Progressive Design and Assessment of MEMS-Based Devices for Healthcare and Computer Science Applications

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ABSTRACT
Microelectromechanical Systems (MEMS) transformed healthcare and computer science by making possible miniaturized, high-performance, low-cost devices. In this paper, the design methodologies and evaluation frameworks employed in these fields are discussed, with emphasis placed on primary design principles, fabrication, performance metrics, and new applications. MEMS technology has made advances in healthcare, including implantable biosensors, wearable medical monitors, microfluidics, and surgical robots. In computer science, MEMS is applied to microprocessors, accelerometers, data storage, optical computing, and security systems. Performance evaluation entails determining reliability, durability, sensitivity, accuracy, power usage, and scalability. Trends in the future are self-powered MEMS devices, AI-based diagnostics, and quantum MEMS for high-level computing applications.

This research effort is supported on MEMS (Micro-Electro-Mechanical Systems) technology which comprises even the term Bio-MEMS and Microfluidics.MEMS is extremely useful for physical, chemical, and biomedical purposes and it is even possible to integrate it with VLSI chips. The principal emphasis is on investigating and evaluating the numerous physical, mechanical and biological characteristics of MEMS-based devices with varied parameters for multifarious sensing and environmental monitoring-oriented applications. A few MEMS-based devices such as Microcantilever and Pressure sensors are the bulk of this research work. Owing to the flexibility and versatility of the devices, they find applications in a range of areas (e.g. environmental monitoring, biomedical, consumer products, etc.). Except for pressure sensor and microcantilever, design and analysis of some other MEMS-based devices such as Accelerometers, Actuators, Electric Sensors, Micro heaters, Electrodes, etc. has also been completed to learn about the research work depth and better understand the Analytical and Numerical Models. Various MEMS-supported materials have also been analyzed to understand more appropriate materials to build MEMS/BioMEMS devices. Some MEMS materials were analyzed on the basis of their mechanical and electrical properties to choose the optimum sensing materials. In doing so Metals, Semiconductors, Insulators, and Polymers are taken into account and it was observed that Silicon is one of the most prevalent other than that use of polysilicon and silicon dioxide is more significant. A number of other materials such as gold, zinc oxide, PMMA, PDMS, and Nylon along with other materials had excellent response whereas mechanical and electrical properties were under study. Following all the prominent emphasis was placed for a microcantilever and pressure sensor device and its sensing capability in another medium (environmental monitoring). This task has been accomplished with some critical alterations for varied environments such as in the presence of gas, water, and biomolecules. Finally, the result of this work section ensures that with microcantilever-based structures various bio or chemical molecules can be sensed which is beneficial for healthcare and environmental monitoring. According to requirements virtual labs and various tools such as TinkerCAD, MATLAB R2015a, LTspice XVII, Solve Elec: Circuit 1, COMSOL Multiphysics 5.3a, and Proteus 8 Professional were utilized for modeling, simulation, and analysis.

Keywords: Micro-Electro-Mechanical System, Healthcare, Environmental Monitoring, Multiphysics, Comsol, Sensors.

1.1 INTRODUCTION OF MEMS TECHNOLOGY

In our daily life electrical, electronic and mechanical devices are very crucial because they are playing a vital role in our life. One such common technology which is related to all these types of devices is known as MEMS Technology [1]. MEMS stands for Micro-Electro-Mechanical-Systems. In a very simple manner, we can explain that it is a group of extremely small (μ) devices which can be electrical, electronic, or mechanical devices combined under one chip. The size of the component in the case of a microelectromechanical system is one micrometer to 1 millimeter and 1mm equals 1000 micrometers.Fig.1.1 illustrates the block diagram and principle of this MEMS technology.

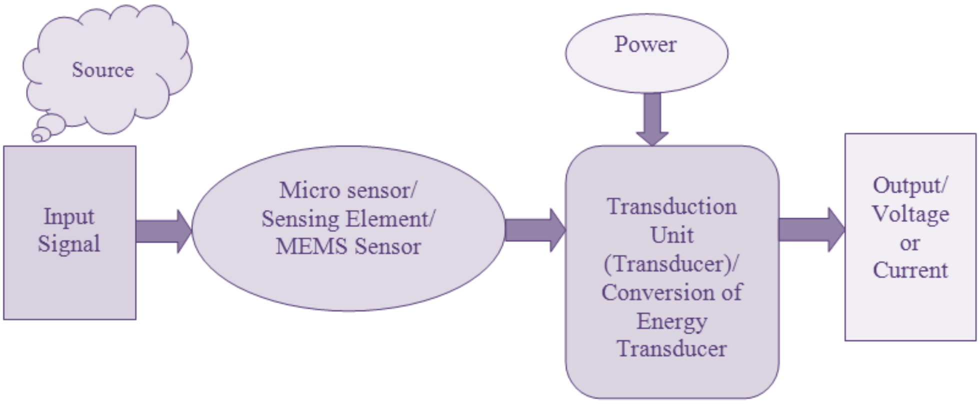

Fig.1.1 Block diagram of MEMS

There is a range of changes in the area of MEMS due to the expansion of silicon technology[2]. There are many aspects and abilities of MEMS-based devices, they can think, sense or even act too. MEMS-based devices incorporate sensing and it may be quantified in terms of movement, vibration, pressure, temperature, or light. One of the very common aspects in all these types of MEMS is the application of transducers, microsensors, and microactuators, without these components, we cannot even think about MEMS. In MEMS, there is a crucial role of machine control systems. Machine-controlled systems are generally known as mechatronic systems. Mechatronics, which combines mechanical, electrical, electronic, computer, and control engineering, has great benefits for MEMS technology. The principal operations of a mechatronics system are illustrated in Fig.1.2

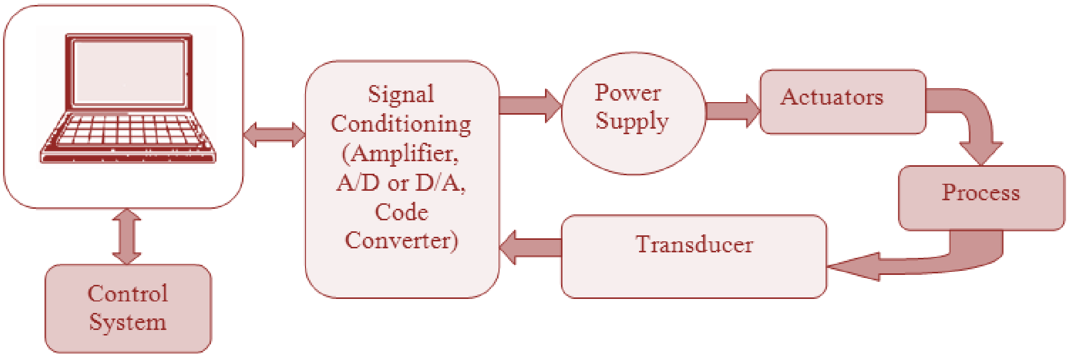

Fig.1.2 Block diagram of a Mechatronics System

The most important role of a sensor or transducer in this system is to provide electrical signals for most parameters, such as displacement, acceleration, pressure, velocity, force, and flow. A transducer's signal plugged into a computer is facilitated through signal conditioning with the help of an amplifier, an A/D or D/A, or by employing a code converter. Control systems develop and integrate control logic as computer or microprocessor software. Mechatronics has unique applications, including process control, environmental science, power generation, etc.[3]. There are two primary classes of miniaturizing devices, namely microsystem technology and nanotechnology. For microsystem technology, bulk micromachining devices are available through a top-down process, with sizes between 0.1m and a few m. In nanotechnology, the bottom-up approach or surface micromachining is more common. This approach produces produced devices whose size ranges from 0.1nm to 0.1m. Through the application of integrated electronics and a batch technique of production, MEMS can be employed to design and construct complex mechanical devices. With smaller systems, there is less mechanical inertia, and users can easily initiate or terminate a device quickly.

