Abstract—Modeling and theoretical characterization of piezoelectric micro ultrasonic transducer (pMUT) using ZnO film sandwiched between nickel aluminum bronze (CuAl$_{10}$Ni$_5$Fe$_4$) electrodes was reported in this paper. The transducer is targeted to be utilized in sonar applications. Analyses on the model were carried out using finite element method. Model’s dimensional parameters were optimized for desired performance. Simplified technique was proposed to determine transmit and receive sensitivities of the model. As the result, micro ultrasonic transducer model with resonance frequency of 40 kHz was proposed with estimated receive and transmit sensitivities of $-93$ dB re $1$ V/pPa and $137$ dB re $1$ pPa/V respectively. Further model validations require actual device fabrication and this will be included in our future works.

Keywords: Ultrasonic transducer, Finite element method, Nickel aluminum bronze, Sonar.

1. INTRODUCTIONS

Advantages synergizing micro-electro mechanical devices (MEMS) technology with underwater sensing applications have been highlighted recently [1] and several issues aroused regarding piezoelectric materials for MEMS based acoustic sensor have already been discussed previously [2]. Two common types of micro-machined ultrasonic transducers (MUTs) are capacitive (cMUT) and piezoelectric (pMUT). Both carry different advantages and disadvantages [3—4]. With higher sensitivity than macro size transducer, pMUT will suit many applications including noise monitoring [5]. Basically, pMUT should at least consist of vibrating area or diaphragm which requires a layer of piezoelectric material sandwiched between top and bottom electrodes. Additional layer may be added as part of vibrating diaphragm for several reasons including strengthening the structure and contributing in effective damping coefficient for bandwidth adjustment. One of the challenge utilizing pMUT for underwater applications is hydrostatic pressure, thus specific technique is a must to encounter large offset deflection on the diaphragm either mechanically [6] or electrically [7].

During vibrations due to inbound acoustic signal, deformation in piezoelectric layer trigger electrostriction process to occur thus generating electric field between electrodes. Since the process is reversible, same vibrations can be observed due to applied electrical field thus generating outbound acoustic wave. Among many piezoelectric materials available today, zinc oxide (ZnO) was one of the earliest being discovered and yet still gaining popularity for its superior piezoelectricity [8] as well as simple and cheaper method of film deposition compare to other piezoelectric thin films [9] such as lead zirconate titanate (PZT). Applied and generated electrical field within piezoelectric material layer are accomplished through conductors. Conductors contribute in overall vibrating mass which affect the performance of the transducer in term of resonance frequency during vibrations and damping coefficient. Furthermore, shape of the conductor will also affect the charge distribution on the surface of piezo active film. Type of material used as electrode also affecting the value of acoustic impedance and electromechanical coupling coefficient of the device. Depend to the applications, various types of material were usually employed as conductors in MUTs such as gold, titanium, aluminum and platinum. Nickel aluminum bronze (CuAl$_{10}$Ni$_5$Fe$_4$) also known as sea bronze was known for its extreme stain resistance capability in highly corrosive environment such as sea water. It has been widely used in marine applications replacing conventional stainless steel as a housing or encapsulation layer to protect sensing element and complementary circuits from corrosive sea water. However, sea bronze was never been used as electrode within any sensor module.
Taking advantage of sea bronze conductivity property, this work introduced sea bronze as pMUT electrodes for underwater applications coupled with sea bronze housing layer aiming for improved response. The shape and thickness of the sea bronze conductor have been optimized to achieve desired performance. Being cheaper than other commonly used electrodes, sea bronze additionally offers cost effective solution for underwater sensing application. Furthermore, impedance matching issue between piezo active material and sea bronze housing layer can be improved by having the same material between them. On other occasion, the usage of polymer in diaphragm type acoustic sensors as adhesive and insulator layer is not new and known as it simplified bonding of two wafer layers at relatively lower temperature [10]. In this work, Cytop was selected as adhesive layer between electroded ZnO wafer and silicon on insulator (SOI) wafer. All analyses and model characterizations were done by utilizing finite element method software package within Coventor™. The results obtained were comparable to several previous works by others [11—14]. However, further model validations still require actual device fabrication [4] as a standard practice [7] and this will be included in our future works.

