Design of Piezo-Resistive Type Acoustic Vector Sensor using Graphene for Underwater Applications

Smitha Prabhu¹, Amrita B Pai¹, Gurumukh Singh Arora¹, Kusshal M R¹, Veera Pandin², Goutham M A³

¹Department of Electronics and communication, NMIT, Bangalore, India
²Center of NanoScience and Engineering, Indian Institute of Science, Bangalore, India
³Department of Electronics and communication, AIT, Chikamagalur, India

E-mail: smitha.prabhu@nmit.ac.in

Abstract. In recent years as the level of radiated noise of submarine drastically got decreased, the requirement of underwater acoustic sensor has become essential for the detection of low frequency acoustic signal. The latest advancement in the field of underwater sensors is the Micro Electro Mechanical Systems (MEMS) sensor. The major advantage of this sensor being determination of directionality along with the measurement of pressure of an acoustic signal. The biological inspiration behind the design of the sensor was derived from fish lateral line sensing system, with piezoresistive transduction principle to obtain the objective of miniaturization and low frequency signal detection. In this paper, we are reporting the design, simulation of an underwater two-dimensional MEMS acoustic vector sensor which exhibits better sensitivity, flexibility when compared to the traditional acoustic vector sensor. In this work, thin film of piezoresistive material, Reduced Graphene Oxide (rGO) is taken as pressure sensing element instead of traditional polysilicon material and its performance in terms of sensitivity and directivity is analysed. MEMS acoustic vector sensors using Reduced Graphene Oxide and polysilicon were simulated on flexible kapton and silicon substrate respectively using COMSOL Multiphysics 5.5 version. The simulation results indicates that designed vector sensor based on MEMS technology and piezoresistive effect of rGO on flexible kapton substrate is feasible and possesses better sensitivity of -149.47 dB when compared to the sensitivity of -171.37 dB of polysilicon based traditional acoustic vector sensor. The simulated value of eigen frequency of the sensor is found as around 47 Hz, which almost matches with the theoretical value of resonance frequency of the sensor as per the design considerations of the sensor and hence capable of detecting low frequency acoustic signals.

1. Introduction

Underwater acoustic plays a vital role in underwater operations such as detection of the location of the submarines, ships, target detection, and in navigation. Sound wave in an elastic medium is known as acoustic wave. In water, acoustic wave is due to the molecular vibrations in the medium that travels at the speed of light. A sound wave propagating in water consists of alternating compressions and rarefactions of the water molecules. The rarefaction and compression of water molecules exerts restoring force. This restoring force that resists the motion is labeled as pressure. The variation in pressure is detected by the hydrophone, which converts them to the voltage proportional to the pressure. At any point in acoustic field the vector sensor will be able to measure both acoustic particle velocity and acoustic pressure. This vector hydrophone provides the direction and magnitude of...
pressure [1]. The vector sensor made up of an array of hydrophones, has drawbacks such as inconsistency and larger volume. A four-beam structure with an acoustic cylinder at the centre forms the basic structure of the vector sensor. An acoustic wave, on striking the cylinder leads to the distortion of the beam structure [2]. The shape of the support frame to which the four beams are attached plays an important role in improving the sensitivity of the sensor.

The largest centre of deflection is seen in the circular diaphragm having lowest stress on its edges when compared to the other diaphragms as in square diaphragm, and this helps in the distribution of stress on cantilever beams [3]. In recent times the level of noise transmitted from submarines has become lower and hence making SONARs inefficient to locate and track them. A single acoustic sensor was developed by China based on bionic, piezoresistive and MEMS technology [4]. The sensor is based on the piezoresistive transduction principle. The benefit of using piezoresistive transduction principle is that it detects the low-frequency signal even to the extent of zero hertz and it exhibits two-dimensional directivity.

The biological inspiration in the design of the MEMS vector hydrophone comes from the sensing system of the fish as indicated in Figure 1, which goes from head to tail, resembling an array, having sensing organs called stitches, spaced at intervals along the nerve fibre. Each stitch consists of many neuromasts as shown in Figure 2 and each neuromast in turn contains several mechanosensory hair cells. Stereocilia is the apical portion of the hair cell is. When the fish swims in water, stereocilia vibrates and thereby, acts as sensor for flow noise. This turbulence causes the movement of hair cell, intern causes the change in synapses connected to the main nerve fibre. It is observed that the lateral line of fish is sensitive to the motion of fluid of low frequency. The entire structure of the hydrophone resembles that of a neuromast. The hair cell is similar to that of the piezoresistors and the stereocilia is similar to the cylindrical rod [5].

