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Original Article

Analyzing the Performance of Various Piezoelectric Materials in Transverse Mode: A Comprehensive Study

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Abstract *- Piezoelectric materials are essential to many technological applications because of their extraordinary capacity to transform mechanical energy into electrical signals and vice versa. The performance of several piezoelectric materials in transverse mode a mode in which the tangential of the induced stress is parallel to the material's surface is the main subject of this investigation. The piezoelectric materials show different output voltages in different operation modes as they possess different piezoelectric coefficients for different operation modes. In this study, the various piezoelectric materials, viz., AlN, ZnO, PZT-5A, PZT-5H, PZT-5J, and PVDF, are considered and find out which piezoelectric material produces a higher output voltage. These materials play a vital role in the development of sensors, actuators, and devices for harvesting energy. Many piezoelectric sensors, particularly those based on diaphragm, bridge, and cantilever structures, operate primarily in transverse mode. Therefore, it is essential to conduct thorough investigations or analyses to enhance the understanding of their performance and behaviour in transverse mode. In order to vary the performance of the sensors with different piezoelectric materials, a cantilever-shaped sensor is proposed in this study. A 3D model of the proposed sensor is modelled and simulated in COMSOL Multiphysics to verify the output voltages of the sensor. The results are studied by comparing the simulated output voltage for various piezoelectric materials for the applied voltage range from 0-10 kPa. It has been observed that the sensor's output is higher when the piezoelectric material has a higher voltage coefficient (g_{31}).*

Keywords *- Deflection, Operation modes, Stress, Thickness, Voltage coefficient.*

1. Introduction

The fundamental principle of piezoelectricity is based on the ability of certain crystals, ceramics and polymers to generate an electric charge in reaction to mechanical stress or deformation caused by pressure, acceleration, and vibration. The fundamentals of piezoelectric technology, as described in a number of texts and documents, focus on these three modes of operation of sensing mechanism: longitudinal, transverse, and shear. For the different operation modes, the charge coefficient (d_{xy}) has different values. The d_{xy} of the longitudinal mode, transverse mode and shear mode are represented by d_{33}, d_{31} and d_{15}, respectively. So longitudinal, transverse, and shear modes are also referred to as d_{33}, d_{31} and d_{15} modes, respectively. As the d_{xy} values vary for different operation modes of a piezoelectric material, different quantities of charges are developed on the different surfaces of the piezoelectric material. So, it is very crucial to find out the operation mode of a sensing mechanism. For a cantilever structure with a sensing material on the upper layer of the mechanical structure, the operation mode of the sensor mechanism is transverse mode [1, 2].

There are various piezoelectric materials in the form of crystals, ceramics and polymers. These materials find uses in many different industries and are essential to the development of cutting-edge technologies. Because they can transform mechanical inputs into electrical impulses, piezoelectric sensors are becoming essential in a wide range of industries, including consumer electronics, automotive, and healthcare. Actuators allow for accurate and responsive control in a variety of systems by employing piezoelectric materials. Furthermore, these materials' potential for use in energy-harvesting devices offers hope for the production of sustainable power. Therefore, the choice of suitable materials is critical in determining the effectiveness and efficiency of devices in the field of piezoelectric technology.

The present investigation explores a number of different piezoelectric materials, including Polyvinylidene Fluoride (PVDF), Aluminium Nitride (AlN), Zinc Oxide (ZnO), Lead Zirconate Titanate-5A (PZT-5A), Lead Zirconate Titanate-5H (PZT-5H), and Lead Zirconate Titanate-5J (PZT-5J).

Table 1. Properties of piezoelectric materials for this study

Properties	AlN	ZnO	PZT-5A	PZT-5H	PZT-5J	PVDF	Units
Young's Modulus	343	120	52	51	50	2.5-3.5	GPA
Poisson's Ratio	0.23	0.466	0.31	0.34	0.31	0.35	-
d_{31}	-2.0	-5.43	-320	-190	-270	32	m/Vx10^{-12}

The above piezoelectric materials are discussed in various literature and claimed that they are performing very well with high sensitivity [3-8]. Finding out which of these materials is better at producing output voltage is the main goal because it affects how piezoelectric sensors, actuators, and energy harvesting devices are made and function. The properties of the above piezoelectric materials are tabulated in Table 1.

