

Comparative simulation study of a cylindrical piezoelectric pressure sensor using COMSOL Multiphysics

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Abstract. In this work, a Two-Dimensional (2D) axisymmetric model of a cylindrical piezoelectric pressure sensor was established to exploit its rotational symmetry. Five piezoelectric materials, i.e., PZT-5H, PZT-5A, Polyvinylidene Fluoride (PVDF), Barium Titanate (BaTiO_3), and Aluminum Nitride (AlN), were evaluated to compare their piezoelectric response under internal pressures ranging from 2 to 10 MPa. All five materials show an approximately linear increase in output voltage with increasing pressure. At an internal pressure of 10 MPa, PVDF exhibits the highest output voltage of 262.46 V. This phenomenon is mainly attributed to the dielectric properties of the material. The lower relative permittivity of PVDF leads to a lower equivalent capacitance. For a given amount of generated charge, a smaller capacitance results in a larger potential difference between the electrodes. For the PVDF-based sensor, the inner radius was fixed at 175 μm , and the wall thickness was increased from 50 to 300 μm . As the wall thickness increases, the maximum von Mises stress decreases, while the output voltage increases. From an electrical perspective, increasing the wall thickness enlarges the outer radius, thereby reducing the capacitance. Since the reduction in capacitance exceeds the reduction in mechanical stress, the output voltage increases from 262.64 to 458.83 V. Furthermore, the inverse piezoelectric response of these five materials was investigated. Under a 1 V electrical excitation, PZT-5H produces the largest radial displacement of 1.62 nm, demonstrating its suitability for micro-actuation. This study provides a quantitative basis for material selection and structural optimization of piezoelectric pressure sensors.

Keywords: piezoelectric pressure sensor, COMSOL Multiphysics, PVDF, piezoelectric effect, structural optimization

1. Introduction

1.1. MEMS technology

Micro-Electro-Mechanical Systems (MEMS) have become a key technology for developing miniaturized devices by integrating mechanical structures with electronic circuits on a single substrate. Through the use of batch fabrication processes derived from Integrated Circuit (IC) manufacturing, MEMS devices can achieve dimensions ranging from several micrometers to millimeters while maintaining high consistency and scalability [1]. In recent years, MEMS technology has been widely adopted in various fields, including

consumer electronics, automotive systems, biomedical instruments, aerospace equipment, and wearable devices [1-3]. Compared with conventional sensing technologies, MEMS devices offer advantages such as compact size, reduced power consumption, high reliability, and compatibility with mass production, which have contributed to their increasing importance in modern sensing systems [2].

1.2. MEMS pressure sensors

Among various MEMS-based devices, pressure sensors represent one of the most extensively investigated and commercially developed categories. A typical MEMS pressure sensor converts external mechanical pressure into an electrical output signal and is widely used in applications such as industrial monitoring, automotive control systems, and medical equipment [2, 4]. Based on different conversion mechanisms, MEMS pressure sensors can be generally classified into capacitive, piezoresistive, and piezoelectric types [1, 5].

Capacitive pressure sensors measure pressure-induced deformation by detecting the variation in capacitance caused by the displacement between two conductive plates. These sensors usually exhibit low power consumption and high sensitivity. However, their performance can be affected by parasitic capacitance, electromagnetic interference, and the requirement for additional signal conditioning circuits [2]. Piezoresistive pressure sensors rely on the change in electrical resistance caused by mechanical strain. Although their fabrication process is relatively simple and compatible with conventional MEMS technologies, they commonly suffer from temperature-induced drift and high power consumption during operation [6, 7].

1.3. Piezoelectric pressure sensors

Due to the limitations of conventional pressure sensing mechanisms, piezoelectric pressure sensors have attracted increasing attention, particularly for applications involving dynamic pressure measurement and self-powered sensing. These sensors utilize the direct piezoelectric effect, in which mechanical stress applied to a non-centrosymmetric material generates electrical charges through electromechanical coupling [4, 8]. This conversion mechanism enables piezoelectric sensors to achieve rapid response, high sensitivity, and effective detection of dynamic mechanical signals. Since the sensing signal can be directly generated from mechanical deformation without an external excitation voltage, piezoelectric pressure sensors are suitable for energy-efficient and portable sensing systems [9].