Figure 1: Lateral line of fish Figure 2: Schematic representation of the neuromast organ of the fish

On a conventional approach, Mengran Liu et al. [6] have used silicon as a substrate for the structure. Silicon as a substrate is not flexible and needs to undergo additional chemical processes to make it flexible which increases the fabrication cost. This process is used to decrease the thickness of the silicon substrate. The sensing element used in traditional piezoresistive pressure sensor is polysilicon and the fabrication process of it requires clean room facilities which requires several days. Many researchers have worked on silicon to improve the sensitivity of the model. Wen Dong Zhang et al [7] have designed polysilicon on an insulator and found 3.44 mv/psi as its pressure sensitivity.

In the present-day graphene has taken lead in Micro Electronic Mechanical Systems (MEMS) technology, especially in the domain of pressure sensors, due to their chemical, electronic, mechanical, and physical properties. One of the carbon allotropes, Graphene is utilized to develop a pressure sensor [8]. Graphene is made up of monolayer of carbon atoms, which gives them extreme thinness.
extreme thinness of graphene layers, causes the deflection of the membrane. Graphene is a unique material with excellent mechanical flexibility and high crystallographic quality. It also provides a linear relationship with strain and resistivity. Extraction of pure graphene without any defects is highly complex as per Kaihua Cao et al [9]. Most of the techniques used in the synthesis of graphene do not yield a good amount of graphene. Reduced Graphene Oxide (rGO) is a material whose properties are similar to graphene, when compared to other members of the graphene family. Reduced Graphene Oxide can be easily synthesized in bulk quantities. It is highly isotropic and provides high conductivity [10]. Reduced Graphene Oxide is obtained by reducing Graphene Oxide (GO).

Based on Bionic, piezoresistive principle and MEMS technology an effort is made in this work to design and simulate an underwater bi-directional vector sensor. The proposed design makes use of Kapton as a substrate which is highly flexible in nature and Reduced Graphene Oxide as the piezoresistive sensing element. The device shows two-dimensional directivity, hence overcomes the short comes of scalar hydrophone. Combining MEMS technology and piezoresistive effect of reduced graphene oxide, along with its unique electronic properties, a low frequency sensor can be developed with a simple, low cost and scalable process.

2. Design & Mathematical Modelling

The structure of the bi-directional acoustic vector sensor mainly consists of four horizontal cantilever beams, a rod, support frame and 8 piezoresistors as shown in Figure 3.

![Figure 3: Structure of Acoustic Sensor](image)

Piezoresistors R1, R2, R3, R4 are placed on the beam, which is situated along axial direction & R5, R6, R7, R8 are along radial direction beam as shown in Figure 4a. Using these piezoresistors two wheatstone bridges are formed, one along axial and the other along radial direction respectively as shown in Figure 4b.
2.1 Working Principle of the Sensor

When the pressure wave displaces the rod in axial or radial direction, the cantilever beams of the structure experiences strain. Being sensing elements, these piezoresistors sense the induced stress and hence cause a corresponding variation in the electrical resistance of the same. This change in the resistance of the resistors connected in a Wheatstone network on the sensing beams generates an electrical output voltage. As shown in Figure 4b, Wheatstone bridge is biased by using supply $V_{cc}$ and for the equilibrium condition of the bridge, i.e when $R_1R_3 = R_2R_4$ ---- (1), output voltage $V_x=0$

If the pressure wave is incident along axial direction, then it changes the resistance of axial beam piezoresistors then the output voltage of the axial beam Wheatstone bridge is given by

$$V_x = \frac{(R_1+\Delta R_1)(R_3-\Delta R_3)-(R_2+\Delta R_2)(R_4-\Delta R_4)}{(R_1+\Delta R_1+R_2-\Delta R_2)(R_3+\Delta R_3+R_4-\Delta R_4)} V_{IN}$$ ---- (2)

2.2 Sensor Design Criteria

The dimensions of the sensor depend on Eigen frequency and the stress imparted to the structure. The main objective here is to build a low-frequency acoustic vector sensor. Hence identifying the operational frequency range of sensor is very essential.