This study specifically examines the transverse mode of operation in piezoelectric sensors. These sensors frequently use diaphragm, bridge, and cantilever structures. To maximize their usefulness, it is essential to comprehend the transverse performance properties of the selected materials. The goal of the study in starting the investigation is to provide new information that advances the knowledge of piezoelectric materials, extending the option to improved sensor and energy harvesting device capabilities.

A novel approach is presented in the form of a cantilever-shaped sensor to systematically vary the performance of the sensors across various piezoelectric materials. A platform for evaluating and contrasting the materials' dynamic reactions to transverse stresses is provided by this creative design. Through this approach, the research aims to identify the material producing the maximum output voltage as well as to clarify the complex relationship between material properties and sensor structure.

2. Analytical Model

Let us consider whether a cantilever with length (l), thickness (t) and width (b) is uniformly loaded or apply pressure in a downward direction on the top surface of the cantilever. Now, at a position (x) along the length of the cantilever, the value of x is between 0 (at the fixed end) to l (at the free end); the stress ($T(x)$) equation is given as follow [9-11]:

$$T(x) = \frac{h}{4Il}(Fl^2 + Fx^2 - 2Fxl), \tag{1}$$

Where, F is the applied force, I is the moment of inertia.

For a uniformly loaded or applied pressure on a surface, the applied force is given as follows:

$$F=PA, \tag{2}$$

Where P is the load per unit of area or applied pressure, and A is the area of the surface.

The area of the surface is given as follows:

$$A = lb, \tag{3}$$

The value of the moment of inertia is given as follows:

$$I = \frac{bh^3}{12} \tag{4}$$

Let us apply the maxima and minima conditions in eqn. 1, and by substituting the values of F and I, the maximum stress (T_{max}) and minimum stress (T_{min}) of the cantilever are found at the positions of x = 0 and x = l, respectively. Now, the values of Tmax and Tmin are given as follows:

$$T_{max} = \frac{h}{4Il}Fl^2 = \frac{3Pl^2}{h^2}, \tag{5}$$

$$T_{min} = 0, \tag{6}$$

Now let us consider a thin layer of piezoelectric sensing material with a length (lp), breath (bp) and thickness (tp) placed near the maximum stress is occurs. The electrostatic potential difference developed between the upper and lower surface of the piezoelectric material is given as follows:

$$V(x) = t_p g_{31}, \tag{7}$$

3. 3D Model for Simulation

Comsol Multiphysics is a powerful simulation software that may be used for a wide range of physical phenomena, including piezoelectric sensors. A 3D model of the cantilever-based piezoelectric sensor is developed in the Comsol Multiphysics simulator, as shown in Figure 1.

The physics setting for the simulation in Comsol Multiphysics is chosen as the piezoelectric effect, which is a combination of solid mechanics and electrostatics. In this physics setting, the initials and boundary conditions are configured for simulation. This 3D model has a sensor structure, insulator, electrodes and sensing layer. In the simulation, the sensor structure is taken as silicon (Si), the insulator as silicon-dioxide (SiO2), the electrodes as gold (Au) and the sensing material are piezoelectric materials.

The dimension of the sensor's components is tabulated in Table 2. All of the materials are allocated to the appropriate components once the 3D model has been created, according to Table 2. The physics setting's electrostatics and solid mechanics are then set up. Meshing is completed for the 3D model with a tetrahedral form and finer size once the physics parameter has been configured.

