Optimized Design of CMUT with Hexagonal Membranes

Rashmi Sharma, Rekha Agarwal, Ashwani Kumar Dubey, Anil Arora

Abstract**:** ***A Capacitive Micro-machined Ultrasonic Transducer (CMUT) with hexagonal membrane is constructed to work as a transmitter and compared to a CMUT with circular membrane. In this paper, three desirable combination of circular and hexagon are analyzed to select the dimensions for hexagonal shaped CMUT. Capacitive Micro-machined Ultrasonic Transducer (CMUT) is a micro constructed transducer used both as transmitter for generating ultrasonic waves and as receiver to modulate the electrical capacitance of the capacitive transducer. It can be fabricated with many geometries especially circular, square, rectangular, and hexagon. Circular CMUTs offers optimum performance in terms of deflection with DC, deflection of biased membrane with AC bias, resonant frequency, capacitance and deflection along frequency but for array formation the wafer area is wasted. A CMUT with hexagonal membrane gives an ultrasonic signal of constant amplitude with less deflection of membrane within the cavity and the outside environment. Stationary analysis is carried out with electro-mechanics for discussing the capacitance change of CMUT. The collapse or pull in voltage of hexagon CMUT is found to be high and increases the bandwidth of CMUT. The absolute percent difference of resonant frequency is observed to be 2.3 % with dimensions selected from the COH configuration of the CMUT***.

Index Terms**:** ***Array Formation, COH Configuration, Capacitance, Electro-mechanics, Geometries, Ultrasonic Signal***

I. INTRODUCTION

MIcro fabricated Capacitive Micro-machined Ultrasonic Transducers (CMUTs) became suitable substitute for the piezoelectric devices after large scale research and development in the micromachining techniques [1]-[3]. CMUT provides large improvement over piezoelectric transducers in terms of bandwidth, impedance matching, sensitivity and transduction efficiency [4]. CMUTs are the electrostatic transducers capable of the propagation and exposure of acoustic waves. The principal structure for the acoustic wave formation includes the oscillation of thin plate under the electrostatic forces. CMUTs are the parallel plate arrangement with a moving membrane and a fixed substrate forming a capacitor, the DC voltage is applied between the moving membrane acting as the top electrode and the fixed substrate acting as the bottom electrode. When the biased membrane is subjected to AC voltage the membrane generates the acoustic waves in the surrounding medium and behaves as a transmitter. If on the other hand the acoustic waves are subjected to the biased membrane the capacitance of the structure changes producing an output voltage of the same magnitude and behaves as a receiver. The membranes of the CMUT can be conductive or made from an insulating material topped with a metal layer. The gap among the electrodes can be air filled or vacuum. The membranes are generally of the order of less than hundreds of μm's. With the advent in the silicon micromachining fabrication techniques arrays of CMUTs can be formed in batch utilizing same wafer resulting in reduced costs in comparison to piezoelectric transducers. With extension the CMUT arrays can be easily integrated with the supporting electronics. Lithography methods of fabrication facilitate to produce the CMUTs with divergent shapes and sizes [5] - [7].

CMUTs finds applications in various fields like medical imaging, nondestructive testing, distance measuring in both air and under water etc. In medical applications like intravascular ultrasound (IVUS), flexible or 2D arrays CMUTs provide encouraging results in comparison to piezoelectric transducers [8]-[11]. For increased penetration high transmitted pressures are required with improved signal to noise ratio in ultrasound for medical imaging [12]. For early heating of the tissues, higher output pressures are required in therapeutic applications. The major drawback of the CMUTs is the generation of the low output power in comparison with the piezoelectric [13]. With years, CMUTs have been made to operate in the pull in region and the snapback region for the maximum power output [14].

CMUT can be constructed and fabricated with various feasible geometries namely Circular, Square, Rectangular and Hexagon. From the literature review it has been found that the CMUT with Circular geometry gives the best performance in terms of the resonant frequency, deflection with applied DC voltage, deflection with applied AC bias, and capacitance [15]-[16]. Authors in [17] have discussed the impact of variation in geometrical features on the various performance parameters of CMUT. With clamped square membrane, the pull-in voltage is determined utilizing the linearized electrostatic force model and non-linear deflection model [18]. In this paper, the circular and hexagon configurations are discussed for appropriate dimension selection while modelling of the 3D hexagon CMUT in COMSOL. CMUT with circular and hexagon membranes have been compared with their behavior of generated ultrasound, resonant frequency and displacement of membrane under enforced DC and AC bias. It has been ascertained that the CMUT

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with hexagon geometry having 49.779 µm as side length gives the best performance in comparison to circular CMUT.

