Performance analysis of polyvinylidene fluoride (PVDF) type piezoelectric pressure sensor

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KEYWORDS

Piezoelectricity,
PVDF Film,
β Phase,
Flexible Sensor.

ABSTRACT

This paper reports the design, modelling and simulation of a PVDF based piezoelectric pressure sensor, since PVDF is a semi- crystalline compound and its β phase is most responsive on piezoelectric polymers. The electro-mechanical properties show that the sensor exhibits excellent output response such as Voltage. The output voltage and the applied pressure possess linear relationship with a slope. Design and modeling of the sensor has been carried out using COMSOL Multiphysics. Later, characterization of the fabricated sensor undertaken to examine the parameters of the model and to validate it with simulation and theoretical results obtained, which can be further used for any specific application required.

1. Introduction

Recent years, more and more studies have focused on organic piezoelectric materials such as polyvinylidene fluoride (PVDF) series, because of their flexibility, low cost, and stable performance. At present, they have been widely adapted for various applications, such as ultrasonic measurement [1–5], pressure sensing [6–10], energy harvesting [11–17] and wearable devices [18–21]. It emphasizes that the equipment is "worn" on the body and usually has sensors with the function of collecting and detecting information such as physiological signals, acceleration, and location.

The sensors used for human–computer interaction are one of the more important types, which have the advantages of portability, comfort, non-invasion, and lower power consumption. Over a span of few years, many kinds of pressure sensors were developed. They can be generally categorized as Piezo resistive, Capacitive and Piezoelectric pressure sensors. Piezoelectric sensor develops noticeable charge signal by itself in response to the applied pressure, demonstrating some advantages over other types of pressure sensors, such as self- powering, fast response and relatively simple readout circuit. Mostly, these sensors have diaphragm structure, which is the most adequate design for pressure sensing. And it is in turn ideal for measuring fluctuating input pressure sensor. Some of the applications being engine knock sensors, energy harvesters, and sonar equipment [22]. Certain materials produce electric potential by virtue of the applied stress. This effect is called piezoelectric effect or direct piezoelectric effect. This phenomenon is evident in some of the naturally occurring crystalline materials such as quarts, Rochelle salt and human bone. And some of the artificially produced materials are Polyvinylidene fluoride (PVDF), Lead zirconated titanite (PZT) etc, produce better piezoelectric effect. PVDF is the most popular semi-crystalline compound which is accessible as pellets, powder or semi-transparent films.

It's β phase is the most responsive piezoelectric polymer. PVDF has sturdy electrical, mechanical and chemical response which makes it to be a valuable material. These films are ideal for sensors as a result of their flexibility [23]. PVDF based sensor was fabricated [24] to sense change in pressure between 10 to 150kPa. Sensor showed linear variation of output voltage for the applied pressure input. Sensor developed is small, cost effective and sensitive. Optimization of spin coating of PVDF film can enable increase in β phase content.

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Squared shaped piezoelectric sensor was analyzed by Uday Jyothi et.al [25], which shows that sensitivity follows linear relationship with applied input. And the output voltage is dependent on the thickness of both piezoelectric and diaphragm layers. Thinner the layer, better the sensitivity. Piezoelectric PVDF sensors using graphene-based electrodes were fabricated by Satul Rajal et.al [26]. Sensitivity measurement of the sensor were similar to the reference sensor and hence linear output and negligible hysteresis error was achieved. And finally, operation of the sensor was noted to be stable under variable frequencies.

This paper reports the design, modeling and simulation of PVDF based Piezoelectric pressure sensor consisting of three components i.e., Silicon substrate which acts as base, over which square shaped piezoelectric layer (made up of PVDF) is sandwiched between electrode layers, made up of Aluminum.

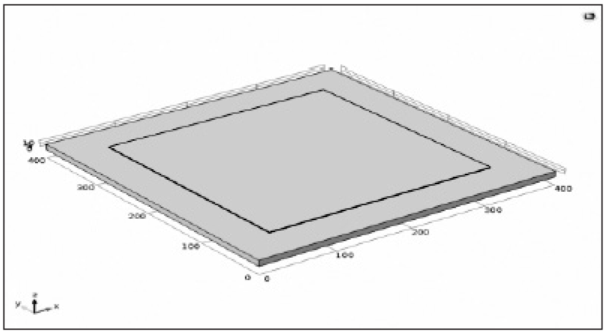

Fig. 1. Sensor model.

