist of atomic thickness of strongly covalent bonded carbon atoms with excellent mechanical behavior remarkable electronic and optical properties and tunable band gap seem to fit this requirement [16]. Many structure provides high promise to MEMS/NEMS applications and based on the use of reduced thin layer graphite sheet membrane has been proposed currently [4]. In this paper, the fundamental investigation of rectangular membrane piezoresitive MEMS pressure sensor is analyzed. graphite sheet inbuilt on a simple rectangular structure, and one half of the piezoresistor placed on membrane and remaining half placed on the clamped rectangular structure which gives linear results and improved sensitivity.

2. MEMS INTRACRANIAL PRESSURE SENSOR

2.1 MEMS Pressure sensor diaphragm design, material and methods

The design of membrane and piezoresistor dimensions is specified in table1. When the pressure sensor gets the pressure on rectangular diaphragm, it produces highest induced stress it means to get pressure sensor with better sensitivity. The selection of material playing important role for increasing the sensitivity. The material of fixed side of the rectangular solid structure is n-silicon (single crystal, lightly doped), the piezoresistor material is p-silicon (single crystal, lightly doped) and the membrane material is graphite sheet. The overall design provides the high stress deflection.

Table 1. Optimized dimensions of the proposed sensor

	Width	Height	Thickness	Side length
Membrane	500nm	1200nm	10nm	-
piezoresistor	-	-	10nm	11nm

The analysis of displacement with different material of diaphragm and its physical properties are presented in table 2. Displacement of the membrane varied by using materials [15]. From the table1 when using

PDMS/graphite sheet getting the highest displacement. In proposed design, Using PDMS in biology research has some drawbacks like, it difficult to integrate electrodes or to carry out deposition directly on its surface, absorb small hydrophobic molecules like biomolecules and drugs from the solution. Although graphite is flexible and it has high electrical, thermal conductivity and chemically inert, high refractory, and it has good electromechanical properties. Because of these characteristics we go with graphite sheet.

Table 2. Material properties and displacement for 100 (kPa) proposed structure for different materials.

	Diaphragm Material	**Density (kg/m^3)**	**Young's modulus (GPa)**	**Poisson's ratio**	**Displacement (nm)**
Metals	Al - Aluminum / Aluminium	2700	70.0	0.35	0.95
	Ag - Silver	10500	83	0.37	0.79
	Au - Gold	19300	70	0.44	0.82
	Cr - Chromium	7150	279	0.21	0.28
	Cu - Copper	8960	120	0.34	0.57
	Ti - Titanium	4506	115.7	0.321	0.61
	Fe - Iron	7860	152	0.27	0.49
	Ni - Nickel	8900	219	0.31	0.34
	Pb - Lead	11340	16	0.44	3.28
	Pd - Palladium	12020	73	0.44	0.79
	Pt - Platinum	21450	168	0.38	0.4
	W - Tungsten	19350	411	0.28	0.19
Semiconductors	Diamond (100)	3515	1050	0.1	0.09
	GaAs - Gallium Arsenide	5316	85.9	0.31	0.81
	Ge - Germanium	5323	103	0.26	0.71
	InSb - Indium Antimonite	5770	409	0.35	0.18
	Si - Polycrystalline Silicon	2320	160	0.22	0.48
	Si - Silicon (single-crystal, isotropic)	2329	170	0.28	0.44
Insulators	Al2O3 - Aluminum oxide / Aluminum oxide	3965	400	0.22	0.2
	SiC (6H) - Silicon carbide	3216	748	0.45	0.1
	Si3N4 - Silicon nitride	3100	250	0.23	0.31
	SiO2 - Silicon oxide	2200	70	0.17	1.09
	ZnO - Zinc oxide	5676	210	0.33	0.34

	Borosilicate	2230	63	0.20	1.19
Polymers	PDMS - Polydimethylsiloxane	970	750	0.49	5.12e4
	PMMA - Poly methyl methacrylate	1190	3	0.40	19
	Polyimide	1300	3.1	0.37	19.6
	Polyethylene	930	1	0.46	46.4
Carbons	Graphite sheet [solid, in-plane]	1.61	4.1	0.17	1.81e4

We can get the pressure range in kPa, the following expression used to convert the pressure in mmHg to kPa.

