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Impact Analysis of Variation in Geometrical Features on Intrinsic Characteristics of Capacitive Micro-machined Ultrasonic Transducers

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ABSTRACT

Capacitive Micro-machined Ultrasonic Transducers (CMUTs) are the ultrasonic devices which produce better features in contrast to piezoelectric transducers. The intrinsic parameter of CMUT varies with the variation in geometrical dimension of the device. The cavity height and the radius of the CMUT with circular membrane is varied in the lumped parallel plate model for its impact on the parameters. In this paper, analytical model of circular CMUTs is developed and analyzed by using the parallel-plate capacitor equations. The impact of geometrical changes has been discussed with the parametric analysis of deflection, capacitance, pull in voltage and pressure. The results discussed here will be more helpful in deciding the miniaturization limit of the CMUT prior to fabrication.

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1. INTRODUCTION

Microelectronic Mechanical Systems (MEMS) based systems have long dominated the society due to its advantages like low cost, integration with electronics, small size etc. MEMS based Capacitive Micromachined Ultrasonic Transducers have become a suitable replacement for the piezoelectric transducers [1]. In this new era, MEMS technology is broadly explored for the designing of capacitive microphones [2]. The MEMS piezoelectric effect based hydrophone sensor is developed using appropriate material properties operating at 80 kHz [3]. CMUTs offer preferences in many areas like bandwidth, frequency, sensitivity and cost in comparison to piezoelectric transducers [4]. Commonly the capacitive pressure sensor constructed through MEMS technology comprises of a conducting membrane acting as one electrode along with a fixed electrode separated by a small gap [5].

For imaging applications CMUTs offers high axial resolutions and is becoming promising for high frequency utilizations as micromachining technologies establishes the required small scale sizes [6]. A circular membrane constructed from silicon produces acoustic waves more efficiently than a piezoelectric counterpart [7]. Furthermore, CMUTs provide massive integration with the front end electronics by making use of low temperature techniques resulting in compressed arrays with minimum noise for use in ultrasonic imaging systems [8].

For constructing CMUT a heavily doped silicon substrate is used to deposit a silicon dioxide layer on which cavity is formed using surface micromachining techniques [9, 10]. A metal layer is overlaid on the cavity which acts as a membrane. CMUT functions as a capacitor with a silicon substrate and metal layer as two electrodes and the cavity with vacuum acts as a dielectric [11]. When the parallel plates of the capacitor are subjected with DC biasing the upper electrode acting as the membrane of the CMUT bends downward towards substrate due to the elctrostatic forces [12]. The membrane's restoring mechanical forces opposes

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electrostatic forces of the substrate. In the state of stationary equilibrium the electrostatic forces and the restoring forces both are balanced [13]. The distance between the top and bottom electrode will keep on decreasing until the restoring forces are not enough to maintain the state of balance with the enlarged DC bias. There comes a condition of merging of both the electrodes with increasing DC bias this DC voltage is termed as Pull in voltage or the Collapse voltage [14]. The mathematical model for pull in voltage for CMUT with square membrane is proposed considering the linear electrostatic force model and deflection nonlinear model [15]. The membrane shape can be circular or square [16] (Figure 1).

When the membrane is deflected towards substrate the AC bias is applied between the electrodes converting the membrane to the state of vibration and generating the acoustic waves with the frequency above the audible range behaving as a transmitter. On the other hand, biased membrane is exposed to acoustic waves leading to the membrane deflection and change in capacitance between the two electrodes. This change in capacitance results in the generation of electrical signal and the device becomes a receiver [17]. CMUT works in both the transmitting mode and the receiving mode. The membrane of CMUT can be made of different materials with varying material properties [18]. Sharma et al. [19] and Nabian, et al. [20] have given strategy for both the mechanisms namely electrostatic actuation and hydrostatic pressure actuation without the need of any numerical computation. The results were in good agreement with the method of step by step linearization using finite difference method proposed [17].