The sensing performance of a piezoelectric pressure sensor is strongly dependent on the properties of the active material. Lead Zirconate Titanate (PZT)-based ceramics, particularly PZT-5H and PZT-5A, are frequently selected due to their relatively high piezoelectric coefficients and strong electromechanical coupling characteristics [9-12]. In addition to PZT materials, other piezoelectric materials, including Polyvinylidene Fluoride (PVDF), Barium Titanate (BaTiO_3), and Aluminum Nitride (AlN) have been widely studied for different sensing applications [9-12].

Apart from the material properties, the structural design of the sensing element plays an essential role in determining sensor performance. Various configurations, including diaphragm and cantilever-based structures, are used to improve the sensitivity and mechanical response [13, 14]. Recently, cylindrical piezoelectric tubes (piezotubes) have received considerable research interest due to their unique structural characteristics. Compared with planar structures, cylindrical geometries provide better compatibility with fluidic systems and enable pressure loading from different directions. The symmetric deformation behavior of the tube structure allows effective conversion of radial mechanical stress into electrical output, making it suitable for both internal and external pressure sensing applications [9]. However, the output voltage and sensitivity of piezotube-based sensors are highly dependent on structural parameters, including wall thickness, inner and

outer radius, and tube height. Therefore, it is necessary to investigate the material properties and geometric parameters to optimize the performance of piezoelectric tube sensors.

1.4. Simulation framework and study objectives

The optimization of MEMS sensor structures through experimental fabrication alone often requires considerable time and cost, especially when multiple material and geometric parameters need to be evaluated simultaneously. Therefore, numerical simulation methods have become an important approach for analyzing and improving the device performance. COMSOL Multiphysics provides a Finite Element Analysis (FEA) tool capable of solving coupled physical problems involving mechanical deformation and electrical response [1, 13]. For piezoelectric devices, the combination of the "Solid Mechanics" and "Electrostatics" modules enables the simulation of stress distribution, structural deformation, and generated electric potential caused by external mechanical load. Such simulations allow researchers to evaluate different designs before fabrication, reducing the development cost and improving the design efficiency [2, 15].

In this work, a comparative simulation study of a cylindrical piezoelectric pressure sensor is conducted using COMSOL Multiphysics 5.6. The effects of different piezoelectric materials, including PZT-5H, PZT-5A, PVDF, BaTiO₃, and AlN, are investigated by analyzing their influence on displacement and induced electric potential under applied pressure. In addition, the effects of key structural parameters, particularly tube wall thickness and height, are examined to determine the most suitable geometric configuration. The purpose of this study is to establish a quantitative understanding of material selection and structural optimization for piezotube-based pressure sensors, providing a reference for future applications in biomedical monitoring, automotive sensing, and energy harvesting [16].

2. COMSOL simulation of the piezoelectric pressure sensor

In this study, COMSOL Multiphysics 5.6 was employed to establish a finite-element model of a cylindrical piezoelectric pressure sensor. The model incorporated the solid mechanics, electrostatics, and piezoelectric effect interfaces to investigate the coupled electromechanical behavior of the sensor under different loading conditions. The simulation results were used to compare the piezoelectric response of different materials and to evaluate the influence of the wall thickness of the PVDF-based piezoelectric sensor on its performance.

2.1. Model geometry construction

Considering the rotational symmetry of the cylindrical sensor, a Two-Dimensional (2D) axisymmetric model was adopted to reduce the computational cost while retaining the main characteristics of the Three-Dimensional (3D) structure. In this model, the cross-section of the cylindrical sensor is shown in Figure 1.

