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Simulation of Piezoelectric Transducer Microphone Diaphragm Based on Different Materials

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ABSTRACT

Piezoelectric microphone which utilizes MEMS technology is a type of transducer that converts an input acoustic signal into an output electrical signal. The characteristics of the microphone diaphragm such as the diaphragm design features and the type of piezoelectric materials used will affect the performance of the microphone in terms of sensitivity. It is hard to control the stress of the diaphragm used in the MEMS transducer microphone. A modification of the diaphragm is done in this project to reduce the residual stress of the piezoelectric transducer. In addition, finite element analysis namely structural, modal and harmonic were carried out using Ansys 15.0 to simulate the mechanical and dynamic behaviour of the microphone diaphragm. Two types of diaphragm structure were designed, namely square and circular, while three types of piezoelectric material which are AlN, PZT and ZnO were used as the diaphragm material. The structural analysis findings of the diaphragm subjected to 1 Pa pressure revealed that the circular diaphragm made of AlN material exhibited the highest stress, reaching 43.05 GPa, surpassing the stresses observed in the other two materials. On the contrary, the square diaphragm composed of PZT material demonstrated the lowest stress, with only 1.55 GPa. In terms of resonance frequency, the circular AlN diaphragm achieved the highest resonant frequency, reaching 449.84 kHz, whereas the square PZT diaphragm exhibited the lowest frequency at 200.25 kHz. In general, the circular diaphragm design consistently yielded higher first resonant frequencies compared to the square design.The results show that the circular diaphragm with AlN piezoelectric materials is the ideal diaphragm in the microphone because of the highest stress generated and the first resonant frequency. The stress is related to the sensitivity of a microphone while the high resonant frequency can lead to the better optimization of signal to noise ratio control.

Keywords: *MEMS, Piezoelectric microphone, transducer, stress, deformation*

1. INTRODUCTION

A transducer is a device that functions to convert energy from one domain into a corresponding output in another form of energy. A microphone is a one of the types of transducers that converts an input acoustic signal into an output electrical signal. In general, microphones use the concept of pressure sensor by detecting the pressures which are generated by sound waves. In essence, microphones are pressure sensors that pick up airborne pressures caused by sound that are 10 orders of magnitude lower than the surrounding pressure [1]. In order to maximize sensitivity, a microphone needs a diaphragm that is extremely compliant. A piezoelectric MEMS microphone is a multi-layer sensor which includes one piezoelectric layer between two electrode layers, with the sensor that has the dimensioned such that it provides a near maximized ratio of output energy to sensor area [2].

Many authors and companies have designed MEMS microphones primarily intended for audio-related applications [3-17]. One of the limitations in increasing the microphone sensitivity is due to difficulties in controlling the residual stress of the diaphragm used in the MEMS transducer microphone.

Basically, the piezoelectric microphone can be divided into two main parts in the system. The first part of a piezoelectric microphone is known as the sensing component, which is designed using MEMS technology and can be optimized through the modification of the diaphragm. The second part is the lumped element, also referred to as the circuitry design of the system, including filters and amplifiers. In the sensing component, it incorporates mechanical information, piezoelectric information, and external loads (usually pressure), while the lumped element model encompasses the acoustic and electric domains.

In the Finite Element Model (FEM) for MEMS design, simulation tools in Finite Element Analysis play an important role in optimizing MEMS sensors. Output results such as displacement, resonant frequency, and electrical potential have an impact on the performance of the piezoelectric microphone. All of these results are influenced by the MEMS design, including geometry, material stack, material properties, circuit connections, and applied pressure.

Typically, a single-crystal silicon wafer is used in the fabrication of micromachined microphones through bulk micromachining [18]. However, there are intrinsic limitations on the shape of the diaphragm due to its anisotropic etching properties [19]. As a result, many diaphragms inside the microphone are quadrangular in shape. Circular diaphragms are rarely used and fabricated due to the complexity of the fabrication process, which is still prevalent in most traditional bulk micromachining processes today. From the comparison result of the circular and square diaphragm that been fabricated from [19], the circular diaphragm overall has the better results in term of magnitude of displacement and consequently affects the sensitivity of the microphone.