In this paper, the effect of varying gap height and the radius of a circular plate CMUT is modelled using lumped parallel plate model [17]. The change in various parameters like capacitance, deflection with static bias, deflection with AC bias, pull in voltage and the pressure have been discussed with satisfactory simulation results. The work can be further extended by utilizing the slotted membrane for improving the sensitivity of the trasnducer [18].

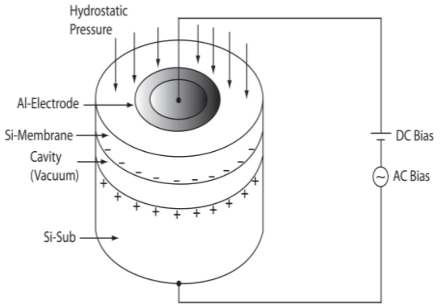

Figure 1. 3D view of Capacitive Micro-machined Ultrasonic Transducer

2. THEORY OF OPERATION

The mechanical behavior of the circular membrane can be examined using Kirchhoff classical thin plate theory considering thickness to length ratio to be very small. The geometrical parameters used for simulation have been listed in Table 1. Amorphous Silicon is used as the membrane material with the material properties mentioned in Table 1. The plate equation can be written in differential form with R as the plate radius ($0 \leq r \leq R$). The Equations (1)-(6) have been derived from literature [17].

$$\frac{d^4x}{dr^4}+\frac{2}{r}\frac{d^3x}{dr^3}-\frac{1}{r^2}\frac{d^2x}{dr^2}+\frac{1}{r^3}\frac{dx}{dr}=\frac{F(r)}{D} \tag{1}$$

where, D refers to the flexural rigidity of the top electrode and is calculated by relating the material properties as shown in Equation (2):

$$D=\frac{Et^3}{12(1-\nu^2)} \tag{2}$$

The electrostatic forces of the silicon membrane acting per unit area for the fixed circular membrane at periphery is given by Equation (3):

$$F(r)=\frac{\varepsilon o V^2}{2\left(d_0-x(r)\right)^2} \tag{3}$$

where, the displacement of the membrane along r is represented by x(r), V, the applied static voltage among the top and bottom electrode, d_0, the original distance within the plates, and ε_o, is the permittivity of the vacuum. With further increasing the DC bias the balance among the top and bottom electrode is no longer balanced and results in the state of collapse. This static collapse voltage is given by Equation (4):

$$V_C=\frac{5.46}{R^2}\sqrt{\frac{Dd_0^3}{\varepsilon_0}} \tag{4}$$

The capacitance among both the plates along d(r) with r the radius of the CMUT with circular membrane is given by equation:

$$C=\int_0^R \varepsilon_0 \frac{2\pi r}{d_0-x(r)} \tag{5}$$

TABLE 1. Geometrical parameters used for CMUT Operation

Material	**Silicon**
Radius, R	45 µm
Thickness, t	1 µm
Young’s modulus, E	130GPa
Poisson’s Ratio, ν	0.23
Density, ρ	2330kg/m3
Initial Gap, d_o	1 µm
Dielectric Constant(Vacuum), ε_o	8.85x10-12 F/m

The base capacitance of the parallel plates can be found by $V \to 0$ is given by the following equation :

$$C_{base} = \varepsilon_0 \frac{\pi R^2}{d_0} \tag{6}$$

The operating frequency of CMUT has been calculated by the FEM simulations done in COMSOL. Figure 2 gives the eigen frequency plot for CMUT with radius as 45 µm. The eigen frequencies with reducing radii are enumerated in Table 2.

