Use of Supporting Post Width to Increase the CMUT’s Resonant Frequency

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ABSTRACT A new method is proposed to increase the resonant frequency of a Capacitive Micromachined Ultrasonic Transducer (CMUT) device while keeping the radii unchanged for devices fabricated by sacrificial release (SR) method. The resonant frequency of a CMUT cell is determined by the properties of the membrane such as the Young’s modulus, membrane dimensions and effective membrane mass. Effective Young’s modulus is used to calculate the resonant frequency of CMUT fabricated by SR method. The supporting post structure will affect the boundary conditions at the edge of the CMUT membrane and in turn affect the deflection together with the effective Young’s modulus of the membrane. The perturbation method is used to derive the solution for the governing von Kármán equations. The results show that the thicker is the supporting post width, the higher is the resonant frequency. This method can also be used to simplify the mask design and CMUT fabrication process.

INDEX TERMS Capacitive micromachined ultrasonic transducer (CMUT), resonant frequency, supporting post width.

I. INTRODUCTION The capacitive micromachined ultrasonic transducer (CMUT) has been a popular research topic [1]–[6] since its invention by the Khuri–Yakub group in the late 1990s. It is a promising candidate technology to conventional piezo transducer [7], [8] in biomedical imaging because of its wider fractional bandwidth, smaller acoustic impedance, better working temperature range, and ease of integration with integrated circuit (IC) [9]. CMUT can also be used in applications such as pressure sensor [10], volatile organic compounds (VOCs) sensor [11], tissue harmonic imaging [12], and high-intensity focused ultrasound (HIFU) [13].

Nowadays, the applications of biomedical imaging require the use of several different CMUT elements with different resonant frequencies working together to get a better
image [5], [14]. There is a need for pressure sensors to detect different pressure ranges and CMUT can fulfill this task [10]. The resonant frequency of the CMUT is determined by its membrane properties such as the dimensions [14], [15], the Young’s modulus [16]. Another factor that can affect the resonant frequency is the effective mass of the membrane, such as CMUT being used as gas sensor [7]. The spring softening effect will change the spring constant as well as affect the resonant frequency of CMUT [7], [10], [17], [18]. The gap height will affect the spring softening effect and thus also the resonant frequency.

Normally, to get a higher frequency device, the membrane will be made smaller [14] or thicker but the area for outputting pressure will change, too. The output pressure can be expressed approximately as (1), and, when the radius of the membrane decreases, the average deflection \( x \) of the membrane under the same condition will decrease, thus the output acoustic pressure will reduce.

\[
\begin{align*}
F_{ac} &\propto \frac{SV_{DC}V_{AC}}{(d_0 - x)^2} \\
P_{ac} &\propto \frac{V_{DC}V_{AC}}{(d_0 - x)^2}
\end{align*}
\]

where \( F_{ac} \) and \( P_{ac} \) are the force and pressure due to the applied voltage, respectively; \( S \) is the membrane area; \( V_{DC} \) and \( V_{ac} \) are the DC and AC voltage, respectively; \( d_0 \) is the initial gap of the CMUT; and \( x \) is the average deflection of the membrane under applied voltage.

A CMUT cell consists of a substrate, a membrane, and a vacuum cavity surrounded by the supporting post, as shown in Fig. 1. The CMUT membrane will undergo deformation when the membrane is subjected to a force either from DC/AC voltage applied between the top and bottom electrodes or from external pressure. There will be a restoring force (or stress) from the membrane to balance the external force, and thus the deformation at the point of the membrane will act on the supporting post [9], [19].

Wafer bonding (WB) method [20] and sacrificial release (SR) method [19] are currently two popular fabrication methods for CMUT. Fabricated by WB method, CMUT devices have supporting posts that are connected together for the inner parts or with thick posts for the peripheral devices. Wong et al. discussed the post width of CMUTs using wafer-bonding technology and stated that the support post bending would result in the neighboring membrane bulging upward, and the post would be stiff enough when the post width is about 5 \( \mu \text{m} \) or more (1.67 times the membrane thickness) [21]. In that case, the supporting post will not deform when bearing forces coming from the membranes, thus the boundary conditions for this type of CMUT is regarded as fixed or clamped.