Two geometric configurations were defined for different simulation objectives. For the material comparison and inverse piezoelectric effect analysis, the inner radius, outer radius, and total height were set to 175 μm , 225 μm , and 1,000 μm , corresponding to a wall thickness of 50 μm . For the structural optimization study of the PVDF-based sensor, the inner radius was kept constant at 175 μm , while the wall thickness was varied from 50 μm to 300 μm . Six thickness values, namely 50, 100, 150, 200, 250, and 300 μm , were investigated to examine the effect of wall thickness on the mechanical and electrical responses of the sensor.

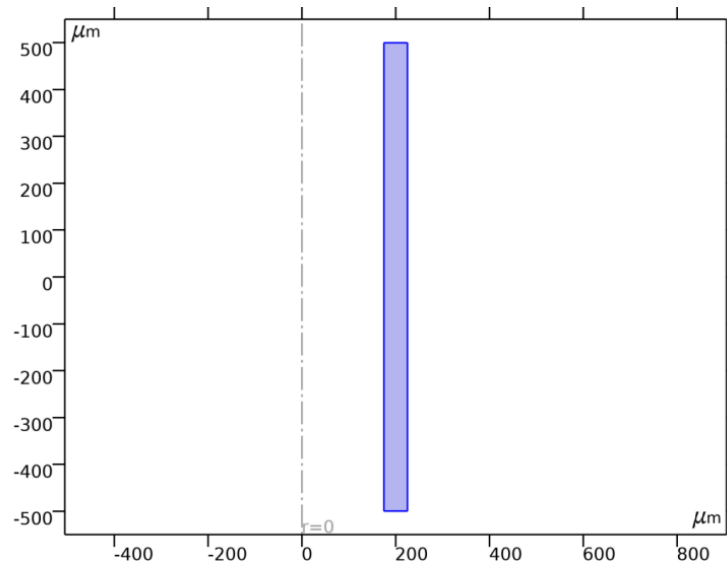


Figure 1. 2D axisymmetric geometry of the cylindrical piezoelectric pressure sensor

2.2. Material selection

Five representative piezoelectric materials were selected for comparison, namely PZT-5H, PZT-5A, PVDF, Barium Titanate (BaTiO_3), and Aluminum Nitride (AlN). The purpose of this comparison was to examine the influence of material properties on both the direct and inverse piezoelectric effects.

Since the required material data were not directly available for all five materials in the default COMSOL material library, custom material nodes were used to define the material properties. The elasticity matrix, coupling matrix, relative permittivity, and density were specified for each material. These parameters were then used in the piezoelectric effect interface to calculate the coupled mechanical and electrical response.

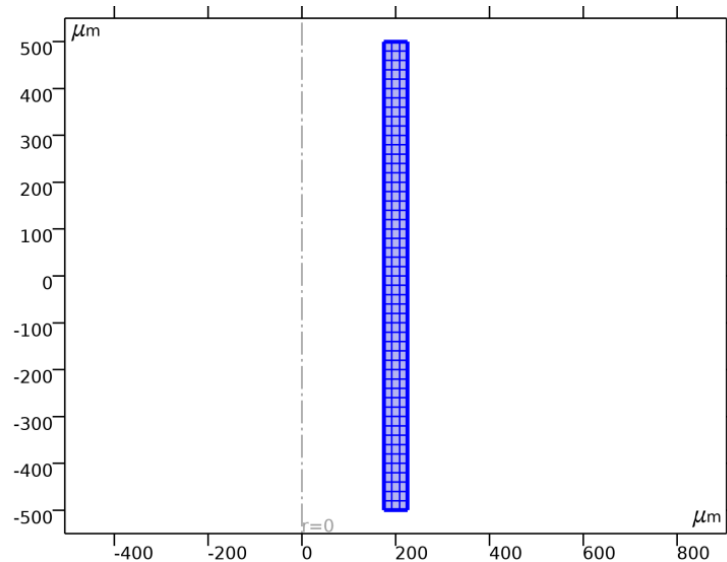


Figure 2. Mapped mesh of the 2D axisymmetric piezoelectric pressure sensor model

The polarization direction was also defined according to the geometry of the sensor. Since the internal pressure mainly induces deformation in the radial direction, the polarization axis of the piezoelectric material

was set along the radial direction rather than the axial direction. In COMSOL, a user-defined cylindrical system was assigned to the piezoelectric material node, and the polarization axis was specified as R. This setting allows the piezoelectric coupling to be described consistently with the radial deformation of the cylindrical structure. A mapped mesh was subsequently applied to the computational domain, as shown in Figure 2.