Pressure (kPa) = pressure (mmHg) X 0.133322387 (1)

2.2 Analysis of sensitivity

In the proposed design sensitivity calculated by equation 2.

$$\text{Sensitivity(s)} = \frac{\text{Change in output (V)}}{\text{Applied Pressure (mmHg)}} \qquad (2)$$

The proposed structure sensitivity range, intracranial pressure range, input potential voltage is represented in table 3.

Table 3. Typical specification for an ICP pressure sensor

Specification	Value
Pressure range (mmHg)	1-40
Input voltage (V)	3
Sensitivity (mV/mmHg)	4.49E-03

3. RESULTS AND DISCUSSION

The cantilever is designed using (both n & p) single crystalline silicon and graphite sheet diaphragm. These all outputs are generated for intracranial pressure range of 6mmHg (i.e., 0.799934324 (kPa)).

3.1 COMSOL Simulation Results

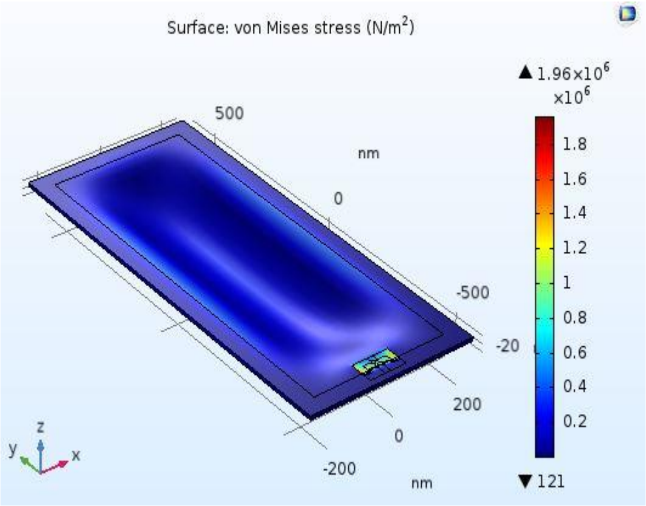

Figure (a)

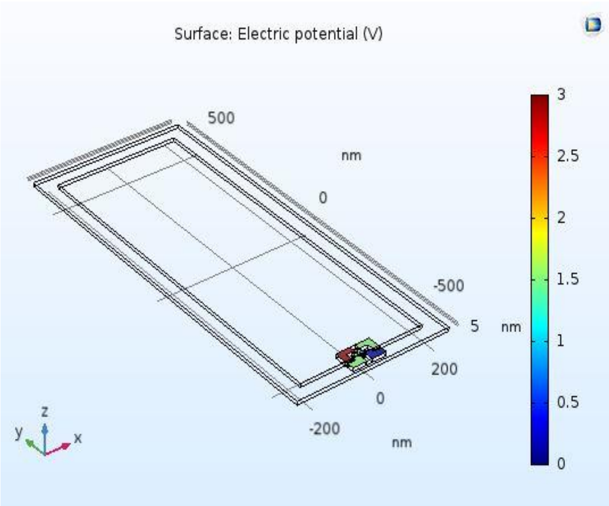

Figure (b)

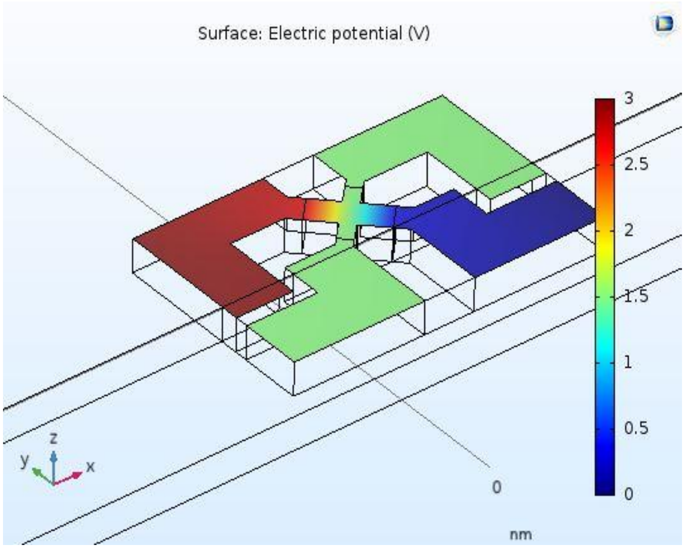

Figure (c)