On the other hand, devices fabricated by the SR method have standalone supporting posts. When there is a force acting on the membrane, the supporting post will endure a force coming from the membrane, and the supporting post will deform, as shown in Fig. 1. Oralukan et al. stated that the induced stress can balance the external force in conventional mode and, when the external force is greater than the stress, CMUT is in collapse mode [9]. The stress during fabrication process also bends the membrane post [22]. For a CMUT cell, the post of the CMUT can be regarded as a combination of many tiny beams, and the supporting post width corresponds to the beam height. According to [23], the bending of a beam will change with the force added on the free end of the beam, and the deformation is inversely proportional to the third order of the beam height. Thus, with different supporting post width, the deformation will be different, and the boundary condition is regarded as elastic support (ES).

Redesign of all the masks related to membrane radius of CMUT is needed even when there is a minor revision of the CMUT [3]. This research is to develop a method to increase the CMUT frequency by modifying the supporting post width without changing the membrane radius. During the sacrificial release fabrication process, alignment marks are mainly used to align the mask with the patterns on the wafers from the previous steps; sometimes, patterns on the wafers are also used to make alignment more precisely. By using this method, the mask redesign process can be reduced to modify only one mask layer (the etch hole protection mask), as described in Section V.

In the current research, the effect of the supporting post width is incorporated into the boundary conditions of the membrane. The main novelty of this article is to increase the resonant frequency by increasing the post width of the CMUT device without decreasing the membrane radius. The contribution of this work is to provide a method to increase the resonant frequency of CMUT by modifying the supporting post width.

In Section VI, the conclusion is presented. The conclusions are drawn in Section VI.
II. ANALYTICAL DERIVATION

The fundamental resonant frequency of a clamped circular membrane in air and vacuum can be calculated using the following equation or its variation [24]–[27].

\[ f_0 = \frac{10.21 h}{2\pi a^2} \sqrt{\frac{E}{12\rho(1 - \nu^2)}} \]  

where \( f_0 \) is the fundamental resonant frequency of the membrane, \( a \) is the membrane radius, \( h \) is the membrane thickness, \( E \) is the Young’s modulus of the membrane, \( \rho \) is the membrane density, and \( \nu \) is the Poisson’s ratio of the membrane.

From (2), the resonant frequency is proportional to the thickness \( h \) and the square root of Young’s modulus \( E \), while inversely proportional to the square of the membrane radius \( a \) and the square root of the mass density \( \rho \). In fact, the boundary condition of the membrane at the edge will affect the resonant frequency of the membrane. Leissa A. W. [28] presented the basic equations for classical plate vibration theory and demonstrated solutions under several different boundary conditions including plates clamped (fixed) all around, plates simply supported all around, etc. In the book, during the derivation of the resonant frequency, a parameter \( k \) is defined for convenience as in (3), and \( \lambda \) is defined as \( \lambda = ka \), where \( a \) is the radius of the plate. The major reason for this arrangement is to simplify the equations in the subsequent derivations. Therefore, \( \lambda^2 \) is expressed as in (4).

\[ k^4 = \frac{\rho\omega^2}{D} \]  

where \( \rho \) is the mass density per unit area of the plate, \( D \) is the flexural rigidity of the plate, and \( \omega \) is the circular frequency of the plate.

\[ \lambda^2 = \frac{\rho}{D} a^2 \omega \]  

where \( a \) is the plate radius.

From the book, for the same nodal diameter \( n \) equal to 0 and the same nodal circle \( s \) equal to 0, the parameter \( \lambda^2 \) value is about double (10.216) for fixed boundary conditions as that of simply supported boundary conditions (4.977). From (4), \( \lambda^2 \) is proportional to the resonant frequency of the plate. It can be inferred that for membranes with the same parameters, the resonant frequency of the simply supported case is about half the clamped case. To explain this phenomenon, the term effective Young’s modulus is introduced for membrane boundary conditions other than fixed boundary condition. The effective Young’s modulus is the value corresponding to that of the fixed case with the same center deflection. The reason for the mentioned resonant frequency difference is that the effective Young’s modulus of the membrane in the simply supported case is smaller when converted into the clamped case. This can be shown by calculating the center deflections of one membrane under the same pressure but with different boundary conditions. For example, for a membrane with radius of 30 \( \mu \)m, thickness of 1.2 \( \mu \)m, Young’s modulus of 200 GPa, and Poisson’s ratio of 0.27, the center deflection in simply supported case is 0.17 \( \mu \)m, while, for the same center deflection, the Young’s modulus is about 48 GPa in fixed boundary condition, which means the effective Young’s modulus is 48 GPa.

From (2), the resonant frequency of a circular membrane is determined by the Young’s modulus when the membrane dimensions are constants. For the CMUT devices, the membrane is always composed of a top electrode layer, which can be incorporated into one layer, as in [29], [30].