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Consequently, smaller devices are strongly suggested. Other than that, in comparison with larger devices, smaller devices experience lower thermal distortion and mechanical vibration as a consequence of having a lower mass. Consequently, these facts offer sophisticated features for implementing MEMS-based devices in different fields [4].

1.2 SENSORS

In very simple terms, we can define the idea of a sensor. It is a device taking an input in the form of a signal and based on this input signal, it will respond. This signal should be in the form of energy, heat, light, motion, or electrical or chemical reaction. For the most part, the sensor converts the transducer's output into voltage or current. The major job of a transducer is to transform one type of energy into another. From the control perspective, the function of a sensor is to detect the signal whereas actuators are helpful to drive a control action. There are some things which is highly necessary while choosing any sensor such as environmental factors- temperature range, size, humidity effects, power consumption, self-test capability, etc.

1.3 TRANSDUCERS

A transducer is a machine or it can also be used for a basic element which is particularly much helpful to change one form of energy into another form (majorly electrical energy). One of the key requirements of conversion is at times the available form is inappropriate or operation is not feasible so for observation, needed measurement, quantification, or manipulation based on the scenario and connected application energy conversion is necessary with the assistance of a transducer. Transducers are able to execute the sensing function as well as measure the physical, electrical, mechanical, and fluidic parameters such as temperature, pressure, vibration, voltage flow, radiation, and so on. The only big difference between a transducer and a sensor is a transducer is sufficient powerful to transform the energy from one form to another form but it is not possible to measure the conversion by a transducer but in the case of a sensor it is sufficient powerful to measure the energy level. So based on this simple principle transducers and sensors are used for various applications[5].

1.4 ACTUATORS

An actuator is a machine that is widely used to achieve the change. It plays a significant role in the area of automation and control. A few of the well-known and very popular actuators are mechanical actuators, thermal actuators, electrostatic actuators, and magnetic actuators. Mechanical actuators are primarily divided into two categories, Mechanical Structure based microactuators and Active material-based microactuators. Mechanical Structure based microactuators come in various shapes such as beam type, cantilever type, plate type including others. Diaphragm-type microactuators are nothing but plate or membrane-type microactuators. One very prominent point is actuators are acting on the principle of the material properties from which that specific actuator was built. Even active materials also contribute a fair amount.

1.5 MICROCANTILEVER

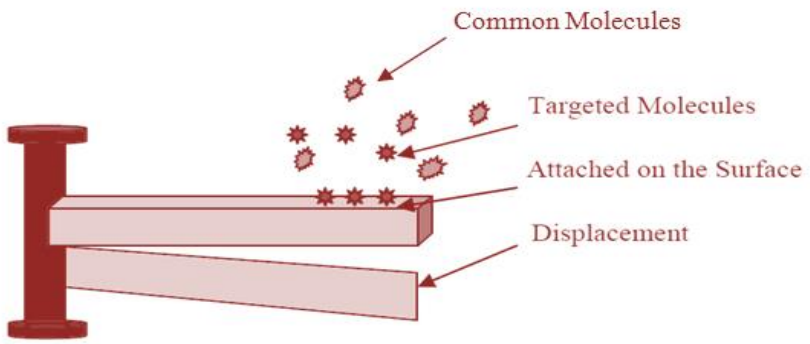

Fig.1.3 Micro Cantilever Setup

Microcantilever is a structure that is anchored at one end and free at the other. Micro beams and cantilever structures are actually highly useful transducer components that may be employed to quantify a lot of physical occurrences. It can be applied as switches, transport devices, needles, probes, transducers, and sensors in numerous sectors because of its flexibility, simplicity, versatility, and uniqueness. Fig.1.3 illustrates the configuration of a microcantilever structure. Microcantilever can measure high and quick mechanical movements and also it operates with low power consumption. Therefore, it can be utilized for multi-purpose.

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By means of Fig.1.4, detecting principle of a microcantilever is illustrated. Briefly, it senses the analytes (bio analytes or chemical analytes) and gives a measurable signal. Micro cantilevers are of various shapes such as rectangular, paddle-shaped, triangular, trapezoidal, V-shaped, step profile, I-shaped, T-shaped, and numerous others. It can be employed for pH Sensing, Sensor for DNA, Electronic Nose, Prostate Cancer, and numerous others. It is a perfect device primarily for the applications such as environmental monitoring and healthcare.

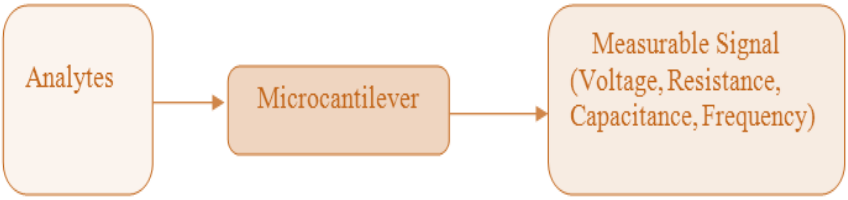

Fig.1.4 Detecting principle of a microcantilever

1.6 PRESSURE SENSOR

The key concept of a system is to study responses from input to output. For a pressure sensor, it detects the pressure that is input and transforms it as an analog electrical signal which is the output of the pressure sensor with respect to the provided input. Another important aspect is the value of the analog electrical signal is based on the pressure applied to that specific surface. There are primarily three various principles of sensing Piezoelectric, Piezoresistive, and Capacitative pressure sensing.

$$Pressure(P) = \frac{Force(F)}{Area(A)} \quad \text{----- (1.1)}$$

The major cause of the phenomenon of Force is due to pressure applied on the surface. Thus, pressure is the ratio of the Force (F) to the Area (A) which has been illustrated in equation-1.1. Pressure can be quantified by quantifying the deflection of the diaphragm which is caused due to pressure applied to the diaphragm. In fig.1.5 illustrates the very fundamental phenomenon of a pressure sensor device.

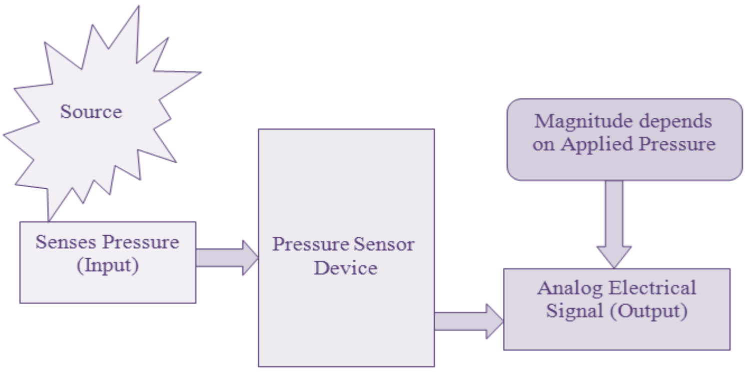

Fig.1.5 Phenomenon of a Pressure Sensor Device

1.7 MULTIPHYSICS FOR MEMS-BASED RESEARCH

In this research to attain the objective predominantly COMSOL 5.3a multiphysics software has been used. This software is able to add more than one physics for a single structure and it is also possible to analyze it in various environments.