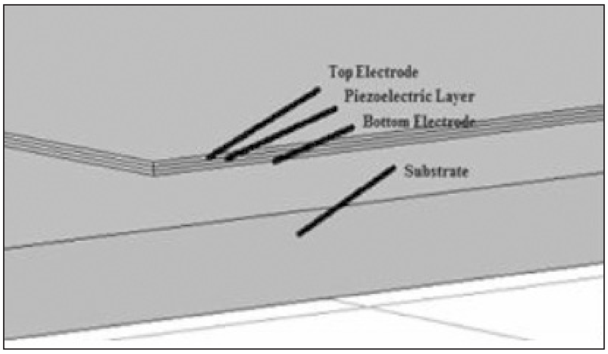

Fig. 2. Sensor model with layers.

Output voltage is optimized by changing and analyzing different parameters such as pressure applied on the top plate, thickness, length and width of the layers.Following which the performance of the sensor analyzed and concluded based on the comprehensive study of the simulation results.

2. Design and Implemention

In order to analyze the performance of the device, it was designed and simulated using COMSOL Multiphysics 5.0 Sensor model consists of Substrate, Piezoelectric layer, bottom and top Electrode layers. Substrate layer is of Silicon material. Piezoelectric layer is obtained by depositing PVDF material on the substrate. Top and bottom Electrode layers are aluminum that are deposited on the either sides of PVDF material.

Figure 1, 2. shows the model of the PVDF based piezoelectric pressure sensor when applied pressure is zero. Table 1 shows the dimensions of different layers of the model designed.

When pressure is applied on the top surface of the PVDF layer, it causes change in the crystalline structure of the elements of the PVDF layer. This enables free movement of charges causing their arrangement on different sides of the plate and hence producing electric potential.

3. Mathematical Modeling

Stress obtained due to the applied pressure on the PVDF layer

$$\text{Stress} = \frac{\text{Force}}{\text{Area}} = \frac{\text{Pressure}}{\text{Area}} \text{ in N}/m^2 \quad (1)$$

Considering the applied pressure as 200Pa and Area = 4.5e-14 m^2,

Stress = 4.44e+15 N/m^2

Strain for the obtained stress with Young's Modulus of PVDF = 8.3GPa,

Table 1
Dimensions of the piezoelectric pressure sensor model.

Layers	Material	Dimension	Thickness
Substrate	Silicon	400 X 400 µm	10 µm
Middle Plate	Piezoelectric Material	300 X 300 µm	0.5 µm
Top and Bottom Electrodes	Aluminum	300 X 300 µm	0.5 µm

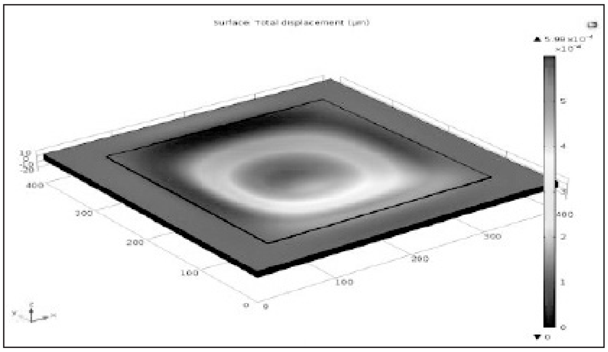
Fig. 3. Total displacement.

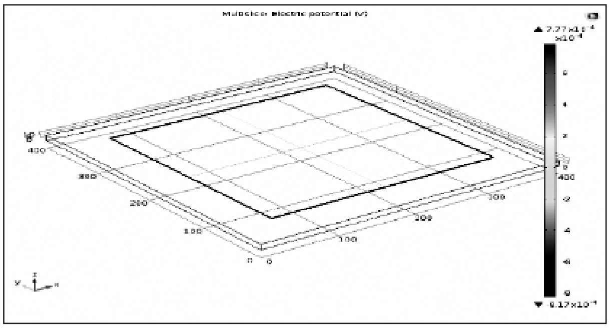
Fig. 4. Electric potential.