To calculate the resonant frequency of CMUT membranes using (2) with different boundary conditions other than fixed case, the effective Young’s modulus is used and can be derived by using the center deflection of the membrane under external pressure. The deflection profile of the membrane under a uniform pressure for membrane undergoing small deflections can be expressed as (5) [31]–[34].

\[ \sigma(r) = \sigma_{pk} \left(1 - \frac{r^2}{a^2}\right)^2 \]  

where \( \sigma_{pk} \) is the center deflection of the membrane, \( a \) is the membrane radius, and \( r \) is the radial position.

However, there will be much error when using this equation to describe membrane undergoing large deflection [35]. For the center deflection of a circular membrane CMUT under external pressure, the governing equations for both small deflections and large deflections can be described by von Kármán Equations (6) and (7) [36].

\[ \frac{r}{Dr} \frac{d}{dr} \left(r^2 N_r \right) = -\frac{1}{2} Eh \left(\frac{d\sigma}{dr}\right)^2 \]  

\[ Dr \frac{d}{dr} \left( r \frac{d\sigma}{dr} \right) = rN_r \left(\frac{d\sigma}{dr}\right) + \frac{1}{2} qr^2 \]  

where \( N_r \) is the lateral force at \( r \), \( \sigma \) is the deflection profile of the membrane, \( h \) is the membrane thickness, \( D \) is the flexural rigidity of the membrane, and \( q \) is the external uniform pressure.

The boundary conditions at the edge of the membrane for devices fabricated by wafer bonding and sacrificial release methods are as fixed boundary conditions (9) and ES boundary conditions ( (10)) [31], [37]. The supporting post can be regarded as many tiny standalone beams interacting with each other and the post will bend under force coming from membrane deformation, the bend size is as in (8), by taking into consideration this phenomenon, a coefficient \( \alpha \) is added to the third one of the original boundary in (10).

\[ u = \frac{4Ft_p^3}{Eb^3p} \]  

where \( u \) stands for the deformation of the beam, \( F \) is the force acting on the beam per unit length, \( Eb \) depicts the Young’s modulus of the beam, \( t_p \) is the width of the beam, and \( t_b \) is
the height of the beam.

\[
\begin{align*}
\sigma &= 0 \\
\frac{d\sigma}{dr} &= 0 \\
\frac{dN_r}{dr} + (1 - \nu)N_r &= 0
\end{align*}
\]

(9)

\[
D \left( \frac{d^2\sigma}{dr^2} + \frac{v}{r} \frac{d\sigma}{dr} \right) = -k_2 \frac{d\sigma}{dr}
\]

(10)

\[
N_r = -\alpha k_1 u = -\frac{\alpha k_1 r}{Eh} \left[ \frac{dN_r}{dr} + (1 - \nu)N_r \right]
\]

where \(k_1\) and \(k_2\) are parameters for certain boundary settings with different post widths. By using the perturbation method, the solutions for the governing equations with both boundary conditions can be derived, thus the center deflection can be calculated as in (11) [35].

\[
\sigma_0 = \frac{hW_m}{3(1 - \nu^2)}
\]

(11)

where \(\sigma_0\) is the center deflection of the membrane and \(W_m\) is the perturbation parameter used during the derivation process, which is a non-dimensionalized value of the center deflection of the CMUT membrane.

To design CMUTs that have different frequencies and the same membrane radius, the following procedure is used. First, the center deflections for one CMUT with different Young’s moduli are calculated under fixed boundary conditions to form a lookup table. Next, the center deflections for the same CMUT with one Young’s modulus value are calculated for SR devices with different supporting post width values. The third step is to approximate the Young’s modulus value to fixed boundary case for the SR device with different supporting post widths using the lookup table formed in the first step. The latter two steps can be repeated for other Young’s modulus values. When the effective Young’s modulus is determined, the resonant frequency can be calculated. Other CMUT devices with different membrane parameters can be designed in the same way. The flow chart of the approximation is shown in Fig. 2.

III. FEM MODELS

Two FEM models were built in solid mechanics physics domain to verify the analytical model using COMSOL Multiphysics 4.4 (COMSOL Inc., Stockholm, Sweden). The COMSOL model for WB devices (fixed boundary case) was depicted as in Fig. 3, and the device was simplified to a membrane, a vacuum cavity and an insulator layer (to represent the insulator layers and the substrate). One boundary Fixed Constraint was set at the bottom boundary of the supporting post and one domain Fixed Constraint was set to the insulator layer. Another 2D axisymmetric annular ring represented the supporting post, the membrane and the supporting post were of the same material. The lower boundary of membrane and the upper boundary of insulator layer was modeled by a contact pair. Physics controlled mesh was used and the normal size was chosen. The deflection profile was derived by using the stationary solver. After simulation, the data of deflection profile were compared with that of analytical results.