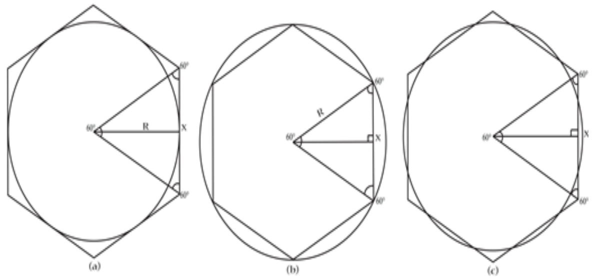

Fig. 1 Possible Combinations of Circular and Hexagon Membrane of CMUT

II. ACHIEVABLE GEOMETRIES

In this paper, three viable combinations of circular and regular hexagon geometries have been discussed for constructing CMUT. As shown in Fig. 1, the circle resides in the hexagon (CIH), secondly hexagon is placed inside the circle (CSH) and in last

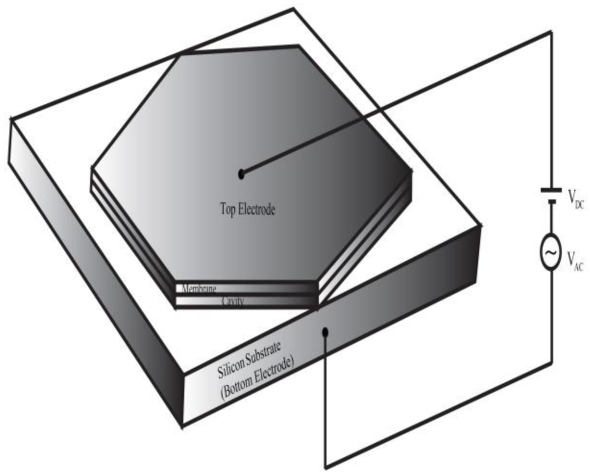

Fig. 2 3D Representation of Hexagonal Capacitive Micromachined Ultrasonic Transducer

TABLE 1
Dimensions for the possible combinations of geometries of CMUT

S. No.	Possible Configuration	Radius of Circle(µm)	Side of Hexagon(µm)
1.	Circle inscribed Hexagon(CIH)	45	51.96
2.	Circumscribed Hexagon(CSH)	45	45
3.	Circle overlapping Hexagon(COH)	45	49.779

circle and hexagon (COH) crosses each other at various points. The dimensions for all the three combinations were calculated as shown in Table 1. Fig. 2 describes a 3D hexagon CMUT whose dimensions are calculated based on the above description. The material properties used for hexagon CMUT are described in Table 2.

Case1. Circle inscribed Hexagon (CIH) as shown in Fig. 1(a), the side length of Hexagon membrane is given by (1):

$$x_1 = 2R/\sqrt{3} \qquad (1)$$

Where, R is radius of the circle.

Case2. Circumscribed Hexagon (CSH) as shown in Fig. 1(b), the side length of Hexagon membrane = Radius of the Circle as shown in equation (2):

$$x_2 = R \qquad (2)$$

Case3. Circle overlapping Hexagon (COH) as shown in Fig. 1(c) is given by (3):

$$b = \sqrt{\frac{R^2\pi}{2\sqrt{3}}} \qquad (3)$$

Where, b is the length of perpendicular on the side of Hexagon. Side length of Hexagon membrane is solved by (4):

$$x_3 = 2b/\sqrt{3} \qquad (4)$$

TABLE 2
Specifications Used For Constructing CMUT

Property	Substrate	Membrane
Material	Isotropic Silicon	Isotropic Silicon
Thickness, t	5 µm	1 µm
Young's modulus, E	170GPa	170GPa
Poisson's Ratio, ν	0.28	0.28
Density, ρ	2329 kg·m-3	2329 kg·m-3
Relative Permittivity	11.7	11.7

III. ANALYSIS OF CMUT

The hexagon geometry of CMUT behaves similar to the circular CMUT when the boundaries are fixed the deflection of hexagon membrane become circular with applied bias and force, as shown in the schematic diagram Fig. 3. In this section, various analysis like resonant frequency, DC analysis, AC analysis and stationary analysis have been discussed further.