1.8 PRIMARY OBJECTIVES OF RESEARCH

1. To know about MEMS technology and study the various properties of materials using a multiphysics-based approach. The key finding, in this instance, is to acquire knowledge of various sensing materials to gain a better sense of more appropriate materials to use in manufacturing MEMS/BioMEMS devices.
2. To research the different effects caused due to changes in dimensions, shapes and material for microstructure devices in a multiphysics scenario. A big study
to focus on various properties such as capacitance, electrical voltage, displacement, stress, strain, velocity, etc.
3. Design and research of a MEMS-based Microcantilevers device for optimal sensitivity. The primary research, in this instance, is the static and dynamic modes of the
microcantilever. Also, reveal microcantilever as a biosensor and its various applications in healthcare under

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various environmental factors.
4. Test and validate the MEMS-based pressure sensor under diverse conditions. (This research is much valuable, particularly in healthcare and environmental monitoring systems).
5. Reliability analysis, sensitivity, and performance with regards to sensing layer and device response. For instance, design and studies of temperature effeteness applied voltage vs. temperature, Properties of heat flow in 3D structures, etc

2.1 REVIEW OF LITERATURE

The current need of the world is to possess some recent technology by which one can track and identify the required things at the first position itself, to have more control and security in life. The primary objective of this research work is to do the same thing with MEMS technology [1-10].One of the renowned American Electrical engineers his name is Harvey C.Nathanson developed the first Micro-Electro-Mechanical System (MEMS) device. In 1958 silicon strain gauges were a commercial product. Later in the year, 1959 Feynman said that MEMS can combine electrical and mechanical components [11-30]. Following a couple of years in 1961 first silicon-based pressure sensor was introduced [31-40]. In the later part of the year, 1970 first silicon accelerometer was launched. In the 1980's enormous research has been conducted regarding the understanding of the concept that how silicon can be made as a mechanical material, the LIGA Process, and micromachining techniques [41-65]. After some years in 1990'sBio-MEMS received more focus due to its medical-related uses, particularly in 1995 onwards Bio-MEMS has a fast growth and became trendy [66-87].

3.1 ASSESSMENT METHODS AND MATERIALS

The prime conclusion of this research is to identify the bio analytes and chemical analytes to identify various diesis at their initial stages. Moreover, environmental monitoring is helpful in protecting the environment, which is of more use in healthcare.

3.2 PROCESS AND METHODOLOGY

For accomplishing the specific research goal, there are plenty of steps and observations which are enlisted below, it gives the line on which research work has been done.

- To begin with, attention was paid to knowing the upcoming trends and current research studies in the domain of MEMS, BioMEMS, and Microfluidics to explore the unknown facts by the mechanical, chemical, and biological behavior of Microstructures with the aid of multiphysics concepts through a predominantly utilized software COMSOL5.3a.
- To comprehend multiphysics, modeling, and design in a multiphysics context with the help of FEM (Finite Element Method) and identify more appropriate sensing Materials for MEMS/BioMEMS-based devices. Also, Sensitivity, overall optimization, reliability, and Performance analysis with respect to various sensing materials using modeling and simulations.
- To Design MEMS-based devices such as Microcantilever and pressure sensors and gain an understanding of the concept of surface chemistry, dimensional variations, shape changes done and sensing material's role for various microstructures which is operating based on the principle of microcantilever or pressure sensor.
- To develop and study Analytical, Numerical, Prototype, static and dynamic Models to realize the idea of MEMS-based devices, Microcantilever bending, piezoresistive and piezoelectric effects, self-heating, choice of the better kind of power supply, etc.

Overall MEMS-based device design under various environmental conditions or under various effecting parameters, which is beneficial for environmental monitoring and healthcare. Also, Justification of the entire research work through study, analysis, optimization, modeling, and simulation outcomes.

3.3 RESOURCES AND TOOLS

To accomplish the research purpose at the circuit level analysis utilized programs are TinkerCAD, MATLAB R2015a, LTspice XVII, and Solve Elec: Circuit 1, but at device level modelingCOMSOL Multiphysics 5.3a, TinkerCAD and Proteus 8 Professional were utilized. Virtual labs are also utilized to perform proper justification for this research work.

3.4 PURPOSE AND USE OF VARIOUS MATERIALS

In the research work process under a multiphysics condition based on MEMS technology, materials play a vast role[6]. Most critical materials have been investigated through literature survey, tested through simulation, and compared performance with each other among the material itself [77]. Overall, it is discovered that the below materials take a prominent role in this research work, Silicon Oxide (SiO_2), Aluminum (Al), Gold (Au), Silver (Ag), Gallium Arsenide (GaAs), Polysilicon, Silicon, Zinc Oxide (ZnO), Silicon Nitride (Si_3N_4)and various polymers. Moreover, Silicon Carbide material is extremely in demand for

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rough environment analysis procedures. Aside from that, the three most vital characteristics of materials are Piezoelectric, Ferroelectric, and Pyroelectric which yield productive outcomes. Also, the smart materials can be used as sensors, which transform the strain imposed on them into an electrical signal that can then be used to compute the levels of strain in the system. Like actuators,they generate strain upon stimulation by stimuli such as voltage. The primary mechanical properties taken into account in this study are elasticity, plasticity, ductility, brittleness, hardness, toughness, stiffness, resilience, endurance, strength, etc.

4.1 DESIGN AND ANALYSIS

The microcantilever and pressure sensor principles have been employed in simulation and modeling for various potential and new constructions to obtain the objective of the research work. Many favorable results were obtained in the simulation and analysis of the pressure sensor and microcantilever in both its static and dynamic modes.

4.2 ANALYSIS OF CANTILEVER USING VIRTUAL LAB

This part is giving details regarding 3 rd research goals. Cantilever behavior can be understood with some kind of experimental investigation. Considering that such research and analysis can be done only with highly limited resources. This resulted in the use of a platform called the virtual lab (A MOE Government of India Initiative), which is accessible to all researchers.

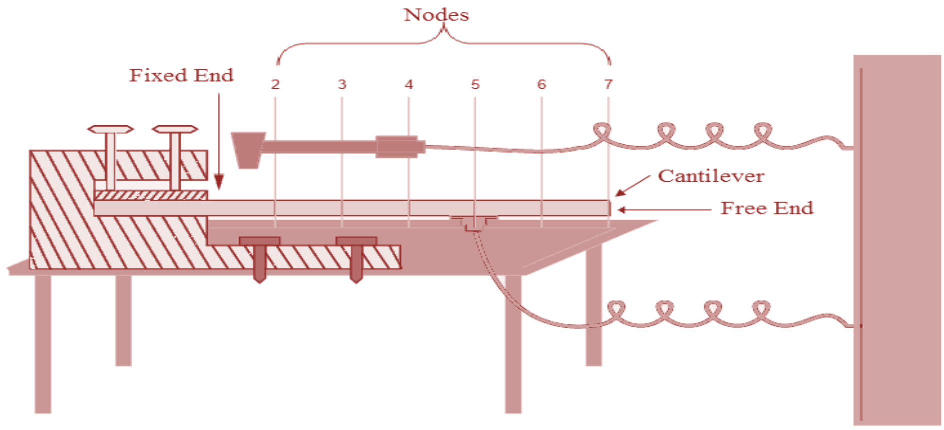
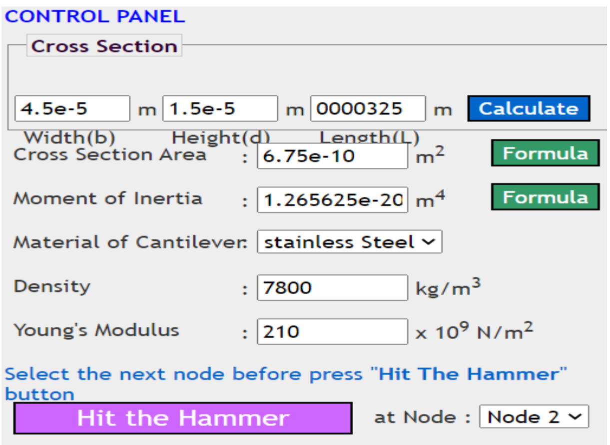


Fig.4.1 Experimental setup of a cantilever
(Source: https://va-coep.vlabs.ac.in/exp/cantilever-modal-analysis/simulation.html)

In this calculation presented in Fig.4.1, measurements are considered as Width=4.5e-5 µm, Height=1.5e-5 µm, Length=0.000325 µm.Already with the single blow of the hammer one after the other with regard to modes (2, 3, 4, 5, 6, and 7) responses have been examined. Fig.4.2 and 4.3displayed mode-2's response.