2. STRUCTURE AND PARAMETERS

Configuration and cross section of the circular pMUT is schematically shown in Fig. 1. Virtual fabrication was carried out to form a complete circular pMUT model. First, bottom side of the ZnO film is evaporated with sea bronze as bottom electrode while partially of the top side is sputtered with the same material as top electrode. Next, the electroded ZnO wafer is adhered to a SOI wafer by using a Cytop polymer. Finally, back side of the silicon is assumed to be etched using deep reactive ion etching (DRIE) and SiO₂ function as a stopping layer producing a straight cut silicon wall under the diaphragm.

The thickness of the upper and bottom electrodes are designated as ℎ₁ and ℎ₃, respectively and ℎ₂ is the thickness of ZnO film as piezoelectric layer. The diameter of diaphragm is denoted with ℓ₁ while ℓ₂ represent diameter of top electrode. Total diaphragm thickness, ℋ is governed by the thickness of sea bronze top and bottom electrodes, piezo-active layer of ZnO, Cytop adhesive polymer layer as well as silicon and SiO₂ bottom SOI wafer layer. Important properties for each material are listed in Table 1. Piezoelectric coefficients of all material were assumed to be zero except for ZnO. As not stated in the table, the density of ZnO film was set at 5.68 × 10⁻¹⁵ kg/μm³. Young’s modulus, ℴ and Poisson’s ratio, ν were taken as the measure of elastic coefficients of all isotropic materials. As the electrodes, sea bronze was set carry 5.21 × 10¹² pS/pm of electrical conductivity. Repective elastic properties and piezoelectric strain coefficient of ZnO piezoelectric layer in crystallographic order are as follow:

\[
\begin{bmatrix}
ε_{xx} \\
ε_{yy} \\
ε_{zz} \\
γ_{yz} \\
γ_{yx} \\
γ_{zz}
\end{bmatrix}
\]

\[
\begin{bmatrix}
7.858 & -3.432 & -2.206 & 0 & 0 & 0 \\
-3.432 & 7.858 & -2.206 & 0 & 0 & 0 \\
-2.206 & -2.206 & 6.94 & 0 & 0 & 0 \\
0 & 0 & 0 & 23.57 & 0 & 0 \\
0 & 0 & 0 & 0 & 23.57 & 0 \\
0 & 0 & 0 & 0 & 0 & 22.58 \\
\end{bmatrix} \times 10^{-12} \text{m}^2/\text{N}
\]
MODELING OF CIRCULAR PIEZOELECTRIC MICRO ULTRASONIC TRANSDUCER

The relative dielectric coefficient for ZnO was set as follow with \( \xi_0 \) is equal to \( 8.854 \times 10^{-12} \text{pF/}\mu\text{m} \).

\[
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\gamma_{xy} \\
\gamma_{xz} \\
\gamma_{yx} \\
\gamma_{yx} \\
\gamma_{zx} \\
\gamma_{zy}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & 0 & -11.34 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-5.43 & -5.43 & 11.67 & 0 & 0 & 0 \\
\end{bmatrix} \times 10^{-12} \frac{E_x}{N} \cdot \begin{bmatrix}
E_x \\
E_y \\
E_z
\end{bmatrix}.
\]

Model was assumed to be a multilayered plate with all outer surface clamped at the fixed edge [11], to simplify the analysis and reduce the number of computation time. Only the vibrating area was included in the analysis as shown in Fig. 2. Simplified model was then split into two separate regions with different mesh setting. Both regions however have undergone the same parabolic tetrahedron meshing. First region, \( A_1 \) consist of electroded ZnO layer and second region, \( A_2 \) complies of remaining Cytop, Si and SiO\(_2\) layers. \( A_1 \) was meshed with smaller element size than \( A_2 \) by the factor of ten. Similar method for analyzing a square pMUT with PZT as a piezoelectric layer has been validated elsewhere [12]. There were five important surfaces on the model. First, is the outer edge of the model, \( S_{pm} \). Next surface is on top of the model, \( S_{top} \) whom will receive inbound acoustic signal and \( S_{bottom} \) as the bottom surface of diaphragm. Another two surfaces located on top and bottom of ZnO layer and permanently in contact with top and bottom electrodes, denoted by \( S_{pt} \) and \( S_{pb} \) respectively in Fig. 2. \( S_{pt} \) and \( S_{pb} \) are the contact point where electric field is generated when drive voltage is supplied.

