Modeling and Theoretical Characterization of Circular pMUT for Immersion Applications

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Abstract*-This paper reported modeling and theoretical characterization of circular piezoelectric micromachined ultrasonic transducer (pMUT) for immersion applications. Zinc oxide (ZnO) was employed as piezo active material and nickel aluminum bronze alloy UNS C63000 ($CuAl_{10}Ni_5Fe_4$) also known as 'sea bronze', was introduced as electrodes. First, virtual fabrication process was carried out within software environment to form a pMUT model. Then, resonance frequency of the model was finalized and fine tuned by manipulating its structural parameters which are diaphragm diameter and piezo active layer thickness. Next, receiving and transmitting responses were estimated using finite element approach through the combination of piezoelectric analysis and modal analysis. From these analyses, the pMUT model having a resonance frequency of 40.82 kHz was successfully modeled. Transmitting response was estimated at 137 dB (re 1 µPa/V) at 41 kHz on the surface of the transducer while the receiving response was estimated at - 93 dB (re 1 V/µPa) at 38 kHz of frequency. Virtual fabrication process and finite element analysis for model performances estimation have proved to reduce the development time. From the comparison made, the usage of sea bronze and ZnO film replacing conventional gold, platinum and lead zirconate titanate (PZT) were proven to deliver exceptional performances with better durability. However, device fabrication is essential in order to validate the findings and this will be included in our future works. Furthermore, the model needs to be extended so that the value of acoustic impedance within the device can be estimated.

I. INTRODUCTION

Micromachined underwater transducers for underwater sensing applications have gain popularity recently and the summary on this expanding technology have been discussed extensively for the last few years [1-3]. Basic pMUT structure was usually formed by a layer of piezo active layer sandwiched between two electrodes. However, the present of additional layer forming a diaphragm seems to be essential for stronger structure and improved bandwidth [4-5].Piezo active layer is the key in sensing mechanism where the electrostriction process occur [6]. This work utilized zinc oxide (ZnO) as piezo active material. It was one of the earliest piezo materials being discovered and yet still gaining popularity for its superior piezoelectricity [7] and cheaper method of film deposition compare to other piezo-active thin films [8]. Wide selections of materials are available today to be used as connector and electrodes in micro fabricated devices such as platinum, gold, copper and titanium, each one offers different performance. In this study, sea bronze alloy ($CuAl_{10}Ni_5Fe_4$) was employed as electrodes as an effort to increase impedance match between piezo active layer and load since most of the housing and encapsulation material also based on this new breed of alloy. Sea bronze also capable to endure longer in extreme corrosion environment and has been widely used in marine applications replacing conventional stainless steel and carry sufficient conductivity value of 5.21×10^{12} pS/µm. On other occasion, the usage of polymer in diaphragm type acoustic sensors has become a common practice and well known as it simplified bonding of two wafer layers at relatively low temperature [9]. In this work, Cytop was selected as adhesive layer between electroded ZnO wafer and silicon on insulator (SOI) wafer. The structure of the pMUT is shown in Fig. 1. Manipulating structural parameters to obtain desired performance have been successfully demonstrated elsewhere for rectangular shaped pMUT. Besides resonance frequency, electromechanical coupling coefficient and acoustic impedance have been proven to be affected by structural parameter changes [4-6]. Furthermore, top electrode diameter of pMUT also found to give an effect on maximum diaphragm deflection [10]. In this work, diameter of diaphragm was manipulated as well as the thickness of ZnO layer for resonance frequency tuning. Once the model dimension is finalized, further investigations were carried out on the model to study the effect of sea bronze on device overall performance.

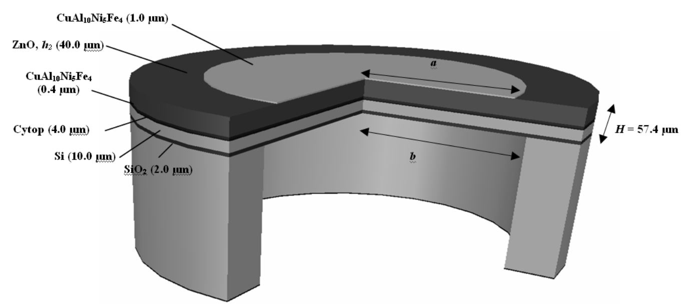

Figure 1. Structure of the circular pMUT with ZnO film sandwiched between sea bronze electrodes

II. MODEL PARAMETERS AND METHOD

All analyses and characterizations were done by utilizing finite element method software package within Coventor™. The assumption of the model to be a multilayered plate with all outer surface clamped at the fix edge has been demonstrated using circular shaped model. Another crucial structural parameter was the ratio of top to bottom electrode widths. The influence of this parameter on device performance will only be discussed briefly in this report and the value of 0.85 was taken for the whole analyses based on previous

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investigation [10]. For finite element meshing, the model was simplified with only the vibrating part left as shown in Fig. 2. There were five important surfaces on the model. First is the outer edge of the model, S_{fix}. Next surface is on the top of the whole model, S_{top} whom will receive inbound acoustic signal. Another two surfaces located on top and bottom of ZnO layer and being in contact with top and bottom electrodes, denoted with S_{pzt} and S_{pzb} respectively and lastly the lowest surface which the bottom part of the diaphragm, S_{bottom}.