Eigen frequency is given by

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \ldots (3)$$

$$f = \frac{1}{2\pi} \sqrt{\frac{2Ew^3}{mLH^2}} \left(\frac{a^2}{L^2} + \frac{a}{L} + \frac{1}{3}\right) \ldots (4)$$

where ‘L’ is length of the cantilever beam, ‘H’ is height of the rod, ‘a’ is the half-width of the central mass, ‘w’ is the width of the cantilever beam, ‘t’ is the thickness of the cantilever beam, ‘E’ is the elastic modulus of the substrate and ‘R’ is the radius of the rod.

To finalise the dimensions of the sensor, the parametric analysis of all above mentioned parameters are carried out. Few results of analysis are shown in Figure 5 and Figure 6.

![Figure 5: Parametric analysis of length of the beam](image1)

![Figure 6: Parametric analysis of width of the beam](image2)

It can be inferred from Figure 5 and Figure 6 that, as the width of the beam decreases and length of the beam increases the stress across the horizontal cantilever beam increases. Similarly, the larger radius of rod will also results in more stress and the size of the central mass exhibits similar impact on stress. Similarly, various dimensions of the structure are considered and its effect on the Eigen frequency and stress are analysed. The dimensions of the device are finalised after parametric analysis and are indicated in table 1.
Table 1. Parameter dimensions of sensor

| Parameter                      | Dimension (mm) |
|-------------------------------|----------------|
| Length of the cantilever beam (L) | 10             |
| Width of the cantilever beam(W)  | 2              |
| Thickness of the cantilever beam(t) | 0.175          |
| Central mass Square(S)            | 6              |
| Length of the rod(L_a)          | 25             |
| Radius of the rod(R)            | 3              |

With these dimensions, the theoretical value of Eigen frequency of the structure was found to be around 41.06 Hz hence capable of detecting very low frequency acoustic signals.

Another design criterion for this sensor is, density of the material used for the rod. The sensing principle of this sensor follows acoustic theory of cylinder. This theory indicates that the density of the surrounding medium and the cylindrical rod should match, so as to have a synchronous vibration, as per equation \( v = \frac{2\rho_o}{\rho_o + \bar{\rho}} v_o \). (5), else the MEMS hydrophone cannot memorize the acoustic information. Hence while simulating, the material used for rod is taken as nylon whose density is almost equal to that of density of water.

3. Modelling Using Comsol Multiphysics

The geometry of the sensor is designed and simulated using COMSOL Multiphysics. Solid Mechanics physics and piezoresistive domain currents are chosen as the environment for the purpose of analysis. The first step is to create the geometry, followed by defining suitable materials for the same. The materials defined for rod, piezoresistors and connector strip are nylon, rGO and aluminium respectively. Kapton is the material used for the central block and the microstructure with density of 1330 kg/m³, Young’s modulus of 3.1G Pa and Poisson’s ratio of 0.34. The piezoresistive property of Reduced Graphene Oxide plays a important role in improving the sensitivity of the MEMS underwater acoustic sensor. The electrical resistance of the piezoresistor varies in accordance with the applied stress. When the sensing beams are stretched or compressed, the piezo resistors placed on these sensing beams experience a change in its length, area and resistivity. The resistivity of the piezo resistors depend on its piezoresistive coupling matrix. Piezoresistive coupling matrix of a material is a 6*6 matrix that defines the relationship between the stress components and its corresponding resistivity [11]. There exist only three non-zero independent stress components (\( \pi_{11}, \pi_{12}, \pi_{44} \)) due to the crystalline nature of graphene, as given below:

\[
\tau = \begin{bmatrix}
\pi_{11} & \pi_{12} & 0 & 0 & 0 & 0 \\
\pi_{12} & \pi_{11} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \pi_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & \pi_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & \pi_{44}
\end{bmatrix}
\]

On simplification, the change in the resistance of a piezoresistor is given by equation

\[
\frac{\Delta R}{R} = \pi_t \sigma_t + \pi_l \sigma_l 
\]

(6) where the transverse and longitudinal piezoresistive coefficients are given by \( \pi_t \) and \( \pi_l \) respectively. The longitudinal and transverse stresses on the surface of the piezoresistors are given by
After defining piezoresistive, structural and electrical properties of the material, the support frame was fixed by applying fixed constraint domain condition and boundary load pressure or force was applied on rod. The deformation of the structure for the applied boundary load of 1N is as shown in Figure 7. Due to the deformation, stress gets generated on the beam and it is found to be maximum at beam central block interface and at the support frame as shown in Figure 8 and act as a optimal position for the placement of piezoresistors.

