Proceedings of the Eurosensors XXIII conference

Capacitive micromachined ultrasonic transducers with novel membrane design

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Abstract

This paper presents a novel membrane design for capacitive micromachined ultrasonic transducers (cMUTs). The proposed design is composed of a thick membrane with reinforcing beams supported by a circumferential thin membrane to improve transducer sensitivity without degrading the membrane resonance frequency. Analytical formulation of sensitivity for the proposed design was newly derived and its validity was verified by finite element analysis (FEA). From the analysis, we confirmed that this thick membrane structure achieved three times higher sensitivity compared to the conventional design by decreasing 70 % of the mass of the thick membrane part with keeping the resonance frequency same.

Keywords: Capacitive micromachined ultrasonic transducer; Modeling; Finite element analysis

1. Introduction

Capacitive micromachined ultrasonic transducer (cMUT) has been attracting attentions as an alternative to piezoelectric transducers for a medical ultrasonic imaging due to its advantages such as ease of integration with electronics components and suitability for fabricating 2-D arrays. cMUT is generally consisted of many identical cells with array form and the each cell is composed of a suspended membrane with top electrode and a substrate acting as a bottom electrode as shown in Fig. 1. During cMUT operation, DC bias voltage is applied between these electrodes and the membrane deformed downward due to generated electrostatic force. Incoming ultrasound is detected as the capacitance changes due to the membrane vibration. Higher resonance frequency of the membrane in the order of several MHz is required for an abdominal diagnosis from body surface to realize higher axial resolution which is dominated by the resonance frequency. On the other hand, the incoming ultrasonic amplitude attenuates with higher the frequency since the amplitude decreases exponentially with propagation into body. Therefore, improvement of cMUT sensitivity has been required to realize higher spatial resolution at deeper measurement area. To address this requirement, Zhou et al.[1] formed trenches at the membrane edge to increase sensitivity but the resonance frequency decreased due to lower stiffness of the membrane. Yaralioglu et al.[2] optimized the size of the top electrode with maintaining the resonance frequency same. However, there is still a

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space to further improve sensitivity by avoiding non-uniform downward deformation of the membrane. In this paper, firstly, a novel membrane design is proposed which is composed of a thick membrane with reinforcing beams supported by a circumferential thin membrane to improve sensitivity without degrading the membrane resonance frequency. Secondly, analytical formulations of the sensitivities for the proposed and the conventional designs are derived and their validities are verified by finite element analysis (FEA). Finally, the sensitivity of the proposed design is calculated using the derived formulation.

2. Analytical Sensitivity Derivation

The thickness and the diameter of the proposed thick membrane design illustrated in Fig. 2 were fixed to 5 times that of the supporting membrane and 80 % of the total membrane diameter, respectively. The reinforcing beams were utilized to reduce the mass with maintaining a high resonance frequency.

Figure 3 illustrates schematic cross sectional view of the proposed and a conventional designs for the analysis. For the conventional design, the diameter of the top electrode was set to 50 % of the total membrane diameter so as to obtain the best sensitivity[2] while the other layers are used as conductors. The ratio of the structural mass to the total volume of the thick membrane part is defined as the equivalent density ρ_{rd}. The diameter of the total membrane $2a$ is fixed to 50 μm. The thickness of the supporting membrane t_m is determined as the resonance frequency f_0 equals to 5 MHz. The bias voltage V_{DC} is fixed to 80 % of a pull-in voltage V_{crit} and corresponding operating gap distance $d(V_{DC})$ is fixed to 0.1 μm. The following material properties of Si_3N_4 are utilized: Young's modulus E of 320 GPa, density ρ_{mem} of 3270 kg/m^3 and Poisson's ratio v of 0.263. The permittivity ε_0 of the gap is 8.854 x 10^{-12} F/m. The sensitivity is defined as $S=(dC/dp)/(C_m V_{DC})$, where dC/dp is the capacitance change under a small pressure dp loading on the membrane, and C_m is the base capacitance under V_{DC}.

Firstly, t_m and an initial gap distance d_0 are determined for the proposed design. When the thick membrane is assumed to be a complete rigid body, f_0 is written as:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{P/u_1(P)}{\pi b^2 \alpha t_m \rho_{rd}}} \qquad (1)$$

where b is the radius of the rigid body and α is the thickness ratio of the rigid body to the supporting membrane. The spring constant of the supporting membrane k is derived from the displacement $u_1(P)$ under a load P on the rigid body as shown in Fig. 4 (a). Then $u_1(P)$ is written as:

$$u_1(P) = \frac{3}{2}\frac{Pa^2(1-v^2)}{\pi E t_m^3}Z_1 \qquad (2)$$

where Z_1 is a function of a and b[3]. Thus, t_m can be expressed from Eqs. (1) and (2) as follows:
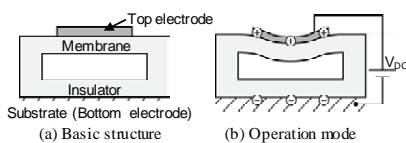

Fig. 1. Schematics of the conventional cMUT cell.