2.3. Boundary conditions

For the mechanical boundary conditions, roller constraints were applied to the top and bottom boundaries. These constraints restrict the displacement in the axial direction while allowing radial deformation of the cylindrical wall under internal pressure. The pressure load was applied to the left vertical boundary, which represents the inner wall of the sensor. A uniformly distributed boundary load was used, with the pressure directed outward along the radial direction.

For the electrical boundary conditions, the inner wall was assigned as ground with a potential of 0 V, while the outer wall was defined as a terminal. In the direct piezoelectric simulations, the outer terminal was configured as a floating potential to obtain the open-circuit voltage generated by the pressure-induced deformation. For the inverse piezoelectric simulations, the terminal condition was changed to voltage, and a potential difference of 1 V was applied between the inner and outer electrodes.

3. Results and discussion

Based on the simulation model and boundary conditions described above, three groups of numerical experiments were conducted. The first experiment compares the pressure-induced voltage response of five piezoelectric materials. The second investigates the effect of the wall thickness of the PVDF-based sensor on the stress distribution and output voltage. The third evaluates the inverse piezoelectric displacement response under an applied electrical potential.

3.1. Output voltage comparison of five piezoelectric materials

The first group of simulations was performed to compare the output voltage of the five selected piezoelectric materials under different internal pressures. The reference geometry described in Section 2.1 was used, and the internal pressure was varied from 2 MPa to 10 MPa.

Figure 3 presents the relationship between the applied pressure and the output voltage for the five materials. All five materials show an approximately linear increase in output voltage with increasing pressure, which is consistent with the linear piezoelectric constitutive relationship adopted in the model. At an internal pressure of 10 MPa, as shown in Table 1, the output voltages obtained for PZT-5H, PZT-5A, PVDF, BaTiO₃, and AlN are 28.07 V, 35.37 V, 262.46 V, 68.50 V, and 61.64 V, respectively.

Among the five materials, PVDF exhibits the highest output voltage. The corresponding electric potential distribution is shown in Figure 4. The difference in output voltage can be mainly attributed to the dielectric properties of the material. The relative permittivity of PVDF is typically in the range of 8–12, whereas PZT ceramics have much higher relative permittivity values, generally ranging from 1,200 to 3,400. Under comparable charge generation, the lower dielectric permittivity of PVDF leads to a lower equivalent capacitance.

The relationship between electric charge and potential difference can be expressed as

$$V = \frac{Q}{C} \quad (1)$$

Therefore, for a similar amount of generated charge, a smaller capacitance results in a larger potential difference between the electrodes. This provides an explanation for the considerably higher voltage output obtained from the PVDF sensor compared with other materials.

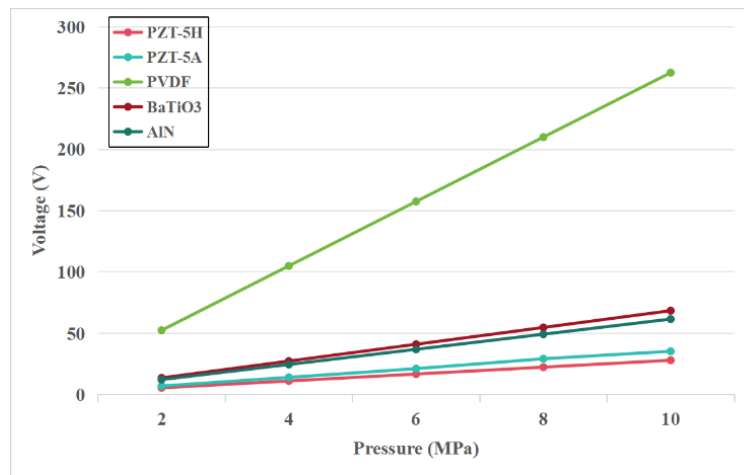


Figure 3. Output voltage as a function of applied internal pressure for the five piezoelectric materials