In a different work Fardin and Farshi [20] conducted research and simulations on different diaphragm shapes suitable for implantable hearing aid applications. They designed diaphragms in square, hexagonal, and octagonal shapes. Using AIN materials and the COMSOL software, they simulated the results of the center diaphragm's displacement and the first resonant frequency based on the evaluated parameters and diaphragm materials.

One of the limitations in increasing the microphone sensitivity is due to difficulties in controlling the residual stress of the diaphragm used in the MEMS transducer microphone. Hence, in this paper, we aim to design and simulate MEMS piezoelectric transducer circular and square diaphragm and investigating the effects of diaphragm shapes and piezoelectric materials towards the piezoelectric microphone performance.

2. METHODS

Ansys 15.0 (student version) was used to design and simulate the piezoelectric microphone diaphragm. Figure 1 shows the cross section of the proposed diaphragm. Only the center of the diaphragm will be considered for simulation and the substrate is ignored because of the large rigidity and thickness of substrate. Force boundary conditions were applied as concentrated forces to center of the structure. Finite element analysis namely structural, modal and harmonic were carried out to simulate the mechanical and dynamic behaviour of the microphone diaphragm. The properties and dimensions of the diaphragm structure are listed in Table 1.

Mesh generation is important in the aspects of engineering simulation as there are too many cells which may result in long solver runs, and too little may cause inaccurate results. Ansys Meshing technology provides a way to balance these requirements and obtain the right mesh for each simulation in this work.

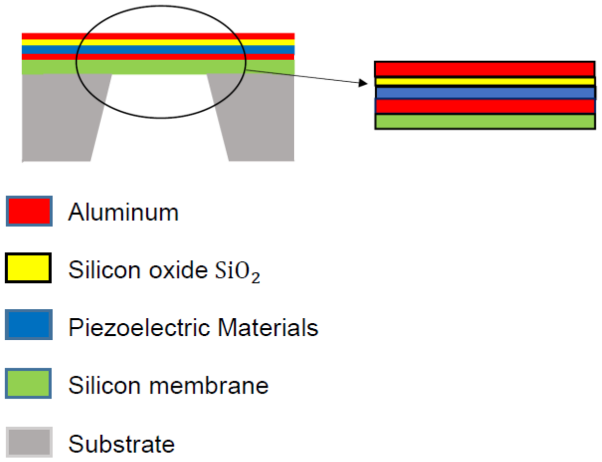

Figure 1. The cross-sectional of diaphragm transducer layer.

Each layer of the acoustic transducer layer is assigned with different materials. The layer of the diaphragm is shown in figure 1. 0.2 µm of Aluminum layer is used as the top electrode and bottom electrode as a barrier layer to prevent the diffusion between piezoelectric layer and the silicon membrane. 0.2 µm of silicon oxide acts as the protecting layer for the piezoelectric thin film. 1.0 µm of piezoelectric thin film layer is used piezoelectric material. 5.0 µm of silicon membrane layer is used as the supporting structure because of its rigidity and stiffness.

Table 2 Piezoelectric Materials Properties

Piezoelectric Materials	AlN	ZnO	PZT
Density (kg/$m3$)	3300	5676	7750
Young Modulus (GPa)	330	127	76
Stiffness constant, Cij (x 1011N/m2)			
$C11$	3.45	2.097	1.21
$C12$	1.25	1.211	0.754
$C13$	1.2	1.051	0.752
$C33$	3.95	2.109	1.11
$C44$	1.18	0.425	0.211
$C66$	1.1		
Piezoelectric constant, eij (Cm2)			
$e15$	-0.48	-0.59	12.3
$e31$ e	-0.58	-0.61	-5.4
33	1.55	1.14	15.8
Permittivity, εij (x 10−11Fm−1)			
$\varepsilon 11$	8	7.38	811.026
$\varepsilon 33$	9.5	7.83	734.88

In structural analysis, a pressure load is applied during the design process. This pressure load involves applying a constant pressure of 1 Pa to the center of the diaphragm to simulate diaphragm deformation. The structural analysis assesses not only deformation but also calculates the total stress and the stress generated in each layer. The second analysis combines modal analysis with harmonic analysis.