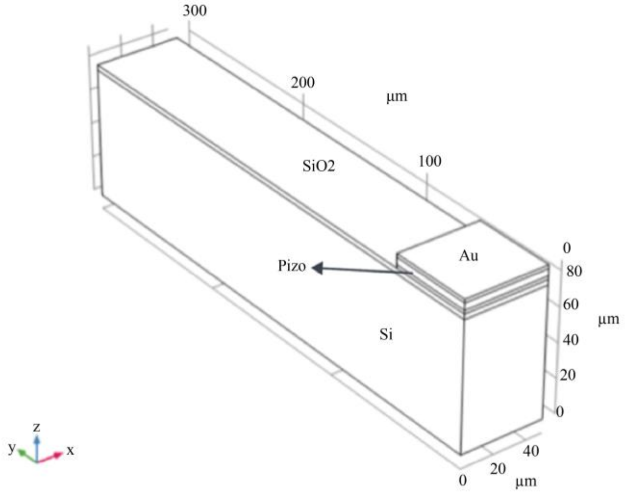

Fig. 1 3D model of the cantilever piezoelectric sensor

Table 2. Dimension of the sensor’s components

Component	Material	Length (l)	Width (b)	Height (t)
Sensor Structure	Si	300 μm	50 μm	75 μm
Insulator	SiO_2	300 μm	50 μm	3 μm
Electrodes	Au	50 μm	50 μm	2 μm
Sensing Material	Piezo Material	50 μm	50 μm	4 μm

4. Results and Discussion

In this study, different piezoelectric materials, namely AlN, ZnO, PZT-5A, PZT-5H, PZT-5J, and PVDF, are substituted one after the other over the input pressure range of 0 to 10 kPa with a step size of 1 kPa for the simulation of the 3D model of the piezoelectric sensor. The simulation's output voltage distribution and terminal voltage (potential differences between the electrodes) for the piezoelectric sensors are displayed in Figures 2, 4, 6, 8, 10 and 12 at an applied pressure of 10 kPa.

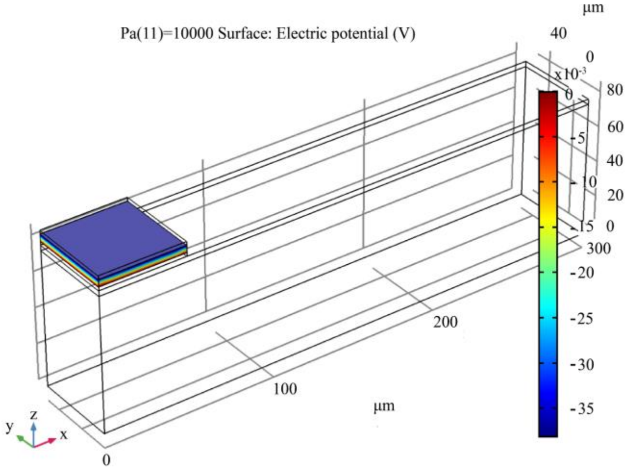

Fig. 2 Potential voltage distribution on the superficial of AlN

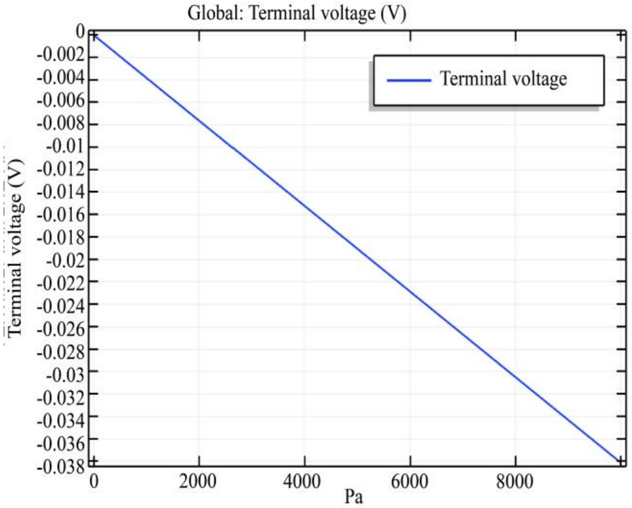

Fig. 3 Changed in potential on the superficial of AlN for applied pressure 0-10kPa