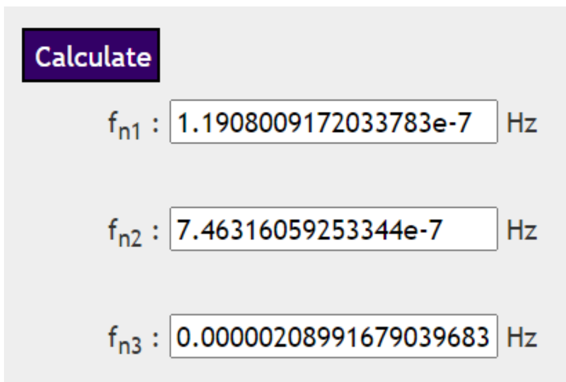


Fig.4.3 Obtained frequencies due to deflection

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Fig.4.2 Response of cantilever at mode-2

4.2.1 Use of Strain gauge sensor for Cantilever Analysis

An electrical resistivity varies due to mechanical tension (strain gauge). A strain gauge is a device that monitors stress in a material at any point. The strain it produces is usually used to assess stress. A strain gauge is a long-length conductor which can place in a zigzag pattern on a membrane. Even by the parameters of finding it can position in various locations on the surface of microstructures such as microcantilevers and needed values may achieve. Compression and mechanical elongation are transferred into measurable values through a strain gauge transducer. A strain gauge characteristic essentially relies on Poisson's ratio, Gauge factor, and Young's modulus. Strain gauge sensitivity is applied to specify their characteristics (gauge factor). Based on the working principle predominantly there are three types of gauge factors i.e. Mechanical, electric and piezoelectric. The gauge factor is a unit change in resistance for each one unit change in the length of the strain gauge wire.

$$\text{Gauge Factor(G.F.)} = \frac{\frac{\Delta R}{RG}}{\varepsilon} \qquad \text{----------} \ (4.1)$$

Where, ΔR– Change in Resistance, RG-Resistance of Unreformed Gauge, ε-Strain. For further proceeding the same principle is been tested which has been depicted in Fig.4.4 and 4.5. By doing the analysis, key findings using this virtual pattern are, that it contains limited materials and even new materials cannot be supplemented by the user. Except that Shape of the cantilever cannot be altered only dimensions can be altered; Deflections with respect to various modes can be observed clearly.

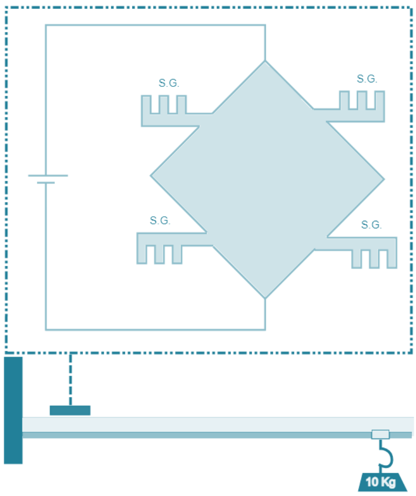

Fig.4.4 Full Bridge

Fig.4.5 Weight versus Voltage

4.3 MODELING AND SIMULATION OF MICROCANTILEVER

This part is fulfilling 3rd Research objective regarding design and study of microcantilever.The simulation of the microcantilever in both modes has been carried out at the initial level with the help of the tool COMSOL 5.3a, which is a multiphysics software with excellent features.

4.3.1 Micro Cantilever in Dynamic and Static Modes

Taken the parameters like Width=45 µm, Depth=325 µm, height=15 µm, and employing silicon material modeling and simulation, the same have been accomplished. Modeling and Simulation have been accomplished for a microcantilever of the same dimensions, shape, and material. By doing this analysis, it has been observed that when the microcantilever is operating in dynamic mode it's yielding complete displacement very high (as illustrated in Table 4.1) compared to its operation mode in static mode. Another important observation is that in dynamic mode displacement takes place due to mass at the free end of the microcantilever whereas in the case of static mode displacement takes place due to by stress. Thus in the static mode, effective values of stress and strain have been computed.

Table 4.1 Comparison of Displacement

Working Modes of Micro Cantilever	Total Displacement	Effecting Parameters
Dynamic Mode	3.56×10^{6}µm	

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		Eigen Frequency=2.4803E6 Hz
Static Mode	1.95×10^{4}µm	Stress=9.25×10^{11}(Maximum Value) Strain=4.71(Maximum Value)

Last but not least, it is apparent that the microcantilever is more sensitive in dynamic mode but this analytical mode is inappropriate for liquid medium. It has also been emphasized that a resonance frequency change is due to mass, if increasing mass decreases the resonance frequency.

4.4 IMPACTS OF CHANGE IN MATERIALS OF A MICROSTRUCTURE

This part is the result of 1st research objective regarding material properties. From the survey of literature, it has been identified that very few materials are showing maximum displacement while exerting force on the microcantilever surface and it has been simulated in FEM-based multiphysics environment for stationary studies by exerting -7N force.

Table 4.2 Maximum displacement(case-I)

Dimensions	Materials	Maximum Displacement(µm)
	Silicon	1.37×10^{4}
	Silicon Nitride	9.37×10^{3}
	Polysilicon	1.39×10^{4}
L=325 µm W=45 µm H=15 µm	Silicon Oxide	3.37×10^{4}
	Gold	3.15×10^{4}
	Polyimide	7.29×10^{5}
	PDMS	2.79×10^{9}
	Silicon Carbide	2.93×10^{3}
	Zinc Oxide	**1.63×10^{13}**

Table 4.3 Maximum displacement(case-II)

Dimensions	Materials	Maximum Displacement(µm)
	Silicon	3.79×10^{6}
	Silicon Nitride	3.79×10^{6}
L=355 µm W=30 µm H=5 µm	Polysilicon	3.79×10^{6}
	Silicon Oxide	3.78×10^{6}
	Gold	**3.8×10^{6}**
	Polyimide	3.79×10^{6}
	PDMS	3.81×10^{6}
	Silicon Carbide	**3.8×10^{6}**
	Zinc Oxide	**3.79×10^{6}**

MEMS materials are generally found in three different types as Metals, semiconductors, and Insulators. A few relevant materials have been selected from each of them and in total 9 materials have been tested and it has been found that Zinc oxide and Gold are the most appropriate materials which have maximum displacement at various Eigen frequencies with load or under no load conditions. Similarly the same thing is demonstrated by means of Table-4.2 and 4.3 through a change of dimensions. In some way gold is quite expensive so we use Zinc oxide instead of gold in some regions but not all applications.

4.5 INVESTIGATIONS THROUGH DIMENSIONAL VARIATIONS

Case-I: This is the 2nd research goal where, dimensional variations and their impact on Eigen frequencies and displacement has been taken into account and analyzed. Material is Silicon and dimensions are taken as Length L is varying whereas W=30µm and H=5µm is constant. In the second step width (W) is varying whereas L=355µm and H=5µm is constant. Again Height (H) is varying whereas L=355µm and W=30µm is constant. Measured in Eigen Frequency Study without any application of load or pressure. The analysis and finding are summarized in Table-4.4.