### 3. MODELING APPROACH AND METHOD

An equivalent circuit was employed to represent performance parameters as suggested in [13—14] and is shown in Fig. 3. The circuit consists of capacitor, \( C_m \) inductor, \( L_m \) and resistor, \( R_m \) that are in series correspond to a resonance frequency. Individually, \( C_m, L_m \) and \( R_m \) represent elasticity or modal compliance, vibrating mass and modal loss respectively. Stack capacitance, \( C_0 \) is a capacitance formed by two electrodes on the surface of ZnO. Approximation values of circuit parameters have been determined accordingly before [14]. However, with assumption of \( h_2 \ll 2r_1 \), total capacitance of the model can be alternatively represented by (4), and its expansion can be derived and shown in (5), by utilizing the dimensional parameters.

\[
C = \frac{\pi r_1^2}{h_2},
\]

\[
C = k \left( \frac{r_1}{r_2} \right)^2 \frac{\xi_{zz}}{h_2}.
\]

In piezoelectric analysis, three boundary conditions involved. AC supply voltage was applied at \( S_{pm} \) and \( S_{pb} \) surfaces which were in contact with the electrodes while \( S_{pt} \) surface was fixed mechanically and neutral electrically. While keeping the amplitude of si-

### Table 1. Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho ) (10(^{-15}) kg/(\mu)m(^3))</th>
<th>( E ) (10(^4) MPa)</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO(_2)</td>
<td>2.70</td>
<td>7.30</td>
<td>0.17</td>
</tr>
<tr>
<td>Si</td>
<td>2.50</td>
<td>16.90</td>
<td>0.30</td>
</tr>
<tr>
<td>Cytop</td>
<td>2.03</td>
<td>0.12</td>
<td>0.38</td>
</tr>
<tr>
<td>CuAl(_{10})Ni(_5)Fe(_4) (Sea bronze)</td>
<td>7.58</td>
<td>11.50</td>
<td>0.33</td>
</tr>
</tbody>
</table>
nusoidal supply voltage constant at 1V, its frequency was varied. Specifically, in order simulate the transmit process, supply voltage was supplied at $S_{pe}$ with $S_{pe}$ as reference. Then, produced charge on top and bottom part of the ZnO, and the upward deformation of diaphragm were observed. By applying a supply voltage on $S_{pe}$ with reference to $S_{pe}$, receiving response of the model can be observed. In modal and mechanical analyses, series of pressure were applied at multiple amplitude and variable frequencies at $S_{up}$ and $S_{down}$ surfaces, deflecting and vibrating the diaphragm upward and downward, mimicking the deflection when AC supply voltage was applied. Another analysis involved was harmonic analysis to generate impedance spectrum. In both piezoelectric and mechanical frequency sweep, same boundary conditions were applied as being used in piezoelectric and mechanical analyses. From the literature, it was previously agreed that series and parallel resonance frequency, $\omega_s$ and $\omega_p$, of the circuit can mathematically been presented as shown in (6). These entities will be used to estimate the electromagnetic coupling coefficient of the device.

$$\omega_s = \frac{1}{\sqrt{L_m C_m}}; \quad \omega_p = \frac{1}{\sqrt{L_m \frac{C_0 C_m}{C_0 + C_m}}}$$

4. RESULT AND FINDING

Structural Optimization

Diameter of top electrode, diameter of diaphragm and the thickness of the diaphragm were three structural or dimensional parameters being manipulated. Optimization process took place so that the desired fundamental frequency of the model could be achieved within design constraint. Initially, diameter of the diaphragm was 2500 µm with total thickness at 57.4 µm and diameter of top electrode was equal to diameter of the diaphragm, giving unity value for $d_1/d_2$. DC analysis was conducted on the model to estimate the value of stack capacitance, $C_0$ between top and bottom electrodes by neglecting the displacement. It can be calculated from the value of charge response on ZnO stack over the applied voltage, in our case 1V. A voltage is applied across the two electrodes to produce an electric field on $S_{top}$ and $S_{bottom}$ surfaces according to Fig. 2 where $S_{bottom}$ as a reference or being supplied with zero potential. It was assumed that on the unelectroded region of ZnO, generated electric field vanished automatically.