Table 1 Material properties and design dimension

Material	Thickness	Radius	Density (kg/m³)	Young's Modulus	Poisson Ratio
Al top electrode	0.2 μm	1000μm	2700	69 GPa	0.33
SiO2	0.2 μm		2500	73 GPa	0.17
Piezoelectric film	1.0 μm				
Al bottom electrode	0.5 μm		2700	69 Gpa	0.33
Si membrane	5 μm		2300	130 GPa	0.25

This combination of analyses is used to simulate the deformation of the diaphragm's shape at specific resonant frequencies. In modal analysis, ten vibrating modes are simulated, and the harmonic analysis covers a frequency range of 0-1 kHz.

3. RESULTS AND DISCUSSION

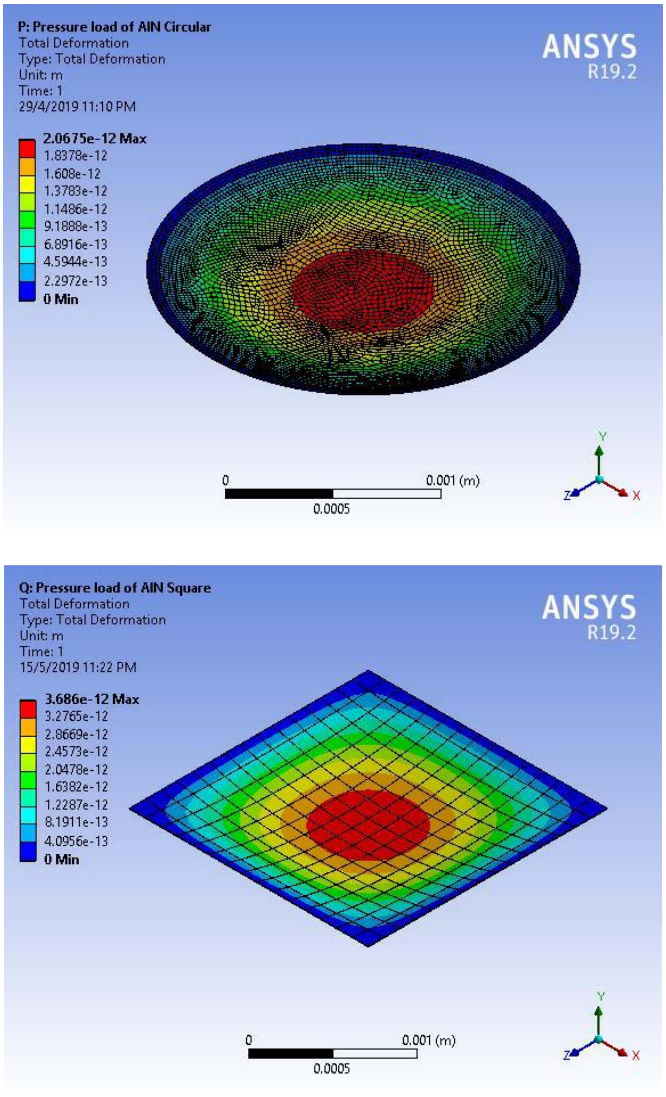

Figure 2. Deformation output for circular and square diaphragm for AlN material.

Static structural analysis was performed for different types of materials and designs. The total amount of stress generated by the diaphragm was simulated when 1 Pa of pressure is applied to the center of diaphragm.

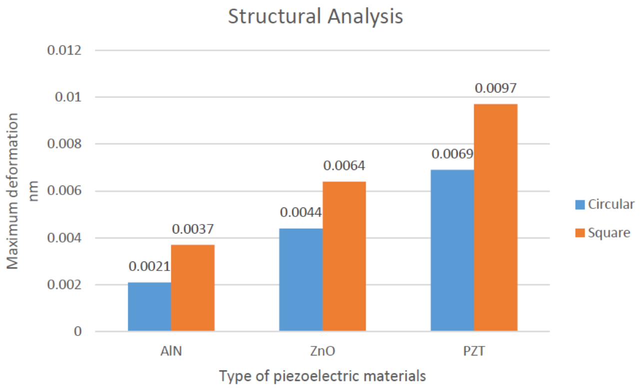

Figure 3. Maximum deformation obtained from structural analysis for different shapes and materials.