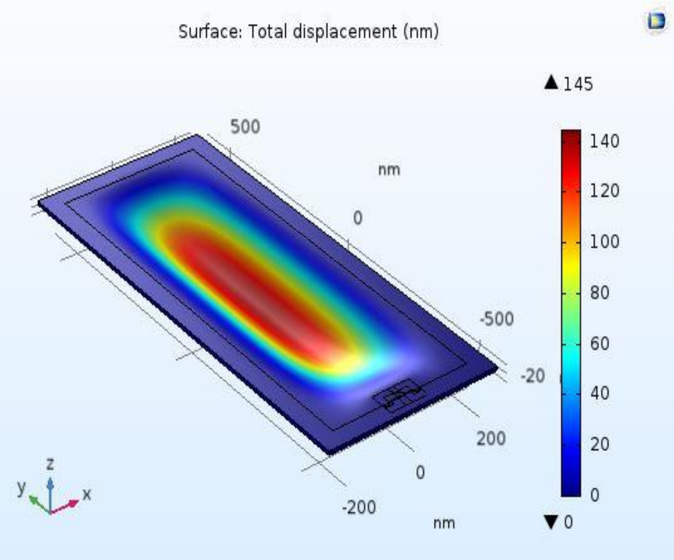

Figure (d)

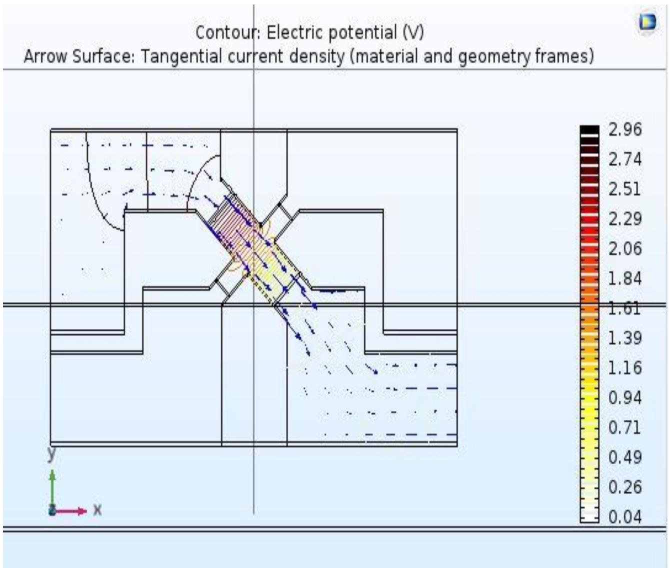

Figure (e)

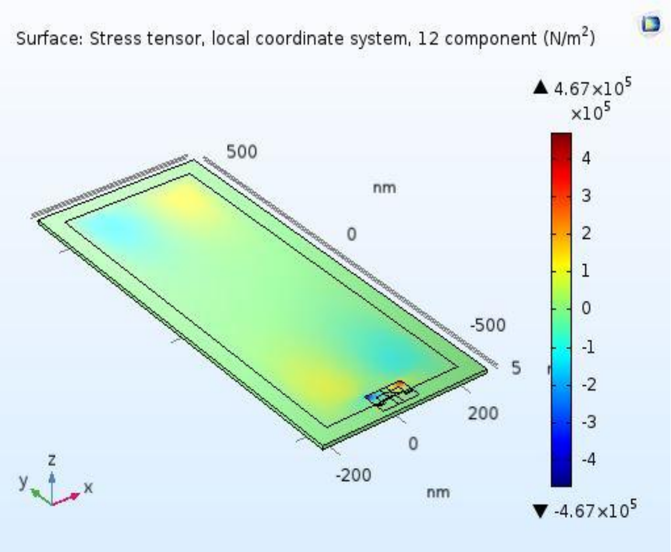

Figure (f)