In piezoelectric analysis, three boundary conditions involved. The potential was applied at S_{pzt} and S_{pzb} surfaces which were in contact with the electrodes while S_{fix} surface was fixed mechanically and neutral electrically. To simulate the transmit process, S_{pzt} was supplied with potential and S_{pzb} as reference. Then, produced charge on top and bottom part of the ZnO, and the upward deformation of diaphragm were observed. By applying a potential on S_{pzb} with reference to S_{pzt} and vise versa, response of the model can be observed. In modal analysis, series of pressure were applied at S_{top} and S_{bottom} surfaces, deflecting the diaphragm upward and downward, mimic the deflection when voltage potential were applied. Another analysis involved was harmonic. In both piezoelectric and modal harmonic analysis, same boundary conditions applied as piezoelectric and modal analyses.

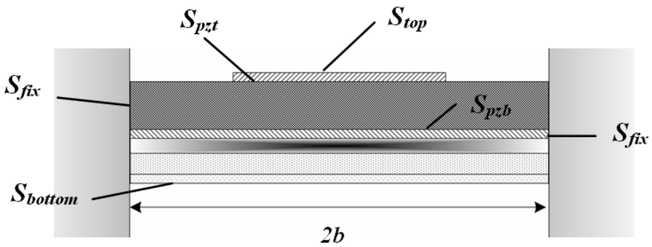

Figure 2. Simplified model for FEA

Simplified model in Fig. 2 was then being split into two separate regions with different mesh setting. Both regions however have undergone the same Manhattan bricks meshing. First region, consist of electroded ZnO layer and second region, complies remaining Cytop, Si and SiO_2 layers. First region was meshed with smaller element size than second region with the factor of 10. Similar method for a square pMUT using PZT as a piezo active layer has been validated elsewhere [11]. Important properties for each material are listed in Table 1. Piezoelectric coefficients of all material were set to be zero except for ZnO. Young's modulus, E and Poisson's ratio, υ were taken as the measure of elastic coefficients of all isotropic materials.

TABLE I
MATERIAL PROPERTIES

Material	ρ (10^{-15} kg/μm^3)	E (10^4 MPa)	υ
SiO_2	2.70	7.30	0.17
Si	2.50	16.90	0.30
Cytop	2.03	0.12	0.38
$CuAl_{10}Ni_5Fe_4$	7.58	11.50	0.33

III. FINDINGS AND DISCUSSION

A. Resonance Frequency tuning

The model consists of six layers of different materials at different thickness; all contribute to the total thickness of the diaphragm. Proposed SiO_2 and Cytop layers was consider fixed based on the recent fabrication [12] conducted by other researchers. Si layer functions to strengthen the diaphragm and provide support during large deflection. Thinning down the Si layer will affect the strength of the vibrating structure during vibrations as suggested by [13], thus the only option left is to manipulate ZnO thickness. By reducing the thickness of ZnO, smooth frequency changes can be observed as shown in Fig. 3. However, major drawbacks regarding this action would be reduced number of charge responded to the applied electrical field, thus affecting the value of device stack capacitance. From the analysis, minimum value for the ZnO layer was set at 20 μm, which is half from the initial value. Below that, redundancy tune may occur since the frequency shift was nonlinear. Linear relationship with 93 % coefficient of determination occurs between 20 – 40 μm of ZnO thickness, involving frequency range of 35 to 50 kHz. In this study, the model having a natural frequency of 40 kHz was our interest, thus appropriate thickness of ZnO piezo active layer is believed to be at 40 μm at constant diaphragm radius at 1800 μm. By keeping the ZnO thickness at 40 μm, total diaphragm thickness is at 57.4 μm.

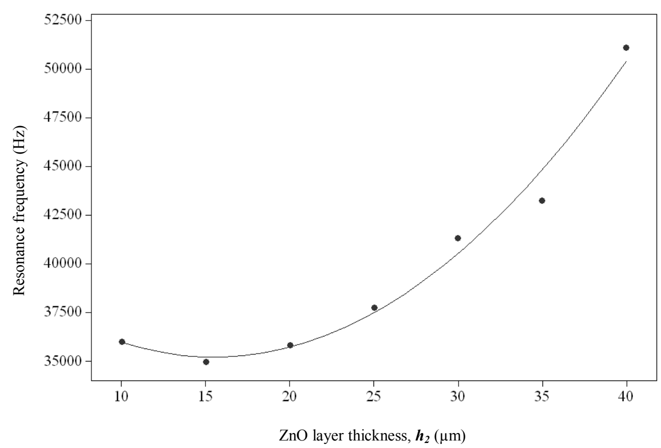

Figure 3. Resonance frequencies of circular pMUT correspond to piezo active layer thickness.