3.1. RESONANT FREQUENCY

When a membrane of CMUT is subjected to a time varying input voltage, it comes into vibration and leads to formation of ultrasonic waves [19]. The resonance frequency is a function of intrinsic stress and increases with its increase. With increased levels of stress, the stress influences the flexural rigidity [20], [21].

The resonant frequency for hexagon CMUT (f_{rh}) can be derived using (5):

$$f_{rh} = \frac{0.94t}{2\pi^2 x_3^2}\sqrt{\frac{E}{\rho(1-\upsilon^2)}} \qquad (5)$$

Where,

x_3= Side of hexagon with COH configuration and

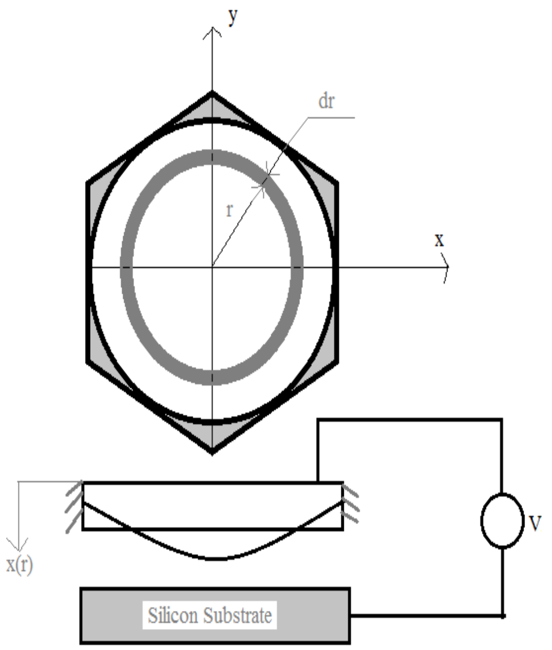

Fig. 3 Schematic Of Hexagon CMUT For Calculating The Deflection

calculated using (4)

E=The Young's modulus of the membrane

ν= The Poisson's ratio

ρ= Density of the membrane

t= Thickness of the membrane

In (5), x_3 is the only dimensions on which properties of membrane responsible for the resonance frequency. The resonant frequency for all the geometries with dimensions, as mentioned in Table 1, for circular and hexagon CMUT are tabulated in Table 3. Table 3 compares the hexagon and circular CMUT and signifies that the hexagon CMUT with equal dimensions for radius of circular and side of hexagon, the resonant frequency is found maximum. The percent difference in resonant frequency of COH configuration with respect to circular configuration comes out to be 2.3 %, which is found minimum as per Table 3. The 3D view of resonant frequencies plot is shown in Fig. 4. Fig. 5 shows the displacement along frequency, which is obtained maximum at the resonant frequency of each configuration.

3.2. DC ANALYSIS

With the parallel plate arrangement of CMUT, the DC bias is enforced between the top plate acting as membrane and the bottom plate i.e. substrate of the CMUT. The membrane starts deflecting downwards due to electrostatic forces of the substrate. With the help of electrostatics, solid mechanics and moving mesh the CMUT is modeled in 3D. The DC voltage is applied from 0 to 100 V by using sweep and applying fixed

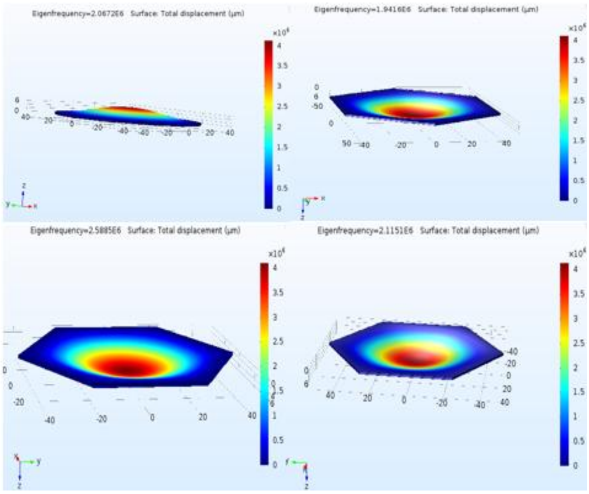

Fig. 4 3D View Of Resonant Frequencies Plot For All The Used Configurations Of CMUT