Table 4.4 Analysis of Eigen frequency effects on displacement

Parameters		Displacement	Eigen frequencies
Length	Increasing	Continually Decreasing	Continually Decreasing
Width	Increasing	Not Increasing Continually, at some particular Eigen frequencies it was decreasing also. So it's a random increment and decrement in displacement.	Random increment and decrement.
Height	Increasing	Continuously Increasing and then started decreasing.	Continually Increasing

Case-II: Dimensional variations under constant applied force -7N in the Z direction and its effects on

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displacement under stationary study have been considered (shown in Table 4.5).

Table 4.5 Displacement under stationary

Parameters		Displacement
Length	Increasing	Continuously Increasing
Width	Increasing	Continually Decreasing
Height	Increasing	Continually Decreasing

4.6 INVESTIGATIONS THROUGH SHAPE VARIATIONS

In this section 2nd point of research objective has been taken into account. Here, Pi, N, and H shapes of a microcantilever have been designed and computed for total displacement. Other than that other shapes such as rectangular, paddle, triangular, trapezoidal, V-shaped, step profile, I-shaped, and T-shaped were also simulated and tested.

4.7 PIEZOELECTRIC PHENOMENA

This section is based on the 1st as well as 2nd research objective. Initially Vibration Characteristics of Aluminium Cantilever Beam using piezoelectric-ceramic sensor has been studied (Fig.4.6) using a virtual lab[78].

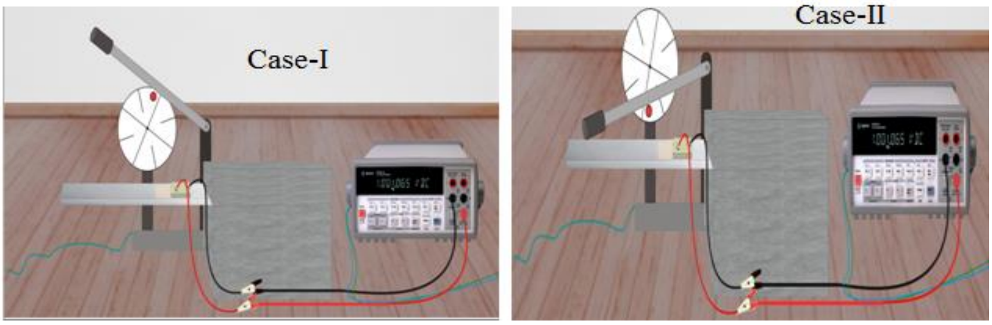

Fig.4.6 Study of Piezoelectric phenomena with the help of virtual lab

(Source:https://vssd-iitd.vlabs.ac.in/exp/piezoelectric-sensors/simulation.html)

4.7.1 Vibrations control of the micro-cantilever

It is extremely necessary to deposit layers of the piezoelectric actuator on the microcantilever in order to control or at least dampen the modal vibrations. In this case, ZnO and PZT-5H are employed as a piezoelectric actuator layer. Design and analysis have been conducted using both materials and comparisons drawn between them. The piezoelectric actuator is constructed of ZnO and PZT, and the microcantilever beam is made up of polysilicon, silica, and platinum.

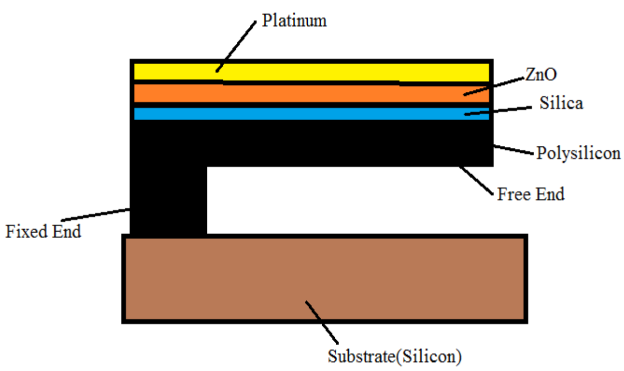

Fig.4.7(a) Piezoelectric(ZnO) layered Microcantilever

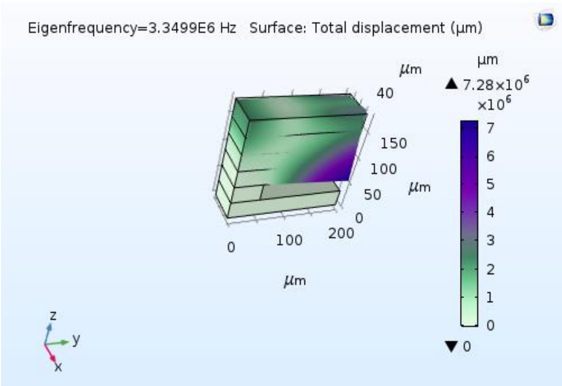

Fig.4.7(b) Displacement Using PZT-5H

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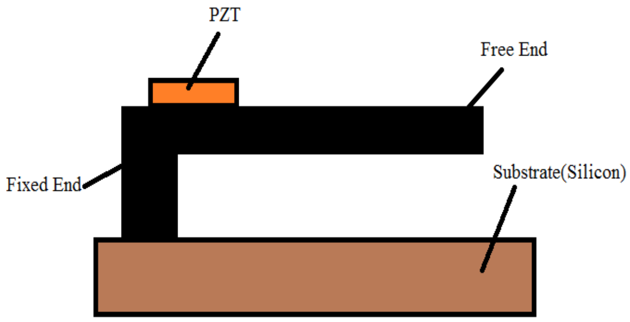

Fig.4.7(c) PZT (Piezoelectric) material analysis

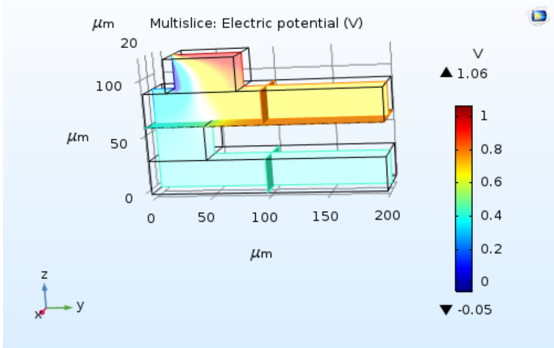

Fig.4.7(d) Increase in electrical potential(Case I)

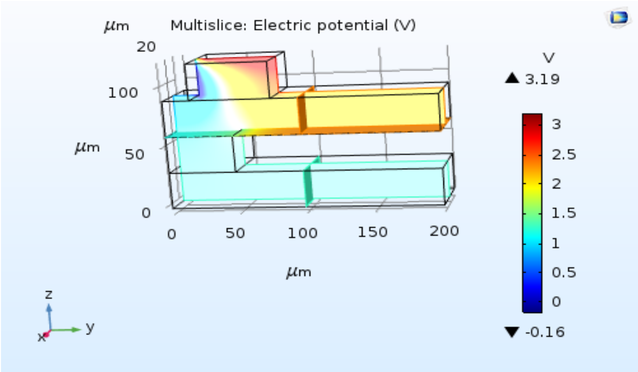

Fig.4.7(e) Increase in electrical potential(Case II)

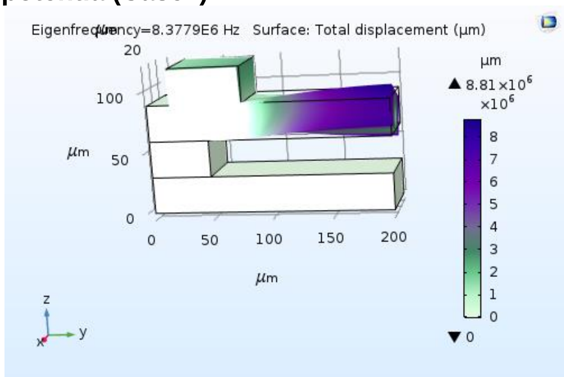

Fig.4.7(f) Displacement Using PZT-5H

There can be the cancellation of unwanted micro-cantilever vibrations and allow the deflection of the cantilever by the required mode of vibration by adding a piezoelectric layer, which is PZT, at the close end of the fixed micro-cantilever beam. The same procedure has been performed that is illustrated in Fig.4.7 (a) to 4.7(f). Node displacement is inhibited by insufficient voltage for the piezoelectric actuator. In addition, with the increase in voltage, the node displacement will also increase. Lastly, it was observed that the length of the cantilever and voltage applied to the piezoelectric actuator can both be varied to obtain the optimal resonance frequency.