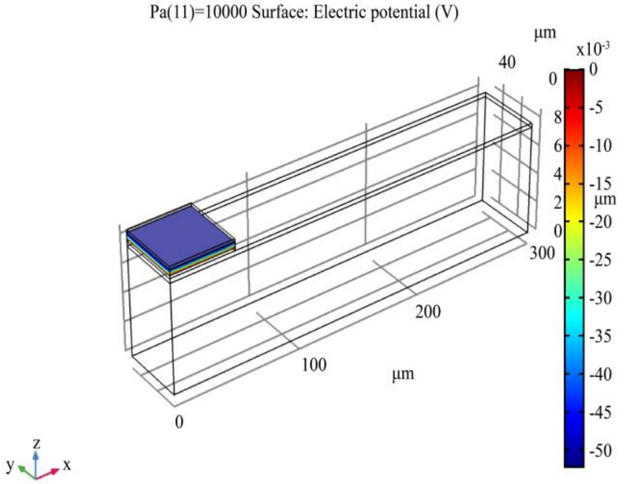

Fig. 4 Potential voltage distribution on the surface of ZnO piezoelectric material

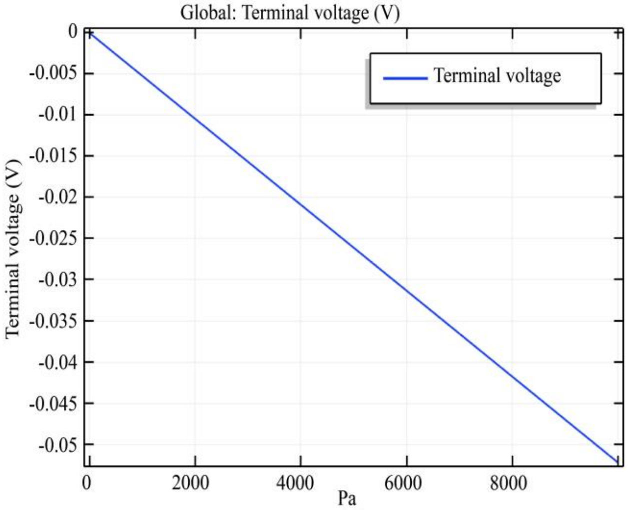

Fig. 5 Changed in potential on the superficial of ZnO for applied pressure 0-10kPa