$$\text{Stress} = \frac{\text{Strain}}{Young's\ Modulus} = 0.53M \quad (2)$$

Output voltage

$$\text{Voltage} = \frac{t_p X\ Strain}{d_{33}\ \text{X L}}\ \text{in Volts} \quad (3)$$

Voltage = 0.2e-4 V

Where,

t_p - Thickness of piezo electric layer in µm
d_{33} - Co-efficient of stress in z-direction
L & W- Length and width of the device in µm

4. Simulation Results

COMSOL Multiphysics used for modeling the piezoelectric effect i.e., Electrostatics (Ground and terminal voltages can be applied) and Solid mechanics (Boundary load i.e., Pressure can be applied). All four sides of the substrate are fixed along with the bottom plate. Top portion of the PVDF layer is grounded. Variable Pressure is applied on the top plate and output voltage is obtained along the z-direction. Fig 3 shows the total displacement of 5.44e-4m obtained, when 1kPa of pressure is applied on the top side of the PVDF layer. Fig 4 shows the electric potential of 7.44e-4 V obtained due to the application of 1kPa pressure on the top side of the PVDF layer.

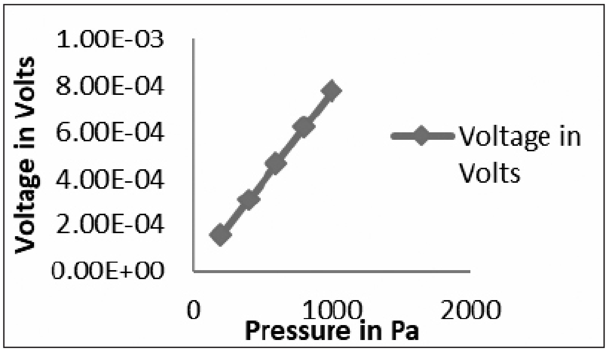

Fig. 5. Pressure v/s voltage.

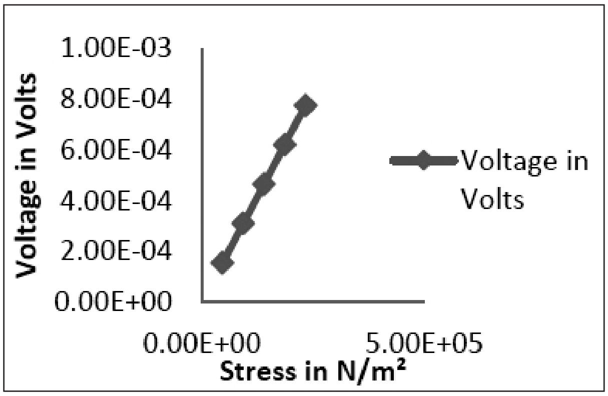

Fig. 6. Stress v/s voltage.

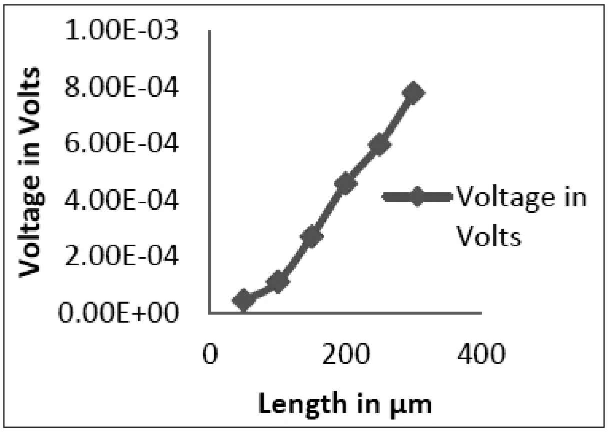

Fig. 7. Length v/s voltage.

Fig 5 shows the plot between applied pressure in the range 200 to 1000 pa on the top side of the PVDF layer and the obtained output voltage. It is evident from the figure that the relationship between input pressure and output voltage is linear. Fig 6 shows the relationship between stress and output voltage. Pressure and Stress are directly proportional. Fig 7 shows the plot between total displacement and output voltage. As displacement increases, voltage increases linearly. Fig 8 shows the relationship between thickness (varied between 0.2 to 0.5 µm) and voltage,

Table 2
Results obtained due to application of pressure between 200-1000Pa.