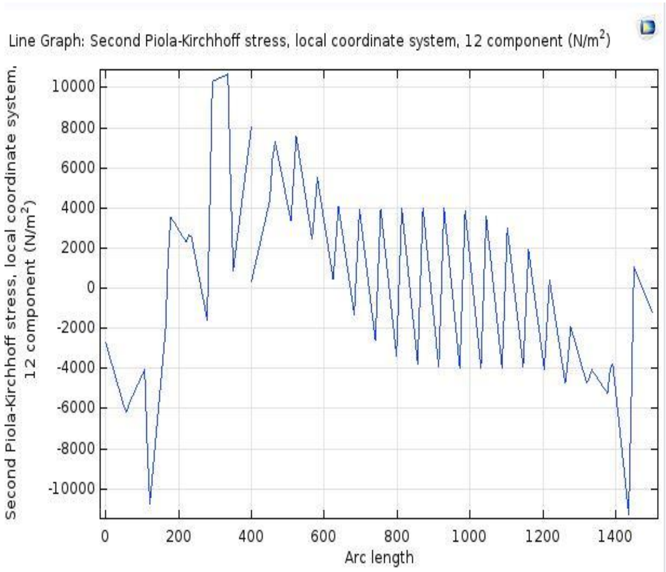

Figure (g)

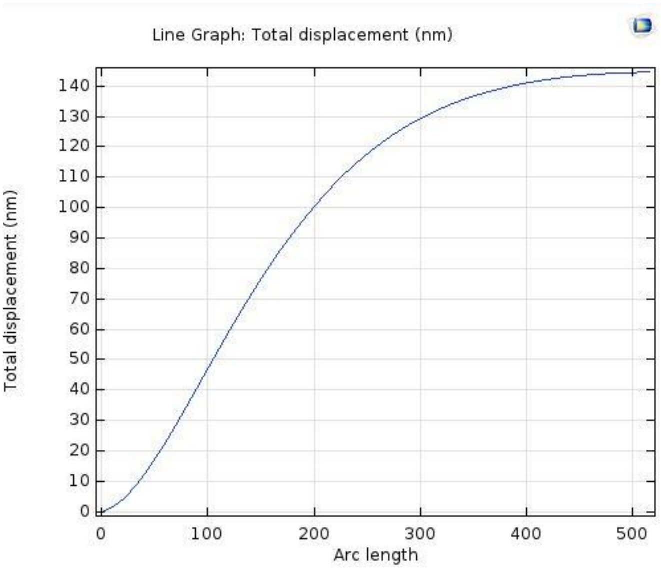

Figure (h)

Figure a. Shows 6mmHg pressure induces 1.96e-6 [N/m^2] von Mises stress.
Figure b. Shows distribution of 3V electric potential
Figure c. Shows figure (b) zoomed view of electric potential
Figure d. Shows 145nm total displacement, 6mmHg applied pressure
Figure e. Shows contour: electric potential (v); arrow surface: tangential current density (material and geometry frames)
Figure f. Shows surface stress tensor, 12 component (N/m^2), local coordinate system
Figure g. Shows Graphical representation between Arc length & second piola-Kirchhoff stress, local coordinate system, 12 component (N/m^2)
Figure h. Shows graphical representation between Arc length and Displacement (nm)

3.2 Proposed graphical representation

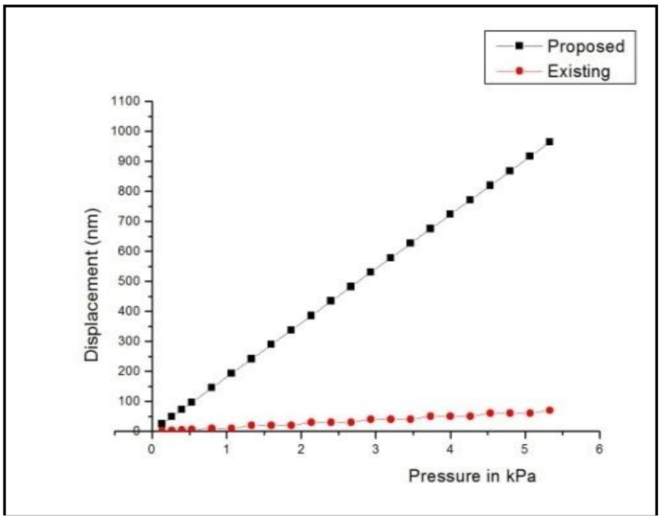

Fig-1: Graphical Representation between the applied pressure and Displacement. From the graph, we can easily understand the pressure increases as the displacement increases. The proposed results compared with existing results.