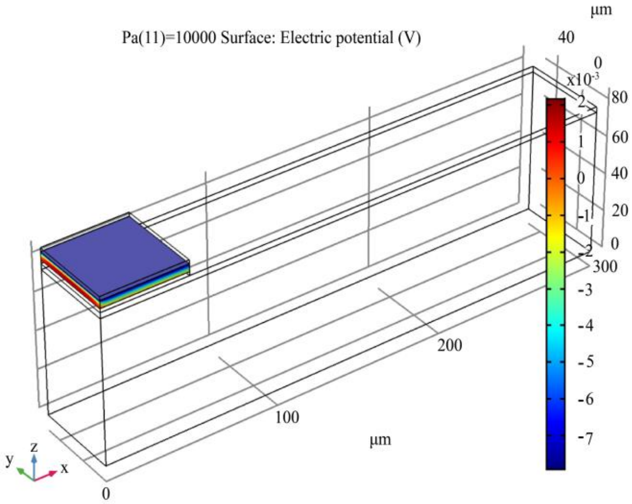

Fig. 6 Potential voltage distribution on the superficial of PZT-5A

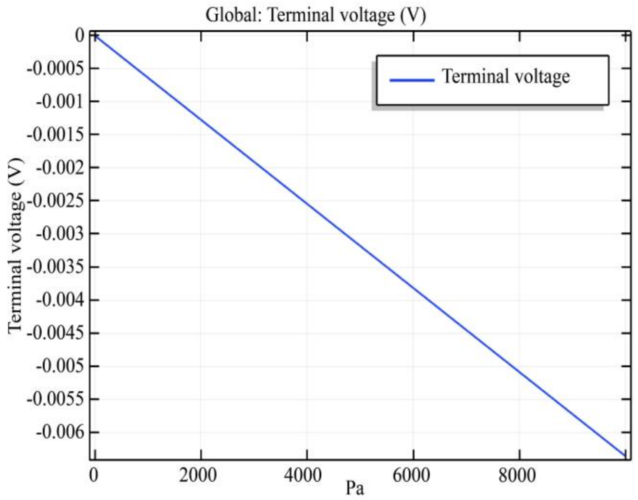

Fig. 9 Changed in potential on the superficial of PZT-5H for applied pressure 0-10kPa

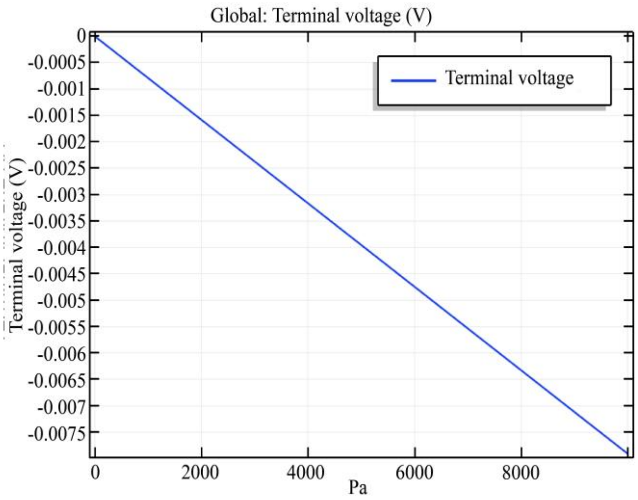

Fig. 7 Changed in potential on the superficial of PZT-5A for applied pressure 0-10kPa