Variation of diaphragm and top electrode radiuses also governed some changes in resonance frequency of the device. By using FEM, the result as shown in Fig. 4 agrees with previous numerical finding [10]. For diaphragm radius, ***b*** approximately less than 1600 μm, any changes in top electrode radius, ***a*** were found to be insignificant. The only reason for these occurrences is the small increment of effective mass of top electrode compare to total diaphragm mass. Relevant and details explanation was done previously by Ramesh and Ebenezer [14] which relate the modal mass of the vibrating area using electrical equivalent circuit. Perhaps for the best fundamental frequency tuning, keeping ***a/b*** constant, and varying ***b*** would probably more reasonable. The trend of the plot is significant for transducer designer which proved that MEMS based MUT offers greater design flexibility; especially during selection of the right frequency range without significantly sacrifice the performance. Since our interest was within frequency range of 40 – 60 kHz, the model with diaphragm radiuses between 1600 to 1800 µm should be suitable. For further investigations and characterizations, we fixed the diaphragm radius at 1800 µm. For maximum response, ***a/b*** was set to be at 0.85 as suggested in [10].

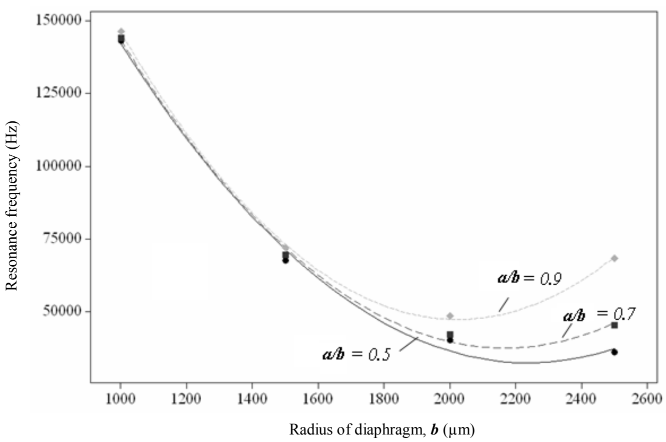

Figure 4. Resonance frequencies of circular pMUT at various diaphragm radiuses.

B. Device Responses

First, receiving response of the model is estimated. Receiving response can be defined as output voltage generated by the transducer per 1 µPa of sound pressure at the surface of the transducer. In this analysis, sound pressure was replaced with the harmonic sinusoidal pressure at S_{top} surface as a function of frequency. In modal analysis, the pressure was directed downward so that minimum displacement of the diaphragm occurs which is in the negative direction of the Z axis. While keeping the amplitude of the pressure constant at the reference value of 1 µPa, the frequency was varied and the minimum displacement at the center of the diaphragm was observed. The modal curve from this analysis in Fig. 5 shows that the minimum displacement at the center of the diaphragm is 3.3×10^{-11} µm. Then, piezoelectric analysis was conducted on the model. At 0.73 pV of supply voltage when the frequency reached 38 kHz, piezo curve intercepts the modal curve which indicate the maximum point of receiving response. In other words, it takes 0.73 pV peak to peak of supply voltage at 38 kHz of frequency to produce the same magnitude of deflection at the center of the diaphragm which correspond to the 1 µPa harmonic pressure at the same frequency. 0.73 pV of peak to peak supply voltage is equivalent to 0.52 pV rms, or -92.84 dB re 1V. Thus, receiving response of the model is -92.84 dB re 1V/ µPa.

Next, transmitting response of the model was observed. This quantity measures the amount of generated SPL, 1 m from the transducer for every volt of supply voltage. However, it was almost impossible to model the generated SPL 1 m away from the transducer. Hence, transmitting voltage response in this analysis is estimated at the surface of the transducer. In piezoelectric analysis, 1 V of harmonic sinusoidal supply voltage was supplied across the electrodes with bottom electrode as a reference. Maximum displacement was then observed, which is in the positive direction of the Z axis. From piezo curve in Fig. 6, 1V of supply voltage was able to deflect the diaphragm upward with 3.2×10^{-3} µm of deflection. After that, modal analysis was conducted on the model and various magnitude of harmonic pressure was applied on the S_{bottom} surface within the same frequency range. At 10 Pa of pressure, the modal curve intercepts the piezo curve at 41 kHz of frequency, which is equivalent to 7.07 Pa rms or 137 dB re 1 µPa. Thus, transmitting response of the model is estimated at 137 dB re 1 µPa/V at 41 kHz of frequency on the surface of the transducer model. Transmitting curve is shown in Fig. 6.