From the graph in Figure 3 of the structural analysis of the diaphragm under pressure load, the result showed that the diaphragm with PZT film material exhibited higher deformation compared to both AlN and ZnO, both in circular and square diaphragm designs. The highest deformation was obtained by the square PZT diaphragm which had the 0.0097nm of displacement and while lowest deformation was obtained by the circular AlN diaphragm which had the 0.0037nm of displacement under 1 Pa of pressure to the centre of the diaphragm. PZT materials typically have a higher piezoelectric coefficient compared to ZnO and AlN. This means they can convert electrical energy to mechanical deformation more efficiently and vice versa. Higher piezoelectric coefficients can result in larger deformations for the same applied electrical field. PZT materials tend to have a lower modulus of elasticity (Young's modulus) compared to ZnO and AlN. A lower modulus of elasticity allows the material to deform more readily under an applied force. Overall, the square design of diaphragm had the higher deformation compared to circular design. In the pressure load, the main target of the analysis is used to investigate the stiffness of the diaphragm with different materials.

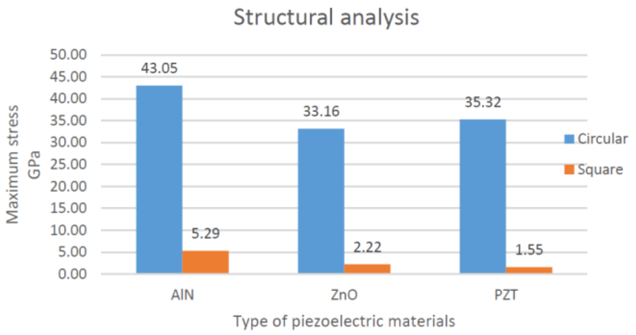

Figure 4. Maximum stress resulting from structural analysis varies depending on the specific shapes and materials involved.

The results of the structural analysis of the diaphragm under 1 Pa of pressure showed that the circular diaphragm with AlN material was generated up to 43.05GPa which was the highest stress among the three different materials, while the lowest stress was generated by the square diaphragm with PZT material which only generated 1.55GPa. Overall, the diaphragm with circular design generated the higher stress compared to the square diaphragm no matter what material was used. The stress distribution in a circular or square diaphragm depends on the specific dimensions and loading conditions. The stress in a circular diaphragm is highest at the center and decreases linearly with radial distance. The stress distribution is more uniform compared to a square diaphragm, as the entire circular surface is subjected to the pressure load. The stress in a square diaphragm is highest at the center of each side and decreases linearly towards the corners.

In modal analysis, the main purpose is to determine the natural frequency of the design. The diaphragm vibrates at specific frequencies due to the stiffness and characteristics based on the different types of materials used in the design. The modal analysis relies on two important elements: eigenvalues and eigenvectors. Eigenvalues represent the natural frequencies of a system, while eigenvectors represent the mode shapes vibrating at a given natural frequency. The first ten vibrational modes have been analyzed for each diaphragm design using different materials. From the graph results of the modal analysis of the diaphragm in mode 1 condition, the result showed that the diaphragm with AlN film materials had the higher resonant frequency compared to ZnO and also PZT materials in the circular design as well as in square design of diaphragm. The highest resonant frequency was obtained by the circular AlN diaphragm which had the 449.84kHZ of resonant frequency while the lowest frequency was obtained by the square PZT diaphragm which had only 200.25kHz. Overall, the circular design of diaphragm had the higher first resonant frequency compared to square design.