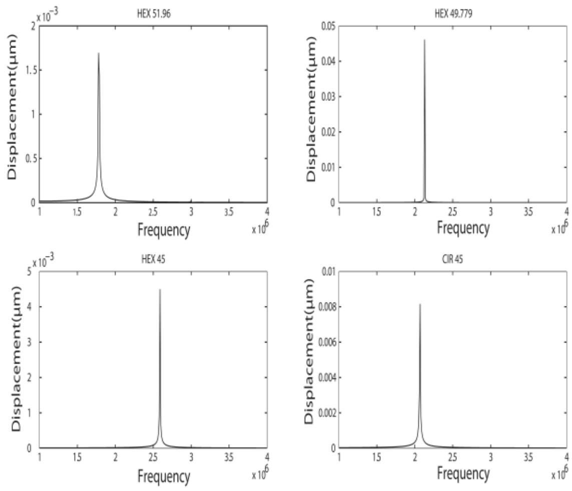

Fig. 5 Displacement Along Frequency Representing Maximum Displacement At Resonant Frequencies

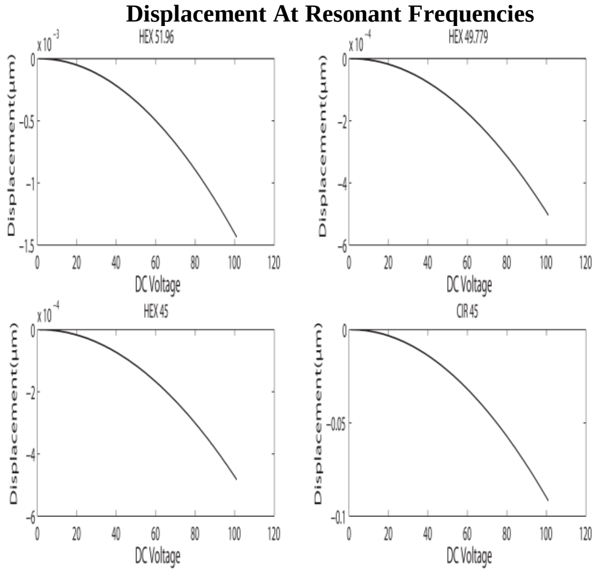

Fig. 6 DC Analysis of Circular and Hexagon CMUT for various dimensions

constraint to the sides of the hexagon and the boundaries of circular CMUT along with the upper side of the substrate.

The behavior of deflection of different geometrical configurations is shown in Fig. 6. It is reflected from Fig. 6 that the behavior of deflection remains same although the deflection is maximum for circular configuration in comparison to hexagon CMUT, but, the collapse voltage should be high so that the membrane does not merge with the substrate.

3.3. AC ANALYSIS

The DC biased membrane when deflected remains between cavity gap and the surrounding medium. When the biased membrane is subjected to AC voltage the membrane starts vibrating within the cavity and generates acoustic waves. The time dependent study is used to simulate the CMUT with applied AC bias along with the Electrostatics, Solid Mechanics and Moving mesh analysis. The Fig. 7 shows the generated ultrasonic waves for all the configurations used for CMUT.

The hexagon CMUT with 49.779 µm dimension generates a stable ultrasonic signal with fixed displacement of the membrane. The hexagon CMUT and circular CMUT with 45 µm generates an ultrasonic signal with same displacement and frequency. Hexagon CMUT with 51.96 µm as side length forms an acoustic wave which is not stable initially but becomes stable with increased voltage and time.