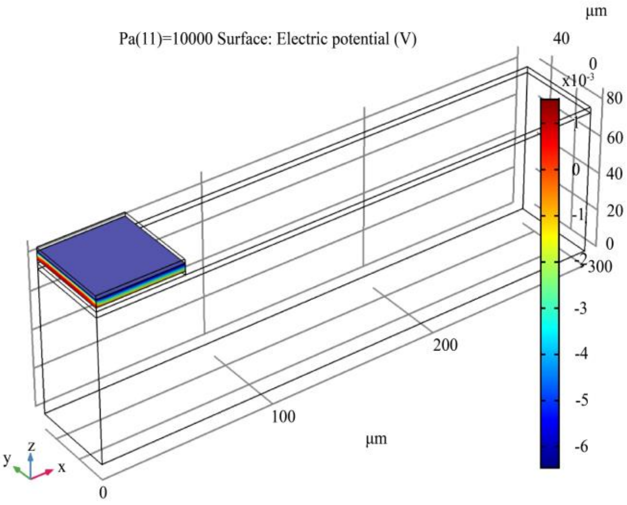

Fig. 10 Potential voltage distribution on the superficial of PZT-5J

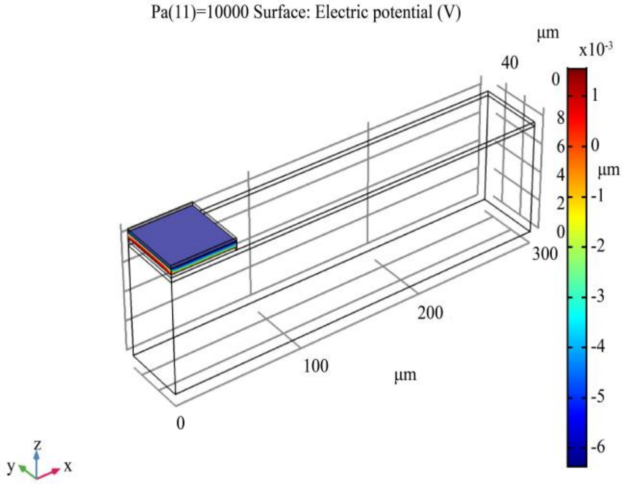

Fig. 8 Potential voltage distribution on the superficial of PZT-5H

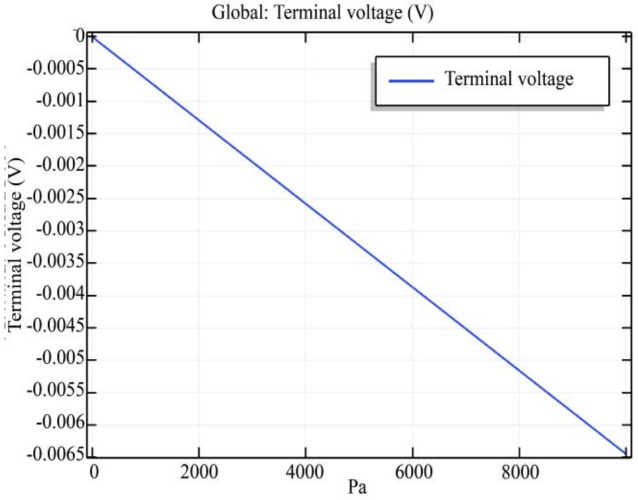

Fig. 11 Changed in potential on the superficial of PZT-5J for applied pressure 0-10kPa

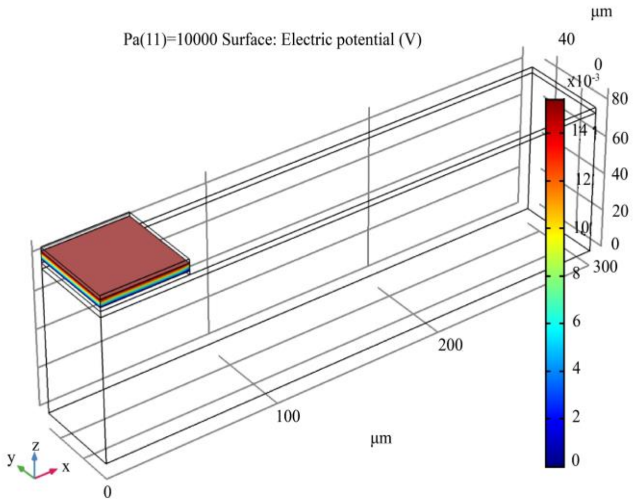

Fig. 12 Potential voltage distribution on the superficial of PZT-5J

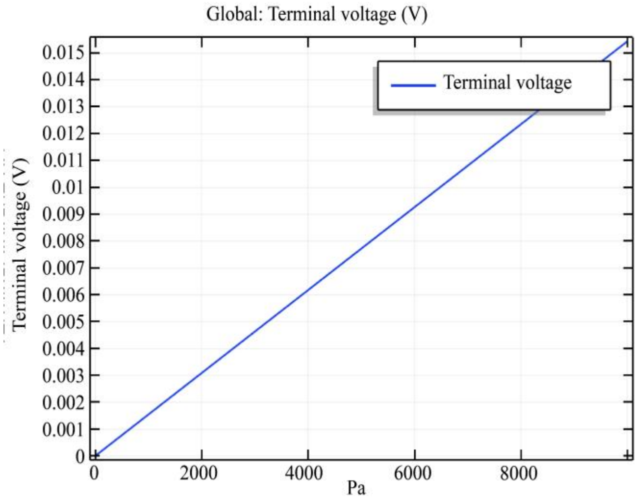

Fig. 13 Changed in potential on the superficial of PVDF for applied pressure 0-10kPa

From Figures 2 to 13, it is observed that the AlN, ZnO, PZT-5A, PZT-5H and PZT-5J generate negative voltage, while PVDF generates positive voltage on the upper surface of the piezoelectric sensing material where tensile stress. Further, it is also observed that ZnO produced the highest magnitude of voltages, but PZT-5H produced the lowest magnitude of voltages.