Pressure in Pa	Stress in N/m²	Total Displacement	Practical Voltage in Volts	Theoretical Voltage in Volts
200	4.64E+04	1.24E-04 µm	1.55E-04	2.44E-04
400	9.31E+04	2,40E-04 µm	3.11E-04	4.88E-04
600	1.40E+05	3.60E-04 µm	4.66E-04	7.30E-04
800	1.86E+05	4.79E-04 µm	6.22E-04	9.76E-04
1000	2.33E+05	5.99E-04 µm	7.77E-04	10.22E-04

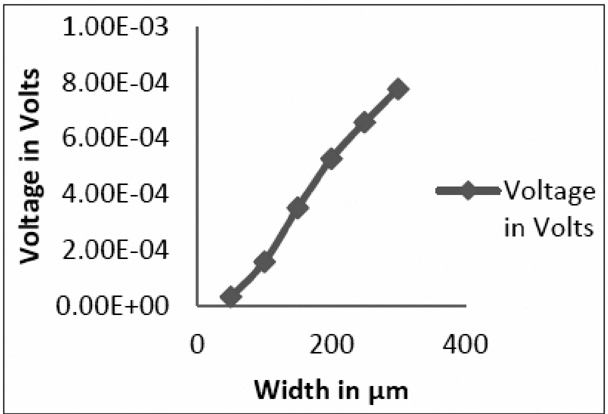

Fig. 8. Width v/s voltage.

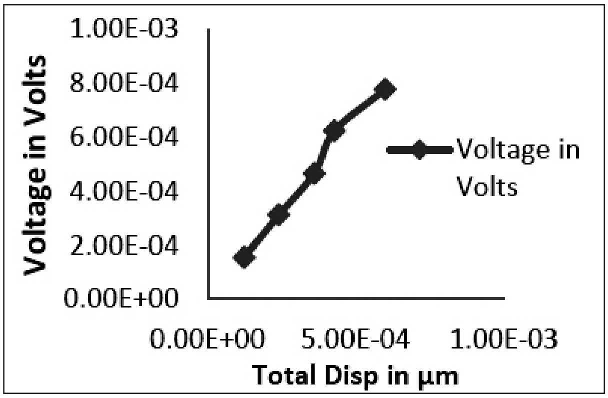

Fig. 9. Total displacement v/s voltage.

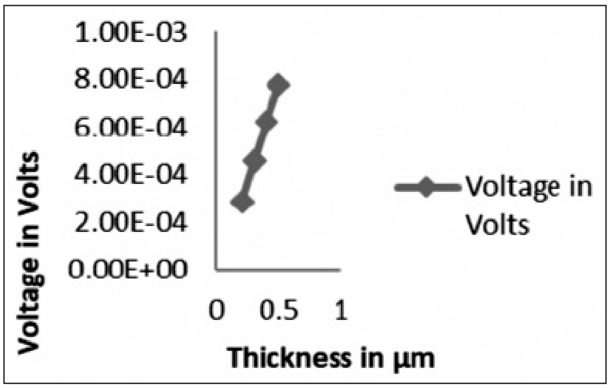

Fig. 10. Thickness v/s voltage.

It is evident that as thickness increases, there is a linear increase in voltage. Fig 9 and 10 shows the plot between length and width (varied between 50 to 300 µm) of the layers with respect to the output. It is evident from the graphs that the output increases linearly with increase in length and width. Table 2 shows the results obtained for various pressure values applied on the top side of the PVDF layer.

5. Conclusion

This research work presents design of piezoelectric pressure sensor using as PVDF as sensing element and Aluminum as electrode. Further, simulation has been carried out using COMSOL Multiphysics to obtain the required Output i.e., voltage, when variable pressure is applied. It is seen that the relationship between input and output is linear. Some of the other parameters responsible for optimization of the sensor are stress, total displacement and thickness. Reduction in the thickness of the layers is proportional to increase in sensitivity of the output voltage. Fabrication of the piezoelectric layer can be carried out using spin coating. Depending on the concentration of the mixture for the piezoelectric thin film, β Phase concentration increases, thereby increasing the output of the sensor. Later characterization of the fabricated sensor can be carried to examine the parameters of the model and to validate it with simulation and theoretical results obtained which can be further used for any specific application required.

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