The COMSOL model for the SR device was depicted as in Fig. 4, and the device consisted of a membrane, a vacuum cavity and an insulator layer (to represent the insulator layers and the substrate). One boundary Fixed Constraint was set at the bottom boundary of the supporting post and one domain Fixed Constraint was set to the insulator layer.

Similar to that of the fixed boundary model, two 2D axisymmetric plates were used to present the insulator layer and the membrane, respectively. The lower boundary of membrane and the upper boundary of insulator layer was modeled by a contact pair, and a union
was formed by combining the membrane and the supporting post. Physics controlled mesh was used and the normal size was chosen. The resonant frequency was derived by using the Eigenfrequency solver. After simulation, the data of resonant frequencies were compared with that of analytical results.

### IV. ANALYTICAL MODEL VERIFICATION

To demonstrate the proposed method, $\text{Si}_3\text{N}_4$ was used for the membrane and the parameters listed in Table 1 were adopted. Center deflections of the CMUT with fixed boundary conditions with several Young’s modulus values were derived by using the solution from the previous section, as shown in Fig. 5. The simulation results from COMSOL are also shown. Based on Fig. 5, the analytical and simulation results match well. In the same manner, using the same parameters as in Table 1 and selecting a Young’s modulus value of 210 GPa, center deflections of one CMUT with different supporting post width values were calculated, as listed in Table 2.

**TABLE 1. Parameters of one CMUT.**

| Term                  | Value | Unit |
|----------------------|-------|------|
| Membrane radius, $a$ | 90    | $\mu$m |
| Membrane thickness, $h$ | 0.8   | $\mu$m |
| Young’s modulus, $E$ | 110–210 | GPa |
| Poisson’s ratio, $\nu$ | 0.27 |      |
| External pressure, $q$ | 101   | KPa  |
| Gap height, $t_g$    | 0.5   | $\mu$m |
| Material density, $\rho$ | 3100 | kg/m$^3$ |

**TABLE 2. Comparison of resonant frequencies between analytical and FEM results with different supporting post width values.**

| Supporting Post Width ($\mu$m) | Center Deflection (nm) | Effective Young’s Modulus (GPa) | Resonant Frequency (MHz) |
|-------------------------------|------------------------|---------------------------------|--------------------------|
| 0.5                           | 172.0                  | 157.6                           | 3.09                     |
| 0.8                           | 141.6                  | 192.9                           | 3.42                     |
| 1.0                           | 136.2                  | 200.7                           | 3.48                     |
| 1.5                           | 132.1                  | 207.1                           | 3.54                     |
| 2.0                           | 131.1                  | 208.8                           | 3.55                     |
| 3.0                           | 130.6                  | 209.6                           | 3.56                     |
| 4.0                           | 130.5                  | 209.8                           | 3.56                     |
| 5.0                           | 130.4                  | 209.9                           | 3.56                     |

**TABLE 3. Parameters of the three typical membrane materials ($\text{Si}_3\text{N}_4$, $\text{Si}$, $\text{SiO}_2$).**

| Term                  | Value | Unit |
|----------------------|-------|------|
| Membrane thickness, $h$ | 0.5 – 1.0, step 0.1 | $\mu$m |
| Young’s modulus of $\text{Si}_3\text{N}_4$, $\text{Si}$, $\text{SiO}_2$, $E$ | 210, 170, 70 | GPa |
| Poisson’s ratio $\text{Si}_3\text{N}_4$, $\text{Si}$, $\text{SiO}_2$, $\nu$ | 0.27, 0.28, 0.17 |      |
| External pressure, $q$ | 40, 60, 80, 101 | KPa  |
| Material density $\text{Si}_3\text{N}_4$, $\text{Si}$, $\text{SiO}_2$, $\rho$ | 3100, 2329, 2200 | kg/m$^3$ |

By using the approximation method in the previous section, effective Young’s modulus values corresponding to the fixed boundary conditions were also calculated, as listed in the same table. For this case, the maximum absolute relative error between the analytical and FEM resonant frequencies was 2.80 % and was listed in the fourth line of Table 4. The effective Young’s moduli and resonant frequencies corresponding to other Young’s moduli of fixed boundary conditions could be calculated by using the same procedure.