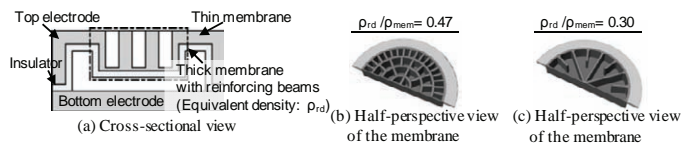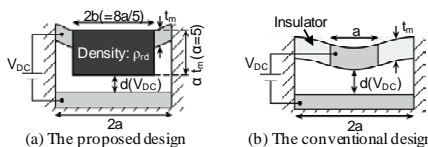Fig. 2. Schematics of the proposed design with the thick membrane reinforced by beams.
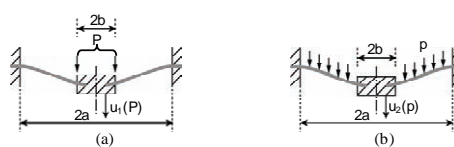

Fig. 3. Simplified models for systematic comparison.

Fig. 4 Superposition model for the displacement of the rigid body.

$$t_m = 2\pi f_0 \sqrt{\frac{3a^2 b^2 \alpha \rho_{rd}\left(1-v^2\right)Z_1}{2E}} \tag{3}$$

d_0 can be derived from the membrane equilibrium equation of the electrostatic force and the restoring force. V_{DC} is expressed as Eq. (4) using an equation for V_{crit} of a plate capacitor. Then, the equilibrium equation is written as Eq. (5):

$$V_{DC} = \frac{4}{5}V_{crit} = \frac{4}{5}\sqrt{\frac{8}{27}\frac{kd_0^3}{\varepsilon_0 \pi b^2}} \tag{4}$$

$$\frac{1}{2}\frac{\varepsilon_0 \pi b^2}{d(V_{DC})^2}V_{DC}^2 = k\left(d_0 - d(V_{DC})\right) \tag{5}$$

Effective solution for d_0 is found to be 1.14 $d(V_{DC})$ as the value only matches displacement range of the rigid body limited by the pull-in phenomenon. For the sensitivity derivation, V_{DC} is expressed as Eq. (6) by substituting k $(=P/u_1(P))$ and Eq. (2) in Eq. (4). On the other hand, C_m is expressed as Eq. (7).

$$V_{DC} = \frac{16}{45}\sqrt{\frac{d_0^3 E t_m^3}{\varepsilon_0 a^2 b^2 \left(1-v^2\right)Z_1}} \tag{6}$$

$$C_m = \frac{\varepsilon_0 \pi b^2}{d(V_{DC})} \tag{7}$$

A displacement of the rigid body $u(p)$ under a loading pressure p on the total membrane is represented by the superposition of Fig. 4 (a) and (b) when a small displacement is assumed. The displacement $u_2(p)$ in Fig. 4 (b) is given by Eq. (8). Thus, the total displacement change du/dp is written as Eq. (9). Note that the load P in Eq. (2) is the product of the area of the rigid body πb^2 and p loading on this area.

$$u_2(p) = -\frac{3}{16}\frac{pa^4\left(1-v^2\right)}{Et_m^3}Z_2 \tag{8}$$

$$\frac{du}{dp} = \frac{d}{dp}\left(u_1\left(\pi b^2 p\right) + u_2(p)\right) = \frac{3}{16}\frac{a^2\left(1-v^2\right)}{Et_m^3}\left(8b^2 Z_1 - a^2 Z_2\right) \tag{9}$$

where Z_2 is a function of a and b[3]. Therefore, using a first order Taylor expansion and Eq. (9) Eq. (10) is obtained.

$$\frac{dC}{dp} \approx \frac{\varepsilon_0 \pi b^2}{d(V_{DC})^2}\frac{du}{dp} = \frac{3}{16}\frac{\varepsilon_0 \pi a^2 b^2 \left(1-v^2\right)}{Ed(V_{DC})^2 t_m^3}\left(8b^2 Z_1 - a^2 Z_2\right) \tag{10}$$