Table 1. Output voltage response (unit: V) of various piezoelectric materials under increasing input pressure (unit: MPa)

Input pressure	Piezoelectric material				
	PZT-5H	PZT-5A	PVDF	BaTiO3	AlN
2	5.62	7.07	52.49	13.70	12.33
4	11.23	14.15	104.99	27.40	24.65
6	16.84	21.22	157.48	41.10	36.98
8	22.46	29.30	209.97	54.80	49.31
10	28.07	35.37	262.46	68.50	61.64

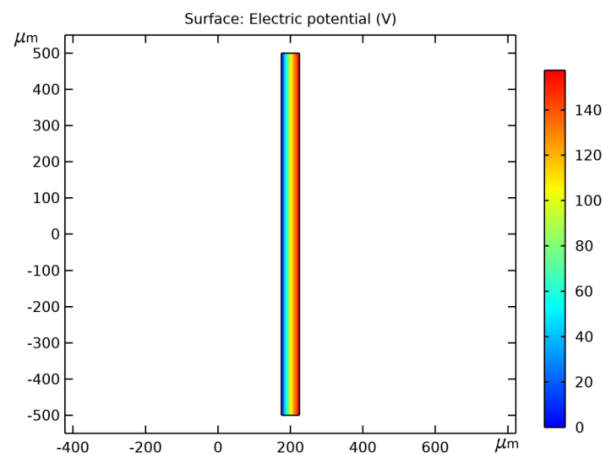


Figure 4. 2D electric potential distribution of the piezoelectric pressure sensor under internal pressure

3.2. Detailed mechanism analysis of PVDF wall thickness variation

The second group of simulations focused on the effect of wall thickness on the performance of the PVDF sensor. The inner radius was maintained at 175 μm , while the internal pressure was fixed at 10 MPa. The wall thickness was varied from 50 μm to 300 μm .

The simulation results show that the maximum von Mises stress decreases continuously with increasing wall thickness, whereas the output voltage shows the opposite trend. Figure 5 compares the von Mises stress distributions for wall thicknesses of 50 μm and 300 μm , and the wall thickness versus output voltage and pressure at 10 MPa is listed in Table 2.

From the mechanical perspective, the decrease in stress is associated with the increased stiffness of the thicker cylindrical wall. As the wall thickness increases, the stress generated by the same internal pressure is reduced. In the present simulations, the maximum von Mises stress decreased from 45.5 MPa at a wall thickness of 50 μm to 24.9 MPa at 300 μm . The reduction in mechanical stress would therefore lead to a decrease in the piezoelectric charge generated by the structure.

The electrical response is also affected by the change in the equivalent capacitance of the sensor. The cylindrical structure can be approximated as a coaxial capacitor, for which the capacitance can be expressed as

$$C = \frac{2\pi\epsilon L}{\ln(b/a)} \quad (2)$$

where a and b are the inner and outer radii, respectively, and L is the length of the cylindrical structure. With the inner radius fixed, an increase in wall thickness corresponds to an increase in the outer radius, resulting in a decrease in the capacitance.

Therefore, two effects occur simultaneously as the wall becomes thicker. The generated piezoelectric charge decreases because of the lower mechanical stress, while the equivalent capacitance also decreases. The simulation results indicate that the reduction in capacitance has a stronger influence on the voltage response. As shown in Table 2, the output voltage increases from 262.64 V at a wall thickness of 50 μm to 458.83 V at 300 μm .

This trend is particularly evident in PVDF due to its low dielectric permittivity. The relatively small capacitance makes the voltage response more sensitive to the change in the sensor geometry, and the decrease in capacitance with increasing wall thickness exceeds the effect of the reduction in generated charge.