After defining piezoresistive, structural and electrical properties of the material, the support frame was fixed by applying fixed constraint domain condition and boundary load pressure or force was applied on rod. The deformation of the structure for the applied boundary load of 1N is as shown in Figure 7. Due to the deformation, stress gets generated on the beam and it is found to be maximum at beam central block interface and at the support frame as shown in Figure 8 and act as a optimal position for the placement of piezoresistors.

![Figure 7: Displacement of the rod for 1N force](image1)

![Figure 8: Surface stress distribution plot](image2)

4. Simulation Results

Performance of the sensor was analysed based on the shape of the support frame, substrate and piezoresistive materials used.

4.1 Shape of the Structure

The shape of the structure is one of the imperative factors to improve sensitivity of the sensor. Contemporarily most of the underwater acoustic sensors use square based structures. Circular structure design and square structural design of the sensor is compared and analysed interms of stress distribution as shown in the Figure 8 and Figure 9 respectively.
Figure 9: Surface stress distribution plot of square structure for 1N force

For precise comparison of stress distribution of both structures, stress versus arc length graph was plotted and they are as shown in Figure 10 and Figure 11 respectively.

On comparing the graphs in Figure 10 and Figure 11, it is observed that amount of stress at the fixed ends of the cantilever beam is more for circular-shaped sensor than the square-shaped sensor. At the end of the beam which is connected to the central mass, von mises stress for square shape is below $3 \times 10^8 \text{N/m}^2$ when compared to $3.4 \times 10^8 \text{N/m}^2$ of circular shape structure. These results indicate how circular structure design is better suited for piezoresistive effect based acoustic sensor.

### 4.2 Substrate Material Consideration

Kapton as a substrate has numerous advantages when compared to conventional silicon based substrates which includes low manufacturing cost, high flexibility and higher temperature tolerance. Kapton is naturally flexible in nature whereas silicon needs to undergo additional chemical processes to make it flexible.
Figure 12: 2nd principle stress distribution plot of n-type silicon based single cantilever beam when a force of 1N is applied

Figure 13: 2nd principle stress distribution plot of Kapton based single cantilever beam when a force of 1N is applied

From Figure 12 and Figure 13, it is observed that Kapton possesses a higher stress value when compared to n-type silicon, both at fixed end of the beam and at the interface of beam and central mass. Maximum stress variation inturn aids in improving the sensitivity of the device.

4.3 Reduced Graphene Oxide as a Piezoresistor

Piezoresistive sensing materials plays a vital role in defining the efficiency of the pressure sensor. In this paper, reduced graphene oxide is introduced and taken as a sensing material and paralleled against the conventionally used silicon. The sensor is simulated for various pressure levels (1Pa to 5Pa) for both rGO and polysilicon as sensing materials.

4.3.1 When various pressure levels are applied along the Positive X-axis direction on the nylon rod

For the applied pressure along axial direction, the beams which are along axial direction will be subjected to deformation due to tensile and compressive stresses on the beams which results in the variation of resistance of the corresponding beam.

The pressure of 1Pa to 5Pa is applied in positive x-axis direction. Resistor R1&R3 experiences compressive stress, hence the change in resistivity keeps on decreasing for R1&R3 (Negative) and
resistors R2\&R4 experiences tensile stress and hence the change in resistivity value is increasing (Positive) for resistors R2\&R4 as shown in Figure 14. The change in resistivity is in the order of $10^7$ ohm-m to $10^6$ ohm-m for R1, R4 and R2, R3 respectively. Change in resistivity of radial axis resistors are found to be negligible in the order of $10^{-10}$ ohm-m. But for polysilicon piezoresistive material, change in resistivity was found to be in the order of $10^9$ ohm-m to $10^8$ ohm-m for R1, R4 and R2, R3 respectively. Higher the change in resistivity more is the change in output voltage across Wheatstone network which leads to higher sensitivity. Hence, reduced graphene oxide is chosen as the piezoresistive material.