4.7.2 Micro battery

By making use of piezoelectric material ZnO and additional suitable materials a micro battery has been designed in which by providing a less input voltage to piezoelectric material greater potential can be generated. It is shown in Fig.4.8 and Table-4.6.

Table 4.6 Electric Potential(V)

Input Voltage	Output Voltage
3	3.22
5	5.37
10	10.7
15	16.1
25	26.9
50	53.7
100	107
200	215

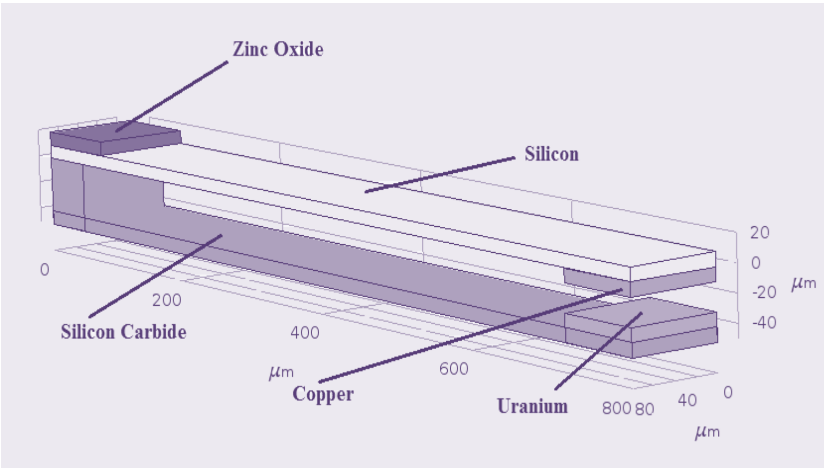

Fig.4.8 Design of a micro battery

4.8 ARRAY OF MICROCANTILEVERS ANALYSIS

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This design process is indicated by Fig.4.9 and Table-4.7. Here, nine materials were narrowed down based on different factors and properties, and it was found that SiO2 has maximum displacement capability. Another fact has been emphasized: through the drilling of two circular holes from the fixed end, effective area of microcantilevers can be lowered, leading to increased displacement. This is one of the findings of 3rd research goals.

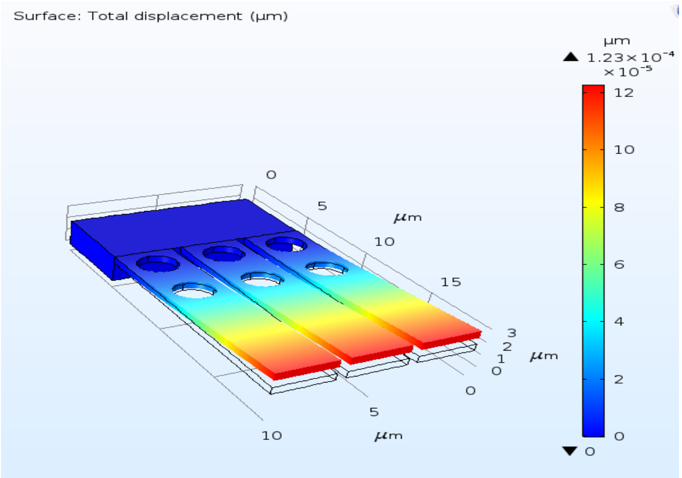

Fig.4.9.Maximum displacement using 2 holes

Table:4.7 Maximum displacement concerning holes

Number of Circular Holes	Maximum Displacement
Without Hole	6.78×10^{-5}µm
2 Holes	1.23×10^{-4} µm
3 Holes	1.17×10^{-4} µm
4 Holes	9.98×10^{-5} µm

4.9 DESIGN AND ANALYSIS OF A PRESSURE SENSOR

This section is fulfilling the key outcomes of 4th research goals. Displacement, pressure, and other different physical parameters can be quantified with capacitive transducers[79]. Since square typed diaphragms are desired and our comparison with similar types of previously contributed[80] work (circular typed diaphragms) is being done, our work is incremental research by adding the mechanical parameters.

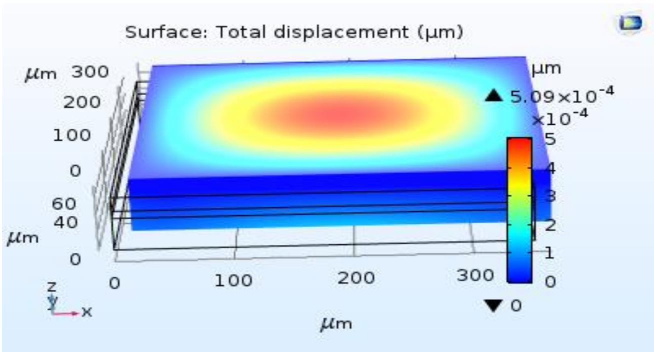

Fig.4.10 (a) Total displacement (surface) due to pressure

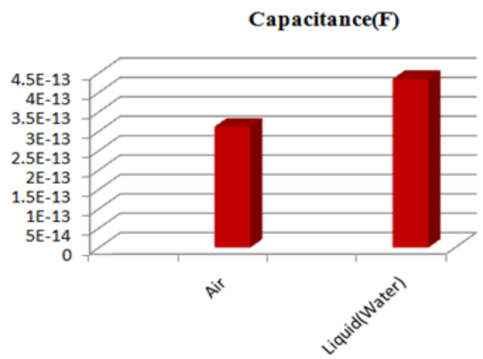

Fig.4.10 (b) Capacitance in air and liquid

Furthermore, the simulated device in this research has a displacement of 5.09×10-4µm as illustrated by Fig. 4.10(a), which is larger than the displacement of the designed devices that are 1.5484×10-5µm[81], 2.18×10-6µm and 1.95×10-6µm[82]. As here the objective is to analyze the various environments, therefore between the gap air and liquid (water) was taken into account by selecting the suitable values from the material properties as well as from a literature survey. By doing the same with air as a medium acquired capacitance is 3.12×10-13 F and for liquid(water) the acquired capacitance is 4.35×10-13 F as demonstrated in Fig.4.10(b).

4.9.1 Intracranial pressure (ICP) Measurement

A pathological rise in intracranial pressure (ICP) induced by an overaccumulation of cerebrospinal fluid (CSF) in the brain is the signature of the medical condition known as "water on the brain" or hydrocephalus. The primary purpose of this simulation is to quantify the size and location of the peak stress developed due to the mechanical load imposed on the surface of the graphene membrane.