Table 2. PVDF tube wall thickness versus output voltage and maximum von Mises stress at 10 MPa. (Unit: wall thickness in μm , output voltage in V, pressure in N/m^2)

PVDF tube wall thickness	Output voltage	Maximum von Mises stress
50	262.64	4.55E7
100	327.25	3.18E7
150	374.93	2.79E7
200	410.61	2.62E7
250	437.78	2.54E7
300	458.83	2.49E7

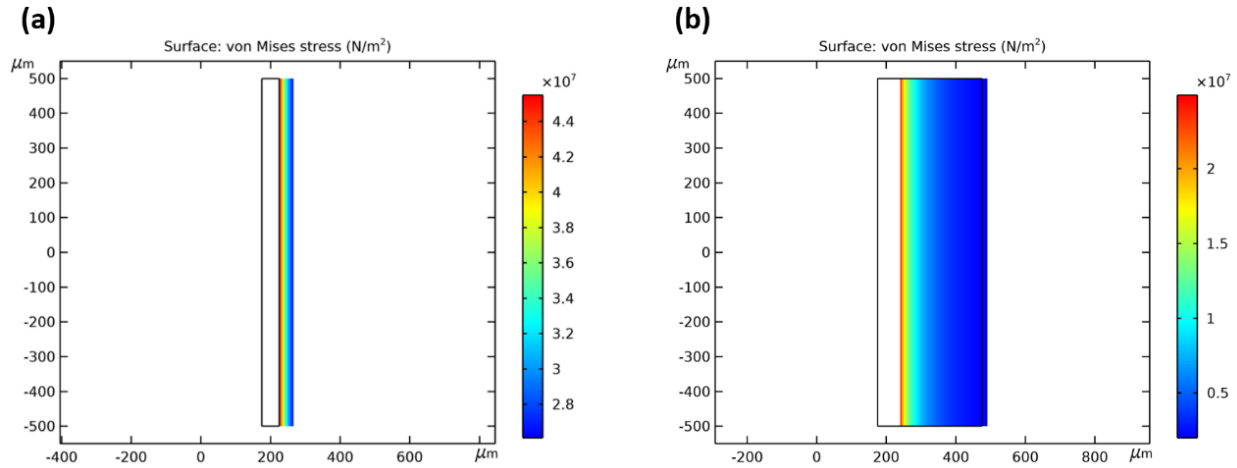


Figure 5. Comparison of the 2D von Mises stress distributions for the PVDF-based sensors with wall thicknesses of (a) 50 μm and (b) 300 μm

3.3. Inverse piezoelectric effect and micro-actuation capability

The third group of simulations investigated the inverse piezoelectric response of the five selected materials. No external mechanical pressure was applied in this experiment. Instead, a potential difference of 1 V was imposed between the inner and outer electrodes, and the resulting radial displacement was obtained.

The simulated radial displacement distribution is presented in Figure 6. The calculated displacement values are 1.62 nm for PZT-5H, 1.06 nm for PZT-5A, 0.04 nm for PVDF, 0.021 nm for BaTiO₃, and 0.012 nm for AlN. A direct comparison of the displacement response under the same 1 V excitation is also shown in Figure 6.