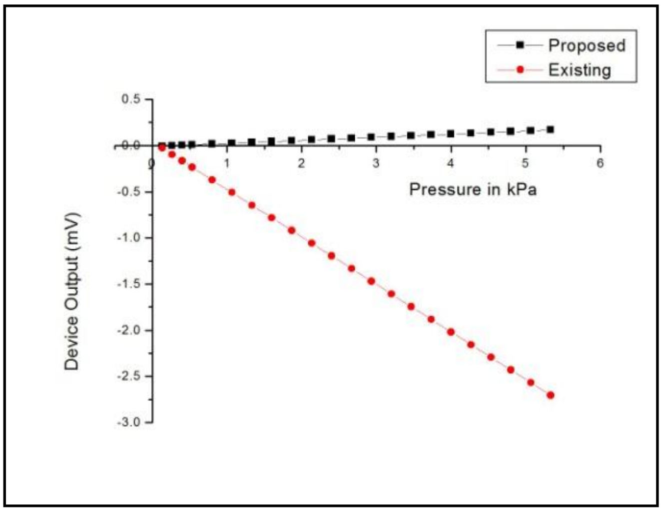

Fig-2: Graphical Representation between the applied pressure and Displacement. The graph shows that the von Mises stress increases as the pressure increases. It also compared with existing results.

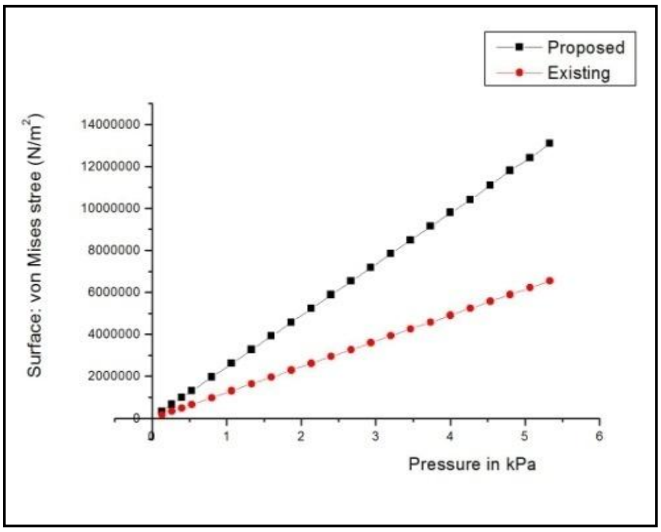

Fig-3: This result represents the comparison of device output with existing. It shows that the device output increases as the pressure increases

3.3 Analysis of Resistivity

Table 4. Proposed simulation results with different pressure (1-40mmHg)

Pressure in mmHg	Displacement(nm)	Maximum Stress [N/m^2]	Device output(V)	Resistivity change(ΔR)
1	24.1	3.27E+05	-7.07E-06	-0.113
2	48.2	6.53E+05	-2.58E-06	-0.0413
3	72.3	9.80E+05	1.91E-06	0.0307
4	96.4	1.31E+06	6.41E-06	0.103

6	145	1.96E+06	1.54E-05	0.247
8	193	2.61E+06	2.44E-05	0.390
10	241	3.27E+06	3.34E-05	0.534
12	289	3.92E+06	4.24E-05	0.678
14	337	4.57E+06	5.13E-05	0.822
16	385	5.22E+06	6.03E-05	0.966
18	434	5.88E+06	6.93E-05	1.11
20	482	6.53E+06	7.83E-05	1.25
22	530	7.18E+06	8.73E-05	1.40
24	578	7.84E+06	9.63E-05	1.54
26	626	8.49E+06	1.05E-04	1.69
28	675	9.14E+06	1.14E-04	1.83
30	723	9.80E+06	1.23E-04	1.97
32	771	1.04E+07	1.32E-04	2.12
34	819	1.11E+07	1.41E-04	2.26
36	867	1.18E+07	1.50E-04	2.41
38	916	1.24E+07	1.59E-04	2.55
40	964	1.31E+07	1.68E-04	2.69

From the table 4 we can analyze the resistance of piezoresistor increased by varying pressure. The proposed displacement, maximum stress and device outputs are tabulated.