5. Directivity and Sensitivity
For the applied axial direction force on the rod, the resistivity of only the resistors placed on axial beam will show significant changes and whatstone bridge formed on the axial beam produces electrical output voltage, thereby indicating the directionality as x axis. For radial force, the wheatstone bridge formed on radial beam gives the output voltage indicating the direction as Y axis. The sensitivity of the sensor depends on the output voltage of the Wheatstone network. The output voltage is observed for both polysilicon and rGO as piezoresistors by simulation. The output voltage observed on x axis Wheatstone bridge, when pressure wave acts on +X axis direction for polysilicon as piezoresistors is found to be 2.7 mV and for rGO as piezoresistors, it is 33.6 mV. Hence, rGO based sensor could achieve a sensitivity of -149.47dB when compared to -171.37dB of a polysilicon based sensor.

6. Conclusion
We have proposed design and simulation of the bi-directional Reduced Graphene Oxide based acoustic vector sensor which is suitable for underwater applications. It is observed that the rGO’s graphene like properties are suitable for detection of the sound in underwater environment, when it is deposited on a uniform thickness flexible Kapton substrate. Due to its piezoresistive transduction principle and miniaturized design parameters, this sensor is best suited for detection of low frequency acoustic signals. This design has additional advantages which include simple structure, small volume and simpler fabrication process by eliminating the need of clean room, and low cost. The simulated value of natural frequency of the sensor is found to be around 47 Hz and it almost a match with the theoretical value of 41.06Hz. Its sensitivity is found to be around -149.47 dB. This sensor can detect horizontally moving underwater acoustic waves and also achieve low frequency acoustic wave detection with enhanced sensitivity.

REFERENCES

[1]. Hu Zhang, H J Chen, W Z Wang., 2014. An underwater acoustic vector sensor with high sensitivity and broad band Sensors & Transducers. Vol. 170, Issue 5.
[2]. Peng Wang, Guo-jun Zhang, Chen-yang Xue, Ji-jun Xiong., 2017. Engineering application of MEMS vector hydrophone and self-adapting root-MUSIC algorithm., IEEE DOI: 10.1109/TRANSDUCERS.2011.5969568
[3]. Shivaleela Melennavar, Ajaykumar C Kategeri., 2016. Theoretical Analysis of the Design of Different Shape Diaphragm for Piezoresistive Pressure Sensor, DOI: 10.17577/IJERTV6IS030408
[4]. Shang Chen, Chenyang Xue, Binzhen Zhang, Bin Xie and Hui Qiao., 2007. A Novel MEMS Based Piezoresistive Vector Hydrophone for Low Frequency Detection. Proceedings of the IEEE, 1839-1844.
[5]. Chenyang Xue, Shang Chen, Wendong Zhang, Binzhen Zhang, Guojun Zhang, Hui Qiao., (2007). Design, fabrication, and preliminary characterization of a novel MEMS bionic vector hydrophone. Microelectronics Journal 38, 1021-1026.
[6]. Mengran Liu, Guojun Zhang, Zeming Jian, Hong Liu, Xiaopeng Song, Wendong Zhang., 2014. Design of Array MEMS Vector Vibration Sensor in the Location of Pipeline Internal Inspector. *TELKOMNIKA Indonesian Journal of Electrical Engineering*, **Vol. 12**, No. 9, pp. 6651 ~ 6657.

[7]. Wen Dong Zhang , Ling Gang Guan, Guo Jun Zhang., 2009. Research of DOA Estimation Based on Single MEMS Vector Hydrophone, Article, *Sensors*, 9, 6823-6834.

[8]. Nagarjuna Nella, V Gaddam, M.M Nayak, K. Rajanna, T. Srinivas, 2015. Highly flexible and sensitive graphene-silver nanocomposite strain sensor. *Proceedings of the IEEE*.

[9]. Kaihua Cao, Xiaodong Ye, Xinhua Guo, 2017. Design and Simulation of Two-Dimensional Graphene-Based Acoustic Sensor Arrays. *Proceedings of the IEEE*

[10]. Raluca Tarcana, Otto Todor-Boera, Ioan Petrovaia, Cosmin Leordeand, Simion, Ioan Astileana Botiza, 2015. Reduced graphene oxide today. DOI: 10.1039/C9TC04916A

[11]. Guo Jun Zhang, Lin Xian Liu, Wen Dong Zhang, Chen Yang Xue., 2014. Design of a monolithic integrated three-dimensional MEMS bionic vector hydrophone. Technical Paper *Springer-Verlag Berlin Heidelberg*