In this way, the analytical sensitivity of the proposed design $S_{A,P}$ as Eq. (11) can be derived using Eqs. (6), (7), (10), (3) and d_0 derived above.

$$S_{A,P} = \left(7.6895\times10^{-3}\right)\frac{\varepsilon_0^{1/2}a^2 E^{3/4}}{\left(\pi f_0\right)^{9/2}\left(ab\right)^{7/2}\left(\alpha\rho_{rd}\right)^{9/4}d(V_{DC})^{5/2}\left(1-v^2\right)^{3/4}Z_1^{7/4}}\left(8b^2 Z_1 - a^2 Z_2\right) \tag{11}$$

In order to derive the analytical sensitivity of the conventional design $S_{A,C}$, piston radiator and plate capacitance theory[4] is adapted. Using the displacement of the radiator $u(V_{DC})$ under V_{DC}, the radiator area A_{PS} and the electrode area on the radiator A_{el} determined in this theory, $S_{A,C}$ is determined as Eq. (12).

$$S_{A,C} = \frac{dC/dp}{C_m^* V_{DC}^*} \approx \frac{10}{27}\frac{u_{mean}(V_{DC})^*}{u(V_{DC})^*}\frac{\left(d(V_{DC}) + u(V_{DC})^*\right)^3}{d(V_{DC})^2}\frac{A_{mem}}{C_m^* V_{crit}^{*3}} \tag{12}$$
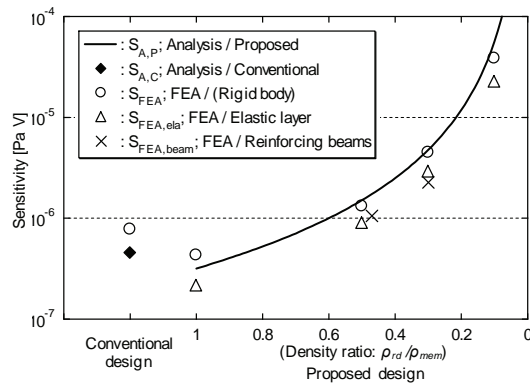
Fig. 5. Sensitivity comparison of the proposed design with the conventional design.

where A_{mem} and $u_{mean}(V_{DC})$ are the membrane area and mean displacement of the membrane, respectively. The calculated parameters by FEA are denoted with * in Eq. (12).

3. Results and Discussion

Figure 5 shows $S_{A,P}$ dramatically increases with decreasing the density ratio ρ_{rd}/ρ_{mem}. $S_{A,P}$ and $S_{A,C}$ are identical when ρ_{rd}/ρ_{mem} equals to 0.85, and 10 times higher at 0.30. To confirm the accuracy of these analytical results, the sensitivities were calculated using FEA software, CoventorWare 2006. In this simulation, a geometrical nonlinearity analysis with two-plane symmetry was adopted. dC/dp was calculated from a capacitance change under a loading pressure of 1 kPa on the membrane. Extremely high Young's modulus was adopted to neglect the deformation of the thick membrane part and density value was set to ρ_{rd}. As shown in Fig. 5, calculated sensitivity S_{FEA} by FEA shows good agreement with $S_{A,P}$. Next, the sensitivities $S_{FEA,ela}$ of the thick membrane with elastic layer with the same modulus as the typical material instead of the rigid body was calculated to consider the deformation effect of the thick membrane. $S_{FEA,ela}$ decreased by 30 to 60 % of the corresponding $S_{A,P}$ due to the deformation of the thick membrane. Please note that sensitivity dependence on ρ_{rd}/ρ_{mem} was well expressed by analytically derived sensitivity. The sensitivities with reinforcing beams, $S_{FEA,beam}$, shown in Fig. 2 were also calculated. Plotted $S_{FEA,beam}$ in Fig. 5 agreed with $S_{A,P}$, and $S_{FEA,beam}$ with ρ_{rd}/ρ_{mem} of 0.30 resulted in 3 times higher sensitivity compared to S_{FEA} of the conventional design which is higher than $S_{A,C}$.

4. Conclusion

We proposed a novel membrane design constructed of the thick membrane with reinforcing beams for improvement of cMUT sensitivity with keeping the resonant frequency same. The validity of the derived analytical formulation for the estimation of the sensitivity of the proposed design was confirmed by FEA. The sensitivity dramatically increased with decreasing the equivalent density of the thick membrane. The sensitivity with decreasing 70 % of the mass of the thick membrane using reinforcing beams achieved 3 times higher sensitivity compared to the conventional design.

References

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