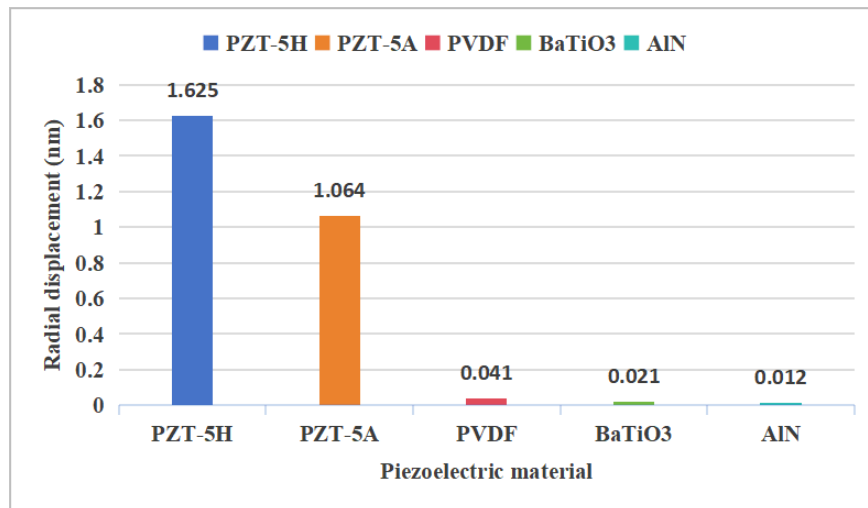


Figure 6. Radial displacement response of various piezoelectric materials under 1 V electrical excitation (Unit: displacement in nm)

The results reveal clear differences in the inverse piezoelectric response of the five materials. PZT-5H produces the largest radial displacement, reaching 1.62 nm under a 1 V excitation, corresponding to an actuation response of 1.62 nm/V. This relatively large displacement indicates a stronger electromechanical

response under the applied electric field. In contrast, PVDF produces only 0.04 nm of radial displacement under the same excitation condition.

Considering the results of these experiments together, different advantages can be identified for pressure sensing and micro-actuation. PVDF exhibits the highest pressure-induced voltage output in Experiment 1, indicating its potential for high-sensitivity pressure sensing. PZT-5H, on the other hand, produces the largest displacement under electrical excitation and is therefore more suitable for applications involving micro-actuation or displacement control. The simulation results provide a basis for selecting an appropriate piezoelectric material according to the specific requirements of sensing or actuation applications.

4. Conclusion and future work

In this study, a comparative simulation of a cylindrical piezoelectric pressure sensor was carried out using COMSOL Multiphysics. A 2D axisymmetric model was established to evaluate the electromechanical performance of five piezoelectric materials. The results demonstrate that PVDF generates the highest output voltage, reaching up to 262.46 V at 10 MPa, which is mainly attributed to its low relative permittivity and the resultant small equivalent capacitance. The structural optimization of the PVDF-based sensor shows that increasing the wall thickness reduces the mechanical stress. Meanwhile, it significantly increases the output voltage because the capacitance reduction dominates over the stress reduction. Additionally, the investigation of the inverse piezoelectric effect reveals that PZT-5H produces the largest radial displacement of 1.62 nm under a 1 V electrical excitation, making it a suitable candidate for micro-actuation applications. The findings of this work provide a quantitative evaluation to select appropriate materials for high-voltage sensing and precise positioning applications.

Based on the results of this study, several directions can be explored in future work. First, the simulation results can be validated through experimental testing of the sensor prototypes. Second, the integration of piezoelectric sensors into practical application scenarios, such as wearable electronic devices and human motion monitoring, can be further investigated. Third, the operating temperature effect on the piezoelectric coefficient can be incorporated into the model to evaluate the sensor performance under thermal variations. Finally, the potential use of the PVDF-based sensor for self-powered biomedical monitoring and the PZT-based actuator for precise positioning systems can be further examined in future experimental implementations.

References

- [1] Nath, S. S., Lingaraja, D., Aravind, P., Thangavel, P., Arun Kumar, P., & Ram, G. D. (2023). Comparison of different shapes MEMS based piezo electric pressure sensor for smart devices. In *2023 5th International Conference on Smart Systems and Inventive Technology (ICSSIT)* (pp. 1–5). IEEE. <https://doi.org/10.1109/ICSSIT55814.2023.10061138>
- [2] Tulaev, A. T., Kozlov, A. S., Belyaev, J. V., Loboda, V. V., Bellavin, M. A., & Korotkov, A. S. (2024). MEMS pressure sensors design, simulation, manufacturing, interface circuits: A review. *IEEE Sensors Journal*, 24(6), 7395–7405. <https://doi.org/10.1109/JSEN.2024.3358951>
- [3] Yuan, W. (2017). Development and application of high-end aerospace MEMS. *Frontiers of Mechanical Engineering*, 12(4), 567–573. <https://doi.org/10.1007/s11465-017-0424-3>
- [4] Li, F., Shen, T., Wang, C., Zhang, Y., Qi, J., & Zhang, H. (2020). Recent advances in strain-induced piezoelectric and piezoresistive effect-engineered 2D semiconductors for adaptive electronics and optoelectronics. *Nano-Micro Letters*, 12, 106. <https://doi.org/10.1007/s40820-020-00439-9>