5. Conclusion

As a result, the thorough examination of several different piezoelectric materials, including AlN, ZnO, PZT-5A, PZT-5H, PZT-5J, and PVDF, highlights the range of voltage responses seen on the upper surfaces of the piezoelectric sensing materials under tensile stress. The findings illustrated in Figures 2 through 7 demonstrate a regular pattern in which PVDF displays positive voltage and AlN, ZnO, PZT-5A, PZT-5H, and PZT-5J produce negative voltages. Moreover, the investigation demonstrates significant differences in the amplitude of voltages generated by various materials, where ZnO exhibits the greatest values and PZT-5H the lowest.

The simulation, run across an input pressure range of 0 to 10 kPa, with a step size of 1 kPa, offered a complete investigation of the 3D model of the piezoelectric sensor. At an applied pressure of 10 kPa, the voltage distribution and terminal voltage that occur, as shown in Figures 2 to 7, provide important information on the properties of each material. This methodical investigation advances knowledge of the response of various piezoelectric materials to mechanical stimuli and facilitates the creation of sensors that are best suited for certain uses.

The results offered here provide a foundation for further investigation and growth in the field of piezoelectric sensing, with possible ramifications for improvements in sensor technology and associated uses.

References

[1] O. Ben Dali et al., “Cantilever-Based Ferroelectret Energy Harvesting,” *Applied Physics Letter*, vol. 116, no. 24, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[2] Rob Carter, and Richard Kensley, Introduction to Piezoelectric Transducer, Piezo. [Online]. Available: https://piezo.com/pages/piezo-education

[3] Hiro Han et al., “PVDF Film Micro Fabrication for the Robotics Skin Sensor Having Flexibility and High Sensitivity,” *Fifth International Conference on Sensing Technology*, Palmerston North, New Zealand, pp. 603-606, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[4] Sherif A. Ghamry et al., “Analysis Sensing Voltage of Lead Zirconate Titanate (PZT) Piezoelectric MEMS Gyroscope and Comparing with Aluminum Nitride (AlN), Zinc Oxide (ZnO) and Barium Titanate ($BaTiO_3$),” *International Telecommunications Conference*, Alexandria, Egypt, pp. 674-677, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[5] K. Prashanthi et al., “A Novel Photoplastic Piezoelectric Nanocomposite for MEMS Applications,” *Journal of Microelectromechanical Systems*, vol. 21, no. 2, pp. 259-261, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[6] Md. Moniruzzaman Likhon et al., “Characterizing Piezoelectric Properties of PZT-4, PZT-5A, PZT-5J, PZT-7A and Lithium Tantalate Material-based Transducers,” *International Conference on Green Energy, Computing and Sustainable Technology*, Miri, Malaysia, pp. 1-4, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] Ho-Wuk Kim, Huaiyu Wu, and Xiaoning Jiang, “Miniaturized Sub-Megahertz Focused Ultrasound Transducer Composed of Multilayer Hard PZT Ceramics,” *IEEE International Ultrasonics Symposium*, Kobe, Japan, pp. 1-4, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[8] Ling-Jie Li et al., “Research on the Decoupling Method of Structure Strain Measurement Based on PVDF Sensors Array,” *Symposium on Piezoelectricity, Acoustic Waves, and Device Applications*, Xi'an, China, pp. 433-437, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[9] Stephen P. Timoshenko, and S. Woinowsky-Krieger, *Theory of Plates and Shells*, 2nd ed., New York: McGraw Hill, pp. 1-580, 1959. [Google Scholar] [Publisher Link]

[10] Ansel C. Ugural, *Plates and Shells: Theory and Analysis*, 4th ed., Boca Raton, London, New York, pp. 1-618, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[11] Minhang Bao, *Analysis and Design Principles of MEMS Devices*, 1st ed., Elsevier Science, 2005. [Google Scholar] [Publisher Link]