First, four models with diaphragm diameter, $d_2$ of 1006, 1500, 2000 and 2500 µm were chosen and for each model, diameter of top electrode, $d_1$ was varied. Then, DC analysis was conducted for every $d_1/d_2$ value of each model and generated charge has been observed. Then, stack capacitance, $C_0$ is calculated and plotted against $d_1/d_2$ as shown in Fig. 4 at different $d_2$. As suggested in (5), regression analysis found the fitted line plot in Fig. 4 shows a quadratic relationship with coefficient of determination at 99.8%. The trend was found to be very helpful in determining $C_m$ and $L_m$ values which will be demonstrated later on.

Next from the same analysis, the amount of deflection on the diaphragm was observed when DC voltage was applied on top electrode with bottom electrode as a reference. The thickness of all materials were kept constant at all time which were 2 microns for SiO$_2$, 10 microns for Si diaphragm, 5 microns for Cytop adhesive layer, 40 microns of ZnO piezo layer and 0.2 micron for both top and bottom sea bronze electrodes. Fig. 5 shows the optimum diameter of top electrode for maximum deflection at the center of the dia-
An optimal $d_1/d_2$ was found to be 0.85 in previous study [11] by using numerical method but only optimal to obtain maximum displacement at resonance frequencies. However, optimum value for $d_1/d_2$ to obtain maximum displacement (positive-Z direction) when DC voltage is applied was found to be at 0.60 as illustrated in Fig. 5.

Variation of diaphragm and top electrode dimensions also governed some changes in resonance frequency of the device as shown in Fig. 6. For diaphragm diameter approximately less than 1600 μm, any changes in top electrode diameter 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 value of $L_m$ in an equivalent circuit in Fig. 3 with the modal mass of the vibrating device. Perhaps for the best fundamental frequency tuning, keeping $d_1/d_2$ constant, while varying $d_2$ would probably more reasonable. The trend of the plot is significant for device designer which offering greater design flexibility when choosing the right frequency range while maintaining reasonable response. In this study, frequency of interest is between 40—60 kHz, thus model with diaphragm diameter of 1600 to 1800 μm were chosen for further investigations and characterizations. For maximum response, $d_1/d_2$ was set to be at 0.6.

Another structural parameters that can also be utilize for fine tuning the fundamental frequency is thickness. The model consists of six layers of different materials giving the combined thickness of the diaphragm. Proposed SiO₂ and Cytop layers was consider fixed based on the recent fabrication [15] conducted by other researchers. Si layer function to strengthen the diaphragm and provide support during large deflection. Thinning down the Si layer will affect the structural stability during vibrations as suggested by [16], 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. 7. However, major drawbacks regarding this action would be reduced number of charge responded to the applied electrical field, thus affecting the value of stack capacitance, $C_0$ which reduce device response and sensitivities. From the analysis, minimum value for the ZnO layer was 20 μm, which is half from 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 diameter for the device believed to be at 1800 μm with $d_1/d_2$ at 0.6, while keeping the ZnO thickness at 40 μm giving the total diaphragm thickness at 57.4 μm. Device with optimum dimension and design was then gone through further performance characterization.

**Performance Parameters**

First, device receiving response is estimated. Receiving response can be defined as output voltage generated by the transducer per 1 μPa of sound pressure received at the surface of the transducer. In this analysis, sound pressure was replaced with the harmonic sinusoidal pressure at $S_{mf}$ 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. 8 shows that the minimum displacement at the center of the diaphragm is
Then, piezoelectric analysis was conducted on the model. At 0.73 nV 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 nV 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 nV of peak to peak sinusoidal supply voltage is equivalent to 0.52 nV 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. 9, 1 V peak to peak of sinusoidal supply voltage was able to deflect the diaphragm upward with $3.2 \times 10^{-3}$ μm of maximum deflection. After that, modal analysis was conducted on the model and various magnitude of harmonic pressure was applied on the 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. 9.