3. RESULTS AND DISCUSSION

The collapse or pull in voltage is expressed by Equation (4) and the response of the pull in voltages with decreasing radius of the circular CMUT is illustrated in Table 2. Table 2 signifies the behaviour of CMUT with increasing pull in voltages with decrease in the radius denoting the more compact the size the more operating voltages it can handle. Figure 3 shows the plot of capacitance change with the applied DC bias with decreasing radius from 45 µm to 25 µm with a gap height of 1µm. The capacitance between the parallel plate's increases with increasing DC voltage for a CMUT with radius 45 µm, as the radius of the device is further decreased the relative increase of capacitance decreases and for the radius with 25 µm the capacitance becomes almost constant. This signifies that more minimization in size of the CMUT cease the change in capacitance.

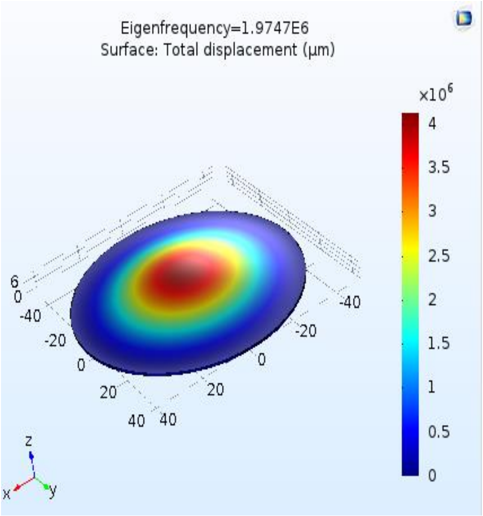

Figure 2. FEM simulation for Eigen frequency with R=45 µm

TABLE 2. Pull in Voltages with decreasing radii of CMUT

Radius (µm)	**45**	**40**	**35**	**30**	**25**
Pull-in Voltage (V)	96.9	122.6	160.2	218.1	314.0
Eigen Frequency (MHz)	1.9	2.4	3.2	4.4	6.3

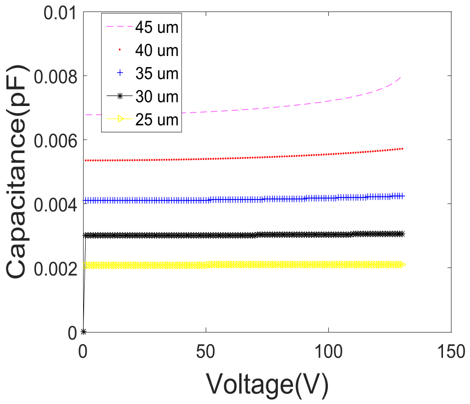

Figure 3. Capacitance along with DC voltage for decreasing radii with gap height = 1 µm

Figure 4 represents the capacitance change with both decreasing radii and reduced gap height to 0.5 µm. As the plot shows the capacitances reaches its peak for a certain DC bias and further it starts decreasing with the rising voltages.

The maximum operating voltage for the capacitance shifts with the decreasing radii which infers the operating voltage of the CMUT expands with the reduction in size. Plots of Figures 4 and 5 are the simulation results of Equation (5). The membrane deflects downwards towards the substrate when the DC bias is applied. Figure 5 gives the deflection plot for increasing voltages the membrane deflection rises with the developing voltage with a gap height of 1 µm. As the plot displays the deflection reduces with the reduction in CMUT dimension i.e. the distance of membrane is reduced with the increase in bias. Figure 6 signifies the change in deflection when the gap height is reduced to 0.5 µm. The graph shows with the increase in applied voltage the membrane collapses with the substrate and then further with increasing bias it reverts and resumes its original position with respect to the substrate.