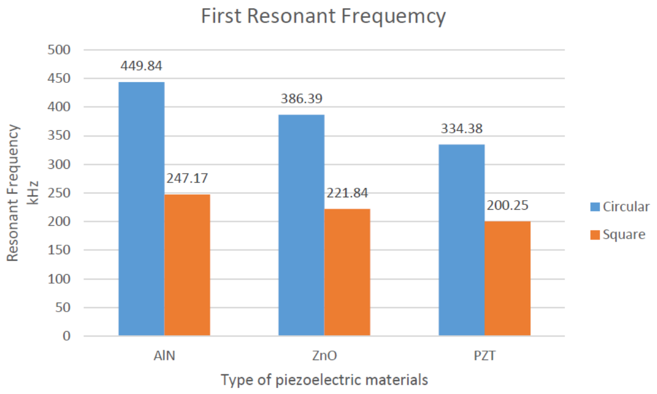

Figure 5. Result of first resonant frequency from modal analysis.

The higher the first resonant frequency implied that the more stiffness of the diaphragm and it may decrease the sensing function of the diaphragm as a pressure sensor. Aluminum Nitride (AlN) generally has a higher elastic modulus compared to PZT and ZnO. Elastic modulus is a measure of a material's stiffness. Higher stiffness tends to result in higher resonant frequencies. The density of a material also affects its resonant frequency. Lighter materials, all else being equal, tend to have higher resonant frequencies. Aluminum Nitride has a relatively low density compared to PZT, contributing to its higher resonant frequency. PZT has a higher density compared to AlN, and this contributes to a lower resonant frequency.

After the modal analysis has been done, the natural frequencies were obtained, and the harmonic analysis used to determine the system response to the oscillating input. In the model analysis, the first resonant frequency is known as the ideal mode to generate sound output due to the symmetrical up and down of the diaphragm. 0-1kHz of frequency range and 1 Pa of pressure were used in the harmonic analysis because this range fell between the first resonant frequency that obtained from the modal analysis.

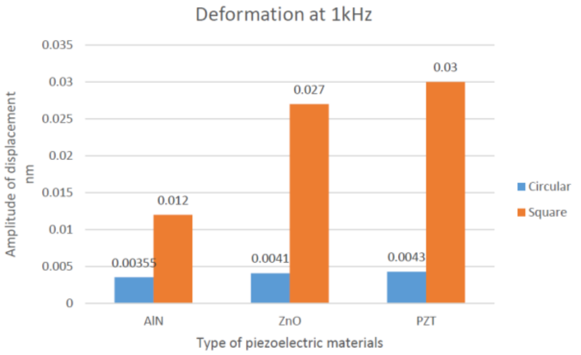

Figure 6. The outcome of deformation resulting from harmonic analysis.

The result showed that the diaphragm with PZT film materials had higher deformation compared to AlN and also ZnO in the circular design as well as in square design of diaphragm. The highest deformation was obtained by the square PZT diaphragm which had the 0.03nm of displacement and while lowest deformation was obtained by the circular AlN diaphragm which had the 0.00355nm of displacement under 1 Pa of pressure to the centre of the diaphragm. Overall, the square design of diaphragm had higher deformation compared to circular design. All the harmonic analysis is made based on the deformation of mode 1 which is obtained from the modal analysis. This study focuses on circular and square diaphragm structures due to their simplicity, common usage in traditional microphone designs, and ease of analysis. Circular and square shapes offer simplicity and symmetry, making them easier to manufacture and analyze compared to more complex geometries. These shapes often result in a more uniform stress distribution across the diaphragm, which can be advantageous for achieving consistent microphone performance.

4. CONCLUSION

In this project, both static and dynamic analyses were conducted to investigate their impact on the performance of a piezoelectric microphone. Regarding the static analysis results, it was observed that the circular diaphragm exhibited lower deformation compared to the square diaphragm. In terms of stress, the circular diaphragm generated higher stress levels when compared to the square diaphragm. Among the three materials used in this project, AlN with a circular design proved to be the ideal choice in terms of the sensitivity of the piezoelectric microphone, primarily due to the uniform stress distribution it offered. Moving on to the dynamic analysis, the first resonant frequencies were simulated in the results. Higher first resonant frequencies are advantageous as they contribute to a better signal-to-noise ratio for the piezoelectric microphone based on optimization parameters. Among the various designs and materials, the AlN circular diaphragm achieved the highest resonant frequency. In conclusion, the simulation results obtained from ANSYS indicate that the circular diaphragm made of AlN piezoelectric material is the ideal design for the piezoelectric microphone based on the analyzed factors.

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