4. CONCLUSION

The proposed rectangular pressure sensor for ICP pressure range from 1 to 40 mmHg using COMSOL multiphysics has been analyzed. The inbuilt graphite sheet diaphragm with dimensions 1200nm X 500nm X 10nm pressure sensor has been simulated. By introducing rectangular graphite sheet membrane, strengthened sensitivity of the sensor has been investigated. These investigations also consider determining the high stress region. This sensor proposes suitability of graphite sheet membrane in MEMS piezoresistive pressure sensor for ICP applications. The simulation results obtained a high sensitivity of 4.49(μV/kPa). The sensor is very small, its sensitivity is not much affected by environmental parameters like temperature, and it could be corrected by using Wheatstone bridge configuration. The results also show that the sensors meet the demand of ICP measurement. Results of this analysis indicates that a huge improvement in the value of maximum displacement and maximum stress values are obtained.

REFERENCES

1. Piezoresistive pressure sensor created in COMSOL multiphysics 5.3.
2. Kalaiyazhagan, N., Shanmuganantham, T & Sindhanaiselvi., D. (2019). MEMS Sensor-Based Cantilever for Intracranial Pressure Measurement. *Microelectronics, Electromagnetics and Telecommunications, springer*, 8(14), 978-981.
3. Mazita Mohamad, Norhayati Soin & Fatimah Ibrahim. (2017). Design optimisation of high sensitivity MEMS piezoresistive intracranial pressure sensor using Taguchi approach. *Microsystem Technologies, Springer Nature* 2018, 5(012).
4. Rahman, S. H. A., Soin, N & Ibrahim, F. (2017). Load deflection analysis of rectangular graphene diaphragm for MEMS intracranial pressure sensor applications. *Microsyst Technol, Springer-Verlag GmbH Germany* 2017.
5. Abdul Rahman, S.H & Soin, N. (2014). Analysis of MEMS Diaphragm of Piezoresistive Intracranial Pressure Sensor. *IEEE conference on biomedical engineering and sciences*.
6. Vasko Lalkov & Mohammad A Qasaimeh, (2017). A Quad-Cantilevered Plate Micro-Sensor for Intracranial Pressure Measurement. *2017 IEEE.*

7. Nagarajan Manikandana, Shanmugam Murugananda, Muthukumar Divagarb & Chinnuswamy Viswanathanb. (2019). Design and fabrication of MEMS based intracranial pressure sensor for neurons study. *Vacuum, 2019 Elsevier Ltd.*
8. Anh Vang Tran, Xianmin Zhang & Benliang Zhu. (2018). Mechanical Structural Design of a Piezoresistive Pressure Sensor for Low-Pressure Measurement: A Computational Analysis by Increases in the Sensor Sensitivity. *Sensors 2018.*
9. Ashritha, Akshata patil, Abhishek, S., Ganesh Arasikere & Sushanth lobo. (2018). Intracranial Monitoring Pressure Sensor using MEMS. *International Journal for Research in Applied Science & Engineering Technology (IJRASET), Volume 6 Issue V.*
10. Mazita Mohamad., Norhayati Soin, & Fatimah Ibrahim. (2016). Design of a high sensitivity MEMS piezoresistive intracranial pressure sensor using three turns meander shaped piezoresistors. 2016 *IEEE.*
11. Rahman, S. H. A., Soin, N & Ibrahim, F. (2016). DESIGN OF GRAPHENE-BASED MEMS INTRACRANIAL PRESSURE SENSOR. *IEEE Instrumentation and Measurement,* 6(16).
12. Welch K. (1980). The intracranial pressure in infants. *J Neurosurg. 52(9).*
13. Andrews BT., Chiles BW., III., Oslen WL., et al. (1988). The effect of intracerebral hematoma location on the risk of brain stem compression and on clinical outcome. *J Neurosurg*, (518–22).
14. Rahman, S.H.A., Soin, N & Ibrahim, F. (2016). Optimization of CNT Based MEMS Piezoresistive Pressure Sensor for Intracranial Pressure Monitoring. *International Federation for Medical and Biological Engineering*, (978-981).
15. Zahid Mehmood,, Ibraheem Haneef & Florin Udre. (2020). Material selection for optimum design of MEMS pressure sensors. Microsystem Technologies, *springer*, (751–2766).
16. Anindya Nag., Nasrin Afasrimanesh., Shilun Feng & Subhas Chandra Mukhopadhyay. (2018). Strain induced graphite/PDMS sensors for biomedical applications. *Elsevier: Sensors and Actuators A : Physical*, 271, (257–269). 2018.