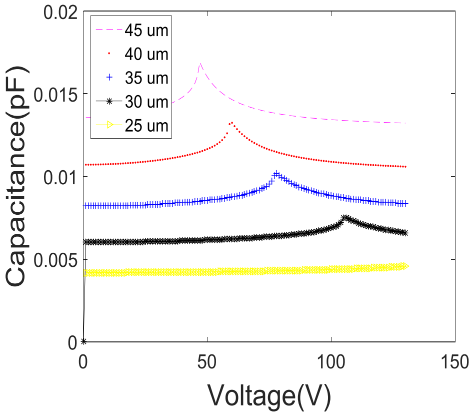

Figure 4. Capacitance along with dc voltage for various radii with gap height = 0.5 µm

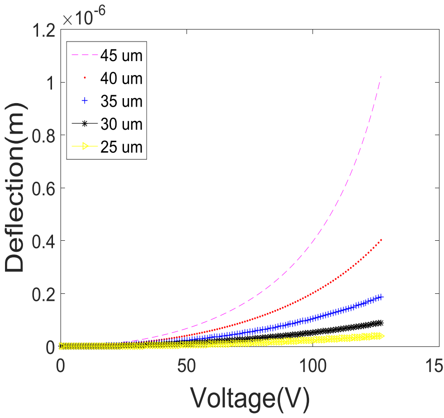

Figure 5. CMUT Membrane deflection along varying DC voltage with gapheight = 1 μm

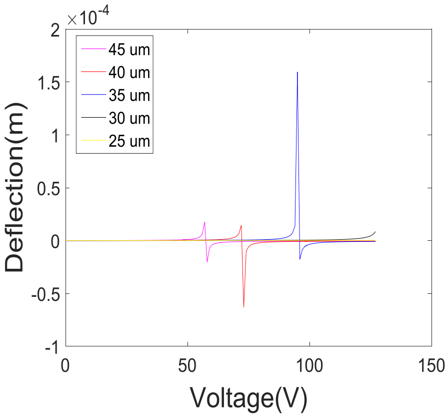

Figure 6. CMUT Membrane deflection along varying DC voltage with gap height = 0.5 μm

The behavior remains the same for the decreasing radii only the distance of deflectionreduces. One more important parameter in CMUT is deflection along radius, maximum membrane deflection occurs at the center of the device and minimum at the periphery as the boundaries are fixed. Figure 7 discusses the simulation outcome of the device for deflection along radius.With the decreasing radii the deflection is less and as shown in the plot it is maximum at the center and minimum at the boundary for each radii.

Figure 8 shows the same variation along radius with reduced gap height of 0.5 μm or less in which deflection becomes negative for CMUT with large radius i.e. 45 μm which shows the limitation of the developed model with presumption of classical thin plate theory. The proportion of membrane diameter to its thickness should be >20 [17]. Figures 9 and 10 represents the pressure developed on the membrane which changes with the distance along the radius. The highest pressure intensity is developed at the center of the membrane and reduces as the movement is towards periphery of the membrane as shown in Figures 9 and 10. As the movement is away from the center the acoustic waves separates out till the perimeter of the device which illustrates pressure intensity reduces with the increasing dimension of CMUT. Further with reduced gap height to 0.5 μm it has no impact on the generated pressure as displayed in Figure 10.