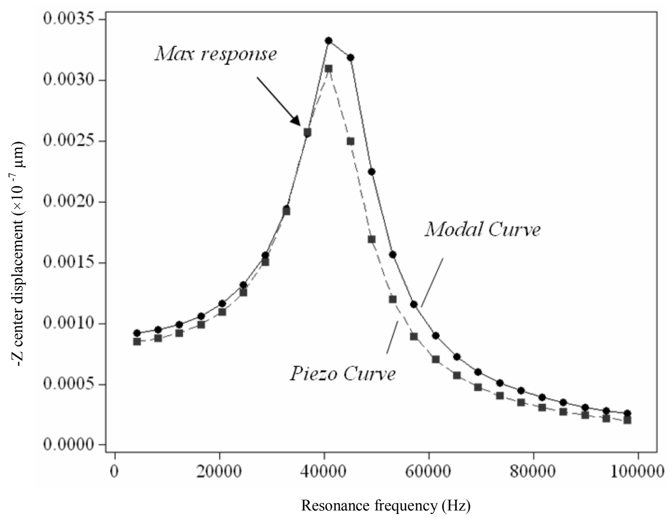

Figure 5.Receiving response curve.

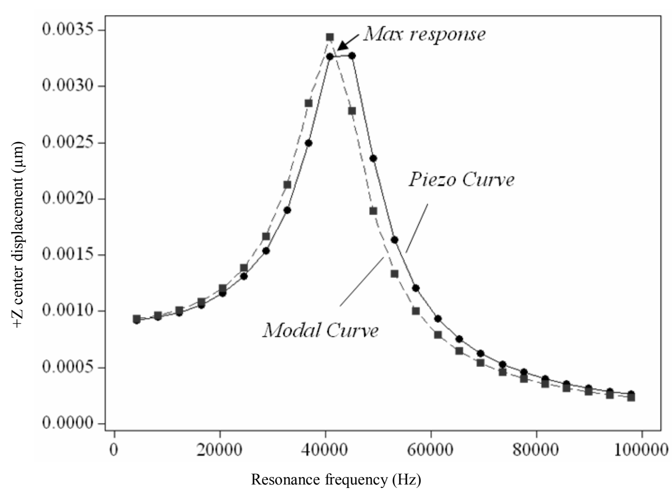

Figure 6. Transmitting response curve.

After all analyses of optimizing model structural parameters and characterization of its responses, final transducer specification was simplified in Table 2. It can be suggested here that for rough estimation of fundamental frequency, the study on the width of the diaphragm is crucial. However, in order to tune the frequency finely, the parameter that should be considered is thickness of the diaphragm. Most importantly, by reducing the thickness of the piezo active layer, reduced value of stack capacitance should be expected. For maximum deflection at the center of the diaphragm, diameter of top electrode would be pertinent parameter. In fact, this study has theoretically covered almost all structural and dimension aspect of the circular pMUT. The effect of reduced stack capacitance is also being discussed in this paper. For estimation of the transmitting voltage response, it is very important to take note that the standard measurement of SPL is usually done 1 m away from the transducer. Actual performance of the transducer might be lower from the projected value since the estimation is done on the surface of the device. However, the estimation procedure has been simplified, and the sensitivity of the device was successfully predicted as a function of the frequency.

TABLE II
FINAL SPECIFICATION OF THE PMUT MODEL

Parameter	Value
Diaphragm radius,	1800 µm (1.8 mm)
Top electrode radius	1530 µm
Diaphragm thickness	57.40 µm
Resonance Frequency	40 kHz
Transmit Response	137 dB re 1µPa/V @ 41 kHz
Receive Response	- 92.84 dB re 1V/µPa @ 38 kHz

IV. CONCLUSION AND RECOMMENDATION

In conclusion, circular pMUT model having ZnO as piezo active layer and nickel aluminum bronze as the top electrode have been successfully studied. The results obtained were comparable to several previous works by others [10-14] by utilizing different materials and approach of analysis. By using nickel aluminum bronze as electrodes, the outcome is theoretically as good as the usage of other expensive conductors such as gold and platinum. Plus, having the same material with the housing might possibly increase the impedance matching between the transducer and water load. The model to predict the acoustic impedance matching will be included in our future study. Furthermore, most physical parameters have been manipulated to understand model behavior as well as optimizing the performance of circular pMUT. Finally, we were looking forward to fabricate the model soon so that further data validation within the scope of this paper can be accomplished.

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