To further verify the model, three typical membrane materials with different properties were selected and the parameters were shown in Table 3, with the membrane radius and the gap height being equal to those in Table 1.

The relationships of the supporting post width and the corresponding resonant frequency data for the three materials with different membrane thickness values are shown in Fig. 6, along with the results from COMSOL for contrast. As shown in the figure, different materials can have different relationship curves between the supporting post width and the resonant frequency. The resonant frequency can be adjusted by modifying the material properties such as thickness and Young’s modulus. The resonant frequency has an upper bound corresponding to the clamped boundary condition. In the clamped boundary condition case, the frequency can be increased by thickening the membrane and/or reducing the membrane radius.

Resonant frequency of the CMUT cell can be estimated from the curve as a lookup table, although the relationship between the Young’s modulus and the resonant frequency is not linear.

For the range of the resonance frequency tuning, according to the current result, the effect of the supporting post width on the resonant frequency is limited to about 10%. Although 10% deviation may not pose significant impact for imaging purposes, this can extend the working ranges when CMUT is used as pressure sensors. In the pressure sensor application,
10% frequency deviation corresponds to about three times the measured pressure range [10].

The maximum relative error between analytical results and FEM results were listed in Table 4.

From Table 4, the maximum relative error between analytical results and FEM results was 4.51%, therefore, the analytical results matched well with the FEM simulation results.

Table 4: Comparison of resonant frequencies between analytical and FEM results for three different materials.

| Membrane Material | Membrane Thickness μm | Maximum absolute Relative error % |
|-------------------|------------------------|-----------------------------------|
| Si₂N₄              | 0.5                    | 1.64                              |
|                   | 0.6                    | 2.00                              |
|                   | 0.7                    | 2.37                              |
|                   | 0.8                    | 2.80                              |
|                   | 0.9                    | 4.49                              |
|                   | 1.0                    | 3.92                              |
| Si                 | 0.5                    | 1.85                              |
|                   | 0.6                    | 1.99                              |
|                   | 0.7                    | 2.36                              |
|                   | 0.8                    | 2.79                              |
|                   | 0.9                    | 4.50                              |
|                   | 1.0                    | 4.36                              |
| SiO₂               | 0.5                    | 1.63                              |
|                   | 0.6                    | 1.97                              |
|                   | 0.7                    | 2.34                              |
|                   | 0.8                    | 2.78                              |
|                   | 0.9                    | 3.91                              |
|                   | 1.0                    | 4.51                              |

V. MASK DESIGN AND FABRICATION PROCESS CONSIDERATION

The fabrication flow chart of the conventional sacrificial release method is shown in Fig. 7. The thickness of the whole wafer is increased during the process of sealing the etch holes. Thus, there is a thinning process to restore the original membrane thickness after the sealing process. Generally, the only protected parts during the thinning process are the etch hole areas. Our proposed method is to add an annular ring around the membrane during the thinning process in order to produce supporting posts with different widths. Thus, the fabrication can be achieved through the conventional sacrificial release method with a minor modification of one of the masks for thinning of the sacrificial layer and etch channels. Step 3 is formation of the membrane. Step 4 is releasing the sacrificial layer through etch holes. Step 5 is sealing the etch holes and thinning the membrane. Step 6 is the formation of the electrodes.
report regarding the present study. The authors declare that they have no conflicts of interest to
Taiwan.

Facility Center, National Chiao Tung University, and for the assistance in CMUT fabrication from the Nano
The authors would like to express their appreciation this method.

can be simplified when modifying the mask design by using can be fabricated simultaneously. The fabrication process for
devices with the same radii but different supporting post
the resonant frequency of a CMUT. By arranging CMUT
verified numerically, the resonant frequency of a CMUT can
calculated by this analytical method, thus the resonant
frequency can be derived. We proposed theoretically and
The proposed method.

Based on the relationship between the wafer bonding and
sacrificial release fabricated CMUT devices, an analytical
method is proposed to increase the CMUT resonant frequency
by increasing the supporting post width. The effective
Young’s modulus of the elastic support device can be calculated by this analytical method, thus the resonant
frequency can be derived. We proposed theoretically and
verified numerically, the resonant frequency of a CMUT can
be tuned by changing the post width. We also propose a
method to minimize the mask re-design procedures to alter the resonant frequency of a CMUT. By arranging CMUT
devices with the same radii but different supporting post
width values, devices with different resonant frequencies
can be fabricated simultaneously. The fabrication process for
configuring CMUTs with different frequencies in one array
can be simplified when modifying the mask design by using this method.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest to report regarding the present study.

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