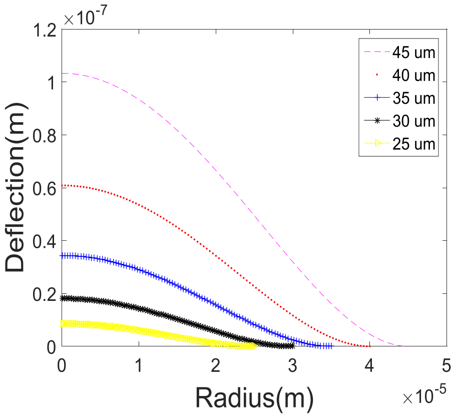

Figure 7. Deflection of Membrane along Radius with Gap Height = 1 μm

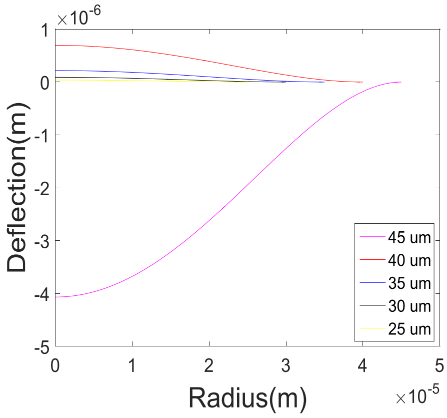

Figure 8. Deflection of membrane along radius with gap height = 0.5 μm

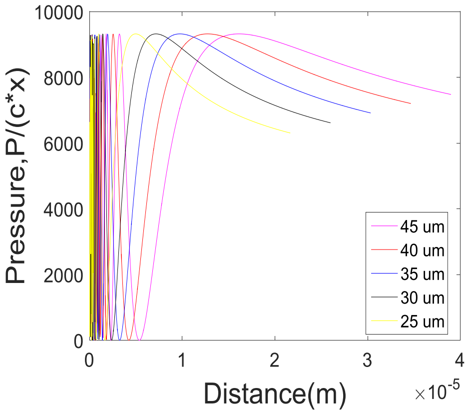

Figure 9. Pressure produced by the membrane with distance from center with gap height = 1 μm

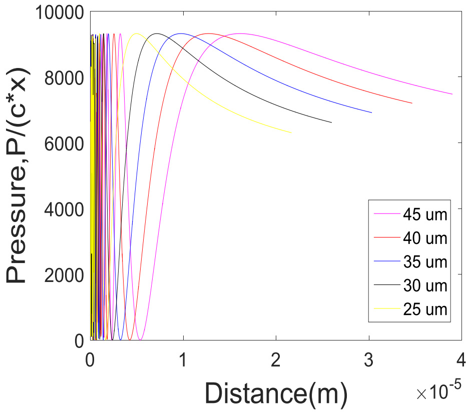

Figure 10. Pressure produced by the membrane with distance from center with gap height = 0.5 µm

4. CONCLUSION

In this paper Capacitive Micro machined Ultrasonic Transducer is simulated with circular geometry by varying the radius and the gap height of the device. The results shown and discussed for various parameters like Capacitance with applied DC bias, Deflection of membrane along DC bias, Deflection with radius from center and variation in pressure intensity along the distance from origin. Behavior of capacitance change remains same for the dimension from 45 µm to 35 µm, after further reduction to 30 µm and 25 µm the capacitance becomes constant which limits the further reduction of dimension of CMUT. Similarly deflection change also becomes nil at the much smaller dimensions. In addition to this it is also observed that CMUT deflects at lower DC voltage around 60 V (Figure 6) for radius 45 µm but as we reduce the radius further it requires more voltage for deflection. In another analysis (Figures 8 and 10) for variation along radius with reduced gap height of 0.5 µm or less, the deflection becomes negative for CMUT with large radius i.e. 45 µm which is the limitation of the developed model and the pressure intensity increases with the increasing dimension of CMUT also it has no impact on the generated pressure with gap height reduced to 0.5 µm. This analysis will help to reduce the effort of researcher for dimension selection of CMUT before its fabrication.

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چکیده

ترانسفورماتورهای التراسونیک با میکرومکانیکی (CMUT) با ظرفیت‌پذیری، دستگاه‌های اولتراسونیک هستند که ویژگی‌های بهتر را در مقایسه با مبدل‌های پیزوالکتریک تولید می‌کنند. پارامتر ذاتی CMUT با تغییرات در ابعاد هندسی دستگاه متفاوت است. ارتفاع حفره و شعاع CMUT با غشاء دایره‌ای در مدل صفحات موازی توزیع شده برای تاثیر آن بر پارامترها متفاوت است. در این مقاله، مدل تحلیلی CMUTهای دایره‌ای با استفاده از معادلات خازن موازی–صفحه طراحی و ساخته شده است. تاثیر تغییرات هندسی با تجزیه و تحلیل پارامترهای انحراف، خازن، ولتاژ و فشار در نظر گرفته شده است. نتایج مورد بحث در اینجا، در تصمیم‌گیری در مورد محدودیت کمینه‌سازی CMUT قبل از ساختن، مفید خواهد بود.

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