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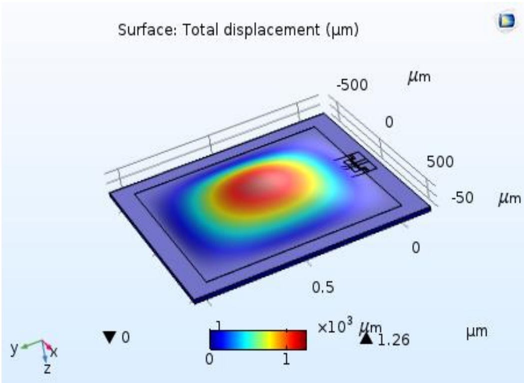
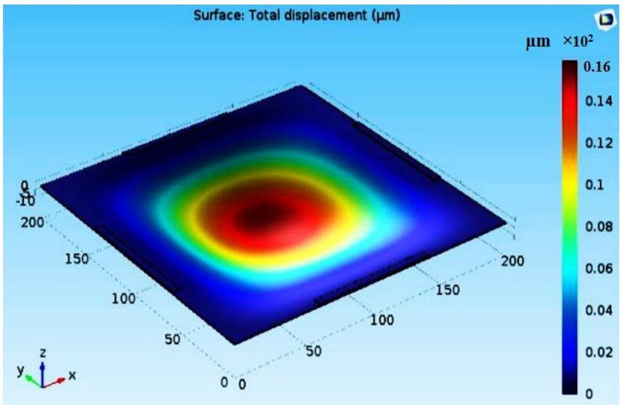
The second target is to verify the displacement and strain values with the hope that the results will lead to a band gap in a graphene-based piezoresistive pressure sensor. With modeling and simulations is observed that Graphene based Intracranial Pressure Sensor is far better than a normal one which is demonstrated in Fig.4.12 (a) and 4.12(b).



4.11(a) Conventional Pressure Sensor



4.11(b) Graphene-Based Intracranial Pressure Sensor

4.10 HEATING EFFECTS AND MONITORING

All aspects of the property of heat conduction, temperature effects, material properties, and heat transmission method have been comprehensively analyzed. It is now apparent that one of the secrets is choosing the best membrane material, besides the selection of sensing material, which is critical. Surface emission (€) values are considered to be 0, 1, and it was demonstrated that surface radiosity is equal in both cases, to 519 w/m2(max.), but the surface temperature fluctuated from 293K to 309K (max.) correspondingly. The diffuse irradiance (Idiff) value for a diffuse surface is 100[W/m^2] and for a diffuse mirror is 0.5[W/m^2]. By surface temperature research, it has also been found that slower heat transmission happens when thermal conductivity is low, while quicker heat transmission happens when thermal conductivity is high, which is extremely useful for heat transmission and environmental observation. Some significant results of 5th research objectives are given in this section.

4.11 ENVIRONMENTAL ANALYSIS AND MONITORING

In gas monitoring, research has been conducted to measure the deflection directly with a piezoelectric crystal instead of a Wheatstone bridge. A piezoelectric produces voltage when stress is applied to it. In comparison to its maximum displacement, the sensor proposed should be the best and most advisable model for gas sensing characteristics. In the same way, the active and substrate layers of the sensor can be tailored to fit a particular target gas[83]. Also, Compared to a multi-layered sensor composed of the same volume of zinc oxide, the multistep arrangement exhibited a rise in sensitivity of nearly 90% across a range of applied pressures[84]. Finally, it is ascertained that the dimensions of the cantilever must be small for high-quality factor and greater sensitivity[85]. Alternatively liquid, middle-level measurement is accomplished with the help of a virtual lab for comprehending facts. Level-sensing sensors provide measurements of fluid concentration. It can be employed in numerous high-pressure industrial operations. This is one of the results of 4th research objective. As a live analysis one instance of the blind cave, fish has been used. Blind cave fish are able to sense flows and movements of objects around them even in cases of dark and muddy water because of a network of neuromasts(sensory organ/ component of the lateral line) known as lateral lines that are spread all over their bodies. Likewise, a set of adjustable pressure sensors worn on submersibles provides for the measurement, identification, and following of underwater barriers in addition to informing about the incident flows that might assist in diminishing the hydrodynamic (movement of water and water forces/power that the vehicle will consume in moving) drag of the Vehicle. As a result of the flow, there is a pressure difference between atmosphere and membrane that causes bending in the diaphragm. The resistance change can be measured as voltage. Through the assistance of PMMA, PDMS, and Nylon material performed the analysis but it is revealed that PDMS is appropriate (offers maximum displacement) presented in Fig.4.12(a) and 4.12(b).

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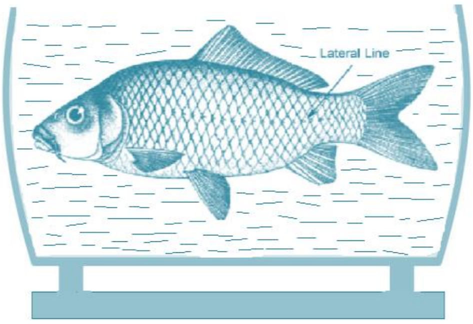

Fig.4.12(a) Blind cave fish with lateral line

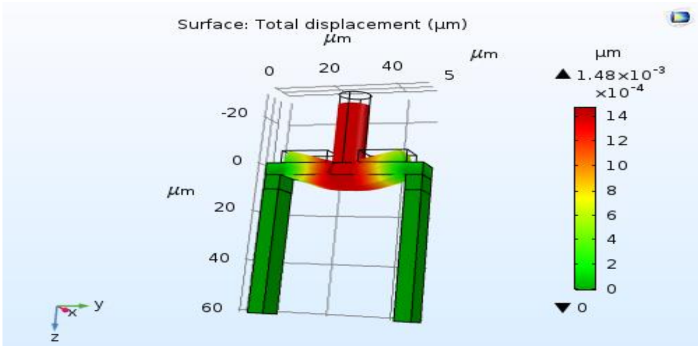

Fig.4.12(b) Maximum displacement using PDMS

4.12 BIOMEDICAL AND HEALTHCARE MONITORING

Here, an appropriate microcantilever has been built by applying the dimensional values as width= 80 µm, Depth=800 µm, and Height=10 µm. Also, Out of 19 various materials, PDMS(Polydimethylsiloxane) gives the maximum displacement. Therefore, by referring to it microcantilever has been designed and experimented. Lastly, it was revealed that the maximum displacement is 1.17×10-7 µm, which was obtained by applying the PDMS (Polydimethylsiloxane) material. There are a number of tests, but three principal shapes have been developed and upon analysis, it was established that the maximum displacement is 1.81×10-6 µm, it was achieved when creating circular holes on the surface of the micro cantilever from the fixed end using 2D to 3D conversion via extruding. By piling and applying different materials, sensitivity has been aimed at the third stage. These analyses have been illustrated in Fig.4.13(a) and 4.13(b).