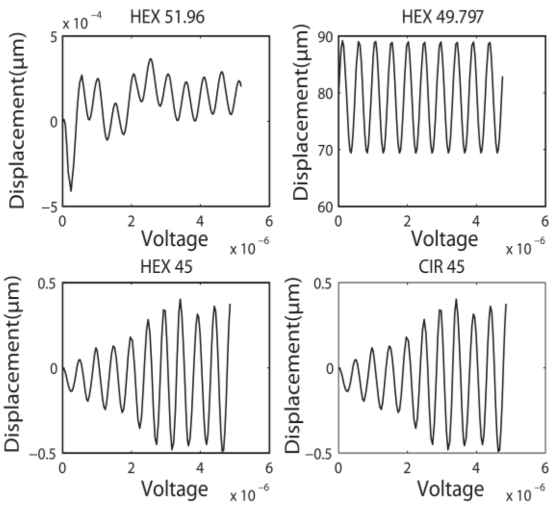

Fig. 7 Behavior of Ultrasonic signal for Circular and Hexagon CMUT

3.4. STATIONARY ANALYSIS

The Electro-mechanics physics is used to model the CMUT for solving the capacitance change of the parallel plate capacitor with applied DC voltage. For modelling the deformation of electrostatically actuated CMUT the Electro-mechanics incorporates solid mechanics, moving mesh and electrostatics. Fig. 8 shows the capacitance plot for circular and Hexagon CMUT the nature of capacitance change remains same for all other combinations the capacitance increases with increasing DC bias.

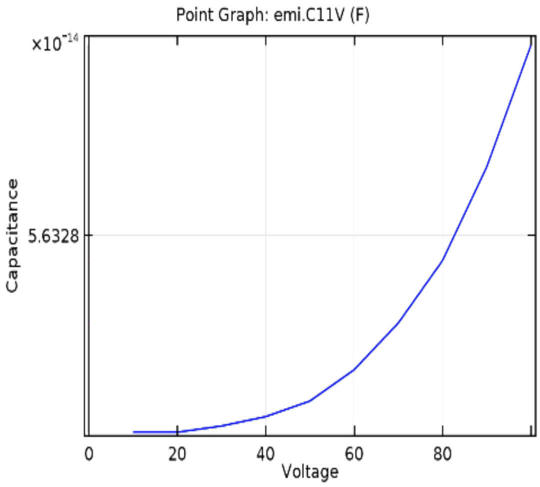

Fig. 8(a) Capacitance Plot With Respect To Voltage For Circular CMUT

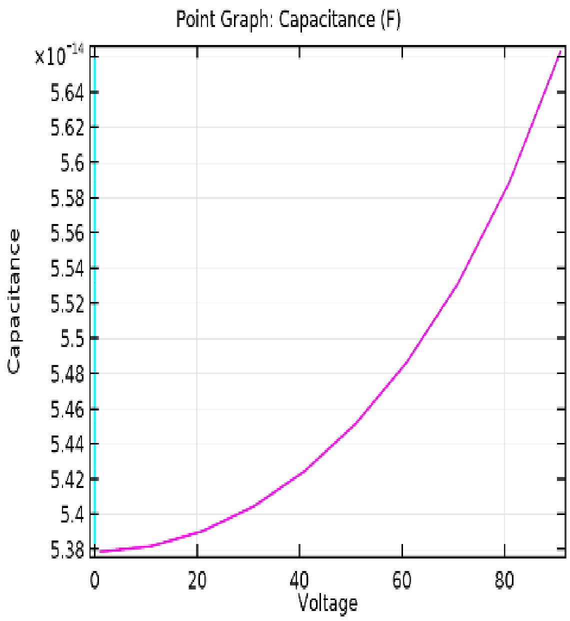

Fig. 8 (b) Capacitance Plot with respect to Voltage for Hexagon CMUT

IV. CONCLUSION

In this paper, possible combination of circular and hexagon geometries is being given for the effective selection of dimension for hexagonal shaped CMUT. Various analysis like DC analysis, AC analysis, resonant frequency and stationary analysis are being done. DC analysis proves the pull in or the collapse voltage for the hexagon CMUT is high as compared to the circular CMUT which makes it more suitable for operating in the wider range of the DC voltage as the deflection is also reduced within the cavity. The AC analysis shows the ultrasound generated for all the mentioned dimensions of the CMUT and reflects that the ultrasound generated for the hexagon CMUT with 49.779 µm is most stable and suitable for the flowmeters. The resonant frequency with COH configuration of CMUT has 2.3 % Absolute difference with respect to circular CMUT. The capacitance change with applied voltage is similar for both the hexagon and circular CMUT. The hexagon CMUT when batch produced utilizes the full wafer area and gives the stable ultrasonic signal and can be a good substitute for Circular CMUT and save the wafer area from being wasted.

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