- [5] Ruth, S. R. A., Feig, V. R., Tran, H., & Bao, Z. (2020). Microengineering pressure sensor active layers for improved performance. *Advanced Functional Materials*, 30(39), 2003491. <https://doi.org/10.1002/adfm.202003491>
- [6] Farhath, M., & Samad, M. F. (2020). Design and simulation of a high sensitive stripped-shaped piezoresistive pressure sensor. *Journal of Computational Electronics*, 19(1), 310–320. <https://doi.org/10.1007/s10825-019-01429-w>
- [7] Kanekal, D., & Jindal, S. K. (2024). Optimizing piezoresistive MEMS pressure sensor on a double cross beam silicon diaphragm with statistical curve-fitting and optimization techniques. *IEEE Sensors Journal*, 24(1), 169–176. <https://doi.org/10.1109/JSEN.2023.3333348>
- [8] Kim, K., Kim, J., Jiang, X., & Kim, T. (2021). Static force measurement using piezoelectric sensors. *Journal of Sensors*, 2021, 6664200. <https://doi.org/10.1155/2021/6664200>
- [9] Meshkinzar, A., & Al-Jumaily, A. M. (2023). Cylindrical piezoelectric PZT transducers for sensing and actuation. *Sensors*, 23(6), 3042. <https://doi.org/10.3390/s23063042>
- [10] Vrtagic, S., Hoxha, M., Abdelgalil, A., Ferko, N., Abdallah, M., Potams, A., Lushi, A., Turan, H. I., & Mourched, B. (2025). Design and evaluation of a piezoelectric pressure sensor for mass detection with COMSOL and machine learning modeling. *Measurement*, 254, 117945. <https://doi.org/10.1016/j.measurement.2025.117945>
- [11] Khan, M. H., Nagar, S., & Mahato, B. (2025). Seamless integration of piezoelectric materials in MEMS technology. In *2025 5th International Conference on Advancement in Electronics & Communication Engineering (AECE)* (pp. 729–733). IEEE. <https://doi.org/10.1109/AECE67531.2025.11386612>
- [12] Covaci, C., & Gontean, A. (2020). Piezoelectric energy harvesting solutions: A review. *Sensors*, 20(12), 3512. <https://doi.org/10.3390/s20123512>
- [13] Kala, S., Panwar, V., Panwar, L., & Sharma, S. (2018). Comparative analysis of MEMS piezoelectric materials for the design of a piezotube-type pressure sensor. In R. Singh, S. Choudhury, & A. Gehlot (Eds.), *Intelligent Communication, Control and Devices, ICICCD 2017 (Vol. 624)*, pp. 1537–1549. Springer. https://doi.org/10.1007/978-981-10-5903-2_160
- [14] Liang, R., & Wang, Q.-M. (2015). High sensitivity piezoelectric sensors using flexible PZT thick-film for shock tube pressure testing. *Sensors and Actuators A: Physical*, 235, 317–327. <https://doi.org/10.1016/j.sna.2015.09.027>
- [15] Yang, Z., Zhou, S., Zu, J., & Inman, D. (2018). High-performance piezoelectric energy harvesters and their applications. *Joule*, 2(4), 642–697. <https://doi.org/10.1016/j.joule.2018.03.011>
- [16] Mangi, M. A., Elahi, H., Ali, A., Jabbar, H., Aqeel, A. B., Farrukh, A., Bibi, S., Altabey, W. A., Kouritem, S. A., & Noori, M. (2025). Applications of piezoelectric-based sensors, actuators, and energy harvesters. *Sensors and Actuators Reports*, 9, 100302. <https://doi.org/10.1016/j.snr.2025.100302>