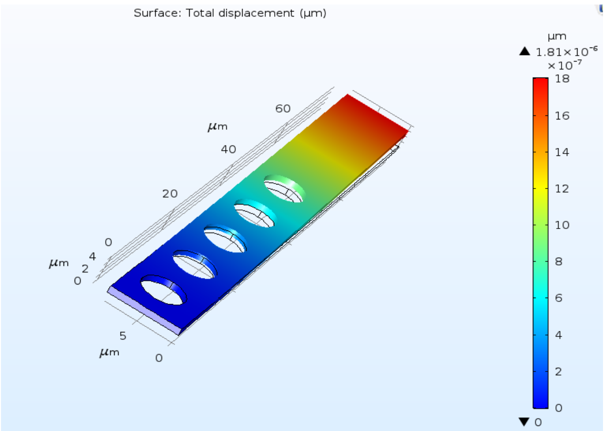

Fig.4.13(a) Circular holes at microcantilever

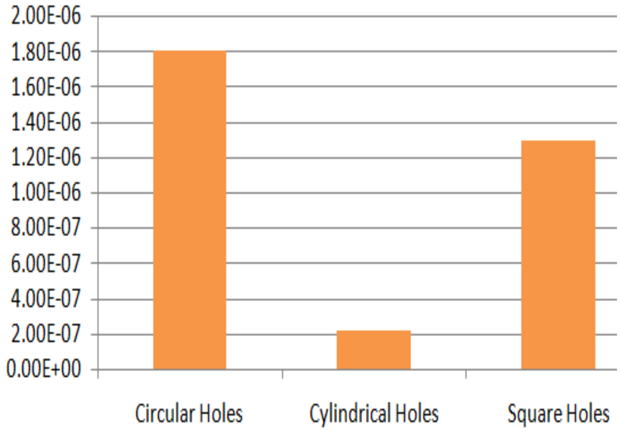

Fig.4.13(b) Maximum displacement through circular holes on microcantilevers

As DNA (Deoxyribonucleic acid), as well as the image-based process for cancer detection, is highly costly and complex so in place of that with Micro Cantilevers the detection process is becoming very easy and sufficient enough to function in a heterogeneous environment. According to this, the single, double, and triple strip microcantilever have been analyzed. By examining the bending, it was observed that the double strip is more appropriate and more sensitive, as indicated by Fig.4.14 (a) and 4.14(b).
This is one of the results of 4th research objective.

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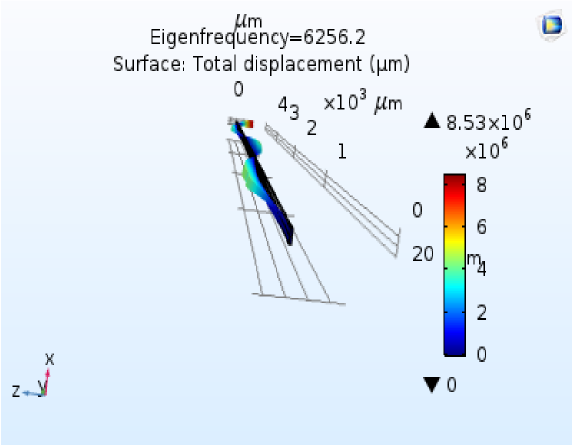

Fig.4.14(a) Total displacement(double strip)

Fig.4.14(b) Analysis of obtained displacement

5.1 RESULTS ANALYSIS AND DISCUSSIONS

This section's primary objective is to effectively convey all the numerous discoveries from Chapter 4. This division makes an effort to highlight all the significant computed values and offer comparisons between various structures to assist in selecting the best microstructure device [86].

5.2 OUTCOME ANALYSIS OF MATERIALS

Metals, semiconductors, and insulators are the three primary types of MEMS materials. We observe that predominantly Silicon Oxide (SiO2), Aluminum (Al), Gold (Au), Silver (Ag), Gallium Arsenide (GaAs), Polysilicon, Silicon, Zinc Oxide (ZnO), Silicon Nitride (Si3N4), PDMS(Polydimethylsiloxane), Graphane are better materials for this research work. Since gold is too costly, we even use zinc oxide instead of gold sometimes, but it is not always suitable. Also, Silicon Carbide material is extremely popular for the harsh environment analysis process.

5.3 OUTCOMES OF NOVEL MEMS-BASED DEVICES

In the case of dynamic mode, there are six sets of Eigen frequencies obtained through the simulation and concerning every Eigen, frequency obtained displacement, shown in Table 5.1. Further by modifying in dimensions displacement, improved which is shown in Table 5.2

Table 5.1 Maximum displacement

Eigen Frequency (Hz)	Total Disp. (µm)
2.4803E6	3.56×10^6

Table 5.2 Maximum displacement (changing dimensions)

Eigen Frequency(Hz)	Total Displacement (µm)
1.0265E6	3.78×10^6
2.6671E6	5.56×10^6
6.0057E6	6.47×10^6

In static mode, the same material and dimensions were used only the type of study chosen as stationary. From this, the parameters obtained such as Total Displacement=1.95×104µm, Stress=9.25×1011(Max. Value), and Strain=4.71(Max. Value). At last, it is understood that the microcantilever is sensitive in dynamic mode but the mode is not appropriate for liquid medium. Beam deflection, Eigen frequencies, and structures are the basis for the analysis of shape variations. With shape variations and analysis the maximum displacement is achieved through Pi-shape which equals 4.09×10-5µm. Various geometrical shapes and forms have been simulated and studied due to which it has been concluded that, with proper tuning and fabrication, we can employ just 2 micro-cantilever based arrays instead of 3 microcantilevers in a microcantilever array, which will drastically decrease costs, consume less power, make the structure simpler, and be portable. Key findings achieved by modeling and simulation of the pressure sensor are Displacement varies linearly with pressure. The first cornerstone of sensitivity enhancement is the positioning of piezoresistive materials or structures (Piezoresistors) at the point of maximum stress. Moreover, through modeling of the microcantilever, it was discovered that a double strip is more suitable and sensitive for cancer detection in the initial stages. Aside from these findings, some significant findings were achieved in chapter 4, which have not been presented here to prevent duplication.

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5.4 SUMMARY OF RESULT ANALYSIS

Microcantilever is a highly flexible sensor. It is providing improved response as a physical, chemical, or even biological sensor by sensing the change (if any) such as bending in microcantilever or vibration frequency. In order to enhance the overall sensitivity of microcantilever, deflection and resonant frequency of the microcantilever must be enhanced. If Eigen frequency is increased, stress will be increased and if stress will be increased then the microcantilever will become more sensitive. Therefore increasing the sensitivity of the microcantilever one can enhance the stress by using various techniques. It is also mentioned that if Eigen frequency will be increased then microcantilever displacement will be large. By increasing the length of microcantilever its sensitivity can be enhanced. By decreasing the thickness of the microcantilever its stiffness will become decrease and sensitivity will become increase. By utilizing material which has a lower young's modulus sensitivity of the micro Cantilever can be enhanced. It implies that selecting an appropriate sensing material in order to enhance the sensitivity of the device. Moreover, with the assistance of microcantilever and pressure sensors, various types of environments can be examined as well as these devices are quite useful for biomedical applications.

CONCLUSION

To achieve the research goal numerous modeling and analysis has been done through various tools and virtual labs. The principal research conducted in this research work is on microcantilever, pressure sensor, mechanical, electrical, and biological characteristics, heat transfer analysis, MEMS materials, surface chemistry for various microstructures, piezoresistive and piezoelectric phenomena, choice of the best type of power supply, structural and device reliability for healthcare and environmental monitoring. Several 2D and 3D microstructures were developed at the most basic level by following material qualities. The properties of a microcantilever and pressure sensor were subsequently studied with different mechanical and electrical properties in different media and by changing different parameters, like changing the size, shape, and composition of the material, among many other things. All these were done using different technologies, such as virtual labs, COMSOL 5.3a multiphysics, etc. and some solutions have been explored. One method of minimizing microcantilever vibrations is proposed.
Further, a micro battery has also been developed with the help of ZnO by which by applying reduced input voltage an increased potential can be achieved.
Another aspect which has been raised is that microcantilevers' effective area can be reduced, thus producing an increased displacement, by creating two circular holes from the fixed end. Another innovation is the development of a piezoresistive pressure sensor using graphene for ICP monitoring. Besides, the bending of single, double, and triple strip microcantilevers was also investigated, and it was revealed that the double strip is more appropriate and sensitive. An example of blind cave fish has been utilized for real-time analysis. PMMA, PDMS, and Nylon materials were utilized in the analysis, however, it was revealed that PDMS is best as it provides the highest displacement. Therefore, environmental and human health monitoring demands this type of effort. Nonetheless, monitoring microcantilever testing for various applications in various settings is essential. For the benefit of society, analysis based on fabrication may be conducted.

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