After that, closed circuit resonance analysis was conducted on the model to determine the series resonance frequency, $f_s$. Closed circuit analysis can be conducted by shorten both electrodes, and for this case both electrodes was set to have zero potential. Next, parallel resonance frequency, $f_p$ was determined from open circuit resonance analysis. Open circuit analysis was conducted by letting the top electrodes float, while bottom electrodes was set as reference point. Both $f_s$ and $f_p$ were important so that the value of $L_m$ and $C_m$ of the equivalent circuit can be calculated as suggested by other researcher previously [13–14]. The vibration modes of the model were observed in determining both $f_s$ and $f_p$ in close and open circuit resonance analyses. In this calculation, the value of $C_0$ will determine the value of $C_m$ as taken from (6). $C_m$ value was then employed to calculate $L_m$. From close circuit resonance frequency analysis, $f_s$ was found to be 43.24 kHz while $f_p$ is equal to 43.32 kHz. From Fig. 4, the value of $C_0$ can be predicted. With selected physical parameters,
After optimization and characterization processes conducted on the device, final transducer specification was simplified in Table 2. It can be suggested here that for rough estimation of fundamental frequency, diaphragm width or diameter adjustment 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 with reduced response characteristics. 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 highlighted in this paper. For estimation of the transmitting voltage response, it is very important that the 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 at the surface of the device. However, estimation procedure has been simplified, and the sensitivity of the device can be predicted as a function of the frequency.

As the conclusion, circular pMUT model having ZnO as piezoelectric layer and sea bronze as the top and bottom electrodes have been successfully studied. The results show that the usage of sea bronze as electrode is as good as other conductors such as gold and platinum. Proposed device is expected to have better durability especially for underwater and immersion applications. Plus, having the same material with the housing might possibly increase the impedance matching between the transducer and water load. The analysis to predict the acoustic impedance matching will be included in our future study. The effect of damping coefficient on pMUT overall performances also have been included as our future work. Most physical parameters have been manipulated to understand model behavior as well as optimizing the performance of circular pMUT. Furthermore, we were looking forward to fabricate the model soon so that further data validation, and calibration [18] within the scope of this paper can be accomplished.

### Table 2. Final specification of circular pMUT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diaphragm diameter</td>
<td>1800 μm (1.8 mm)</td>
</tr>
<tr>
<td>Top electrode diameter</td>
<td>1080 μm</td>
</tr>
<tr>
<td>Diaphragm thickness</td>
<td>57.40 μm</td>
</tr>
<tr>
<td>Resonance Frequency</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Transmit Response</td>
<td>137 dB @ 41 kHz (re 1 μPa/V)</td>
</tr>
<tr>
<td>Receive Response</td>
<td>−93 dB @ 38 kHz (re 1 V/μPa)</td>
</tr>
</tbody>
</table>


c0 of our model was estimated at 17.4 pF and from (6), the C0 and LM value were calculated to be 64.4 nF and 0.018 mH respectively.

Electromechanical coupling coefficient can be calculated referring to previous effort by Muralt et al. [17] by determining resonance, fr, and anti-resonance, fa frequencies from impedance and phase spectrum. Alternatively, admittance curve also can be utilized as suggested elsewhere [14]. In this study, harmonic analysis was carried out and the spectrum of impedance and phase angle were plotted as shown in Fig. 10, and both fr and fa were determined. With the fa at 40.4 kHz and fr at 47.4 kHz, electromechanical coupling coefficient is calculated to be at 27.36%. Although the value for electromechanical coupling coefficient is slightly higher than previous theoretical prediction [17], it is still acceptable as projected by other researchers [4], [7] for fluid based acoustic projection or immersion applications, which is same application targeted for this study.

### 5. DISCUSSION AND CONCLUSION

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