J M M
Journal of Mechanics and MEMS
Special Issue dedicated to Prof. K Y Ye edited by Z M Ye, P Liu and B Sun

ISSN: 0974-8407
© Serials Publications
9(2) 2017: pp. 401-407

AIR CAVITY HEXAGONAL CAPACITANCE MICROMACHINED ULTRASONIC TRANSDUCER

Shailendra Kumar Tiwari[1], Kunal K. Trivedi[2], B. S. Satyanarayana[3] and A. Goaplkrishna Pai[1]

ABSTRACT

Today's ultrasound technology covers a wide range of measurements, diagnostic, and other applications, e.g. from non-destructive testing to medical ultrasonic imaging or from surveillance in process plants to distance measurement. The capacitive micromachined ultrasonic transducers (CMUT) receive increasing acceptance as an alternative to piezoelectric transducers for certain fields of applications due to a number of distinctive features. The present paper focuses on novel technological aspects regarding the improvement in performance of CMUT consisting of Poly-silicon membranes. The simulations were carried out using MATLAB and IntelliSuite 8.0 for air cavity hexagonal CMUT. The study indicates that in the range of study, the best performance is achieved at the natural resonance frequency, which is very desirable. The results are verified with the existing journal papers.

Kewords: Central frequency, CMUTs, Collapse voltage, Mechanical Impedance, snapback voltage, Transducer

1. INTRODUCTION

Currently, the vast majority of ultrasound transducers are fabricated using piezoelectric crystals and composites. However, piezoelectric transducers have drawbacks that motivate micro-machined approach to transducer design. Capacitive Micromachined Ultrasonic Transducers (CMUTs) operate on a capacitive principle of ultrasonic transduction that has several advantages over the more traditional piezoelectric methods, especially when used in air-coupled applications [1]. The membrane material, thickness has a wide impact on the performance of the CMUTs. In this paper we discuss the mechanical impedance of the membrane, collapse voltage and the central frequency for the different thickness of poly-silicon membrane.

The ultrasonic transducer discussed in this paper is formed by a plurality of CMUT cells, each comprising a charged diaphragm plate capacitively opposing an oppositely charged base plate. The diaphragm plate is distended toward the base plate by a bias charge. The base plate includes a central portion elevated toward the center of the diaphragm plate to cause the charge of the cell to be of maximum density at the moving center of the diaphragm plate. For harmonic operation the drive pulses applied to the cells are predistorted in consideration of the nonlinear operation of the device to reduce contamination of the transmit signal at the harmonic band. Figure 1 shows the schematic of a single cell CMUT.

In order to generate acoustic waves, the membrane is driven in oscillation superimposing to the polarization voltage V_{DC} an alternating component V_{AC} which varies the electrostatic force generated by the static voltage V_{DC}. The polarization voltage V_{DC} is necessary also in transmission because as it well known electrostatic force only attractive i.e. a quadratic relationship exist between force and applied voltage. An alternating voltage applied to the CMUT without polarization voltage would cause attraction of the membrane twice in a single cycle forcing the membrane to oscillate at double frequency [3]. If the membrane is biased appropriately and subjected to ultrasonic waves at resonance frequencies, significant detection current will be generated [4].

1. Department of E&C Engineering, Manipal Institute of Technology, Manipal, Karnataka-576104, India

2. Bigtec Private Limited, Bangalore Karnataka-560082, India

3. Manipal Institute of Technology, Manipal, Karnataka-576104, India, *E-mail: trikunal83@gmail.com*

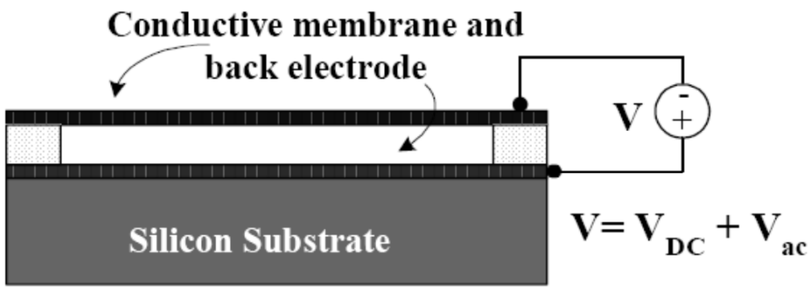

Figure 1: Schematic of One Element of CMUT

2. RESONANCE FREQUENCY

In a CMUT, a membrane is actuated by a time varying input voltage and the vibration of the membrane generates the ultrasound waves in the medium ahead of it. The natural frequency of the membrane is known as the central frequency or the resonance frequency of the transducer.

$$f = \frac{0.47 l_t}{a^2}\sqrt{\frac{Y_0}{\rho(1-\sigma^2)}}$$

where f = resonance frequency, l_t = thickness of the membrane, a = radius of the device, ρ = density of the membrane material, σ = poison's ratio, Y_0 = Young's modulus of the membrane material.

3. COLLAPSE VOLTAGE

Collapse voltage of a CMUT is a critical parameter for employing the device at the optimum operating point. The operating DC bias voltage determines the performance of the transducer. It also determines the operating regime at which the device is operated, such as conventional and collapse mode. As V_{DC} increased there is a point at which the electrostatic force overwhelms the spring's restoring force, and membrane collapses.

The spring constant k can be found a ratio of pressure and volume displacement.

$$k = \frac{TAt_n}{\left(\frac{c}{d} - \frac{a}{2}\frac{J_0(a\sqrt{d/c})}{J_1(a\sqrt{d/c})}\sqrt{\frac{c}{d}} + \frac{a^2}{8}\right)}$$

where

$$c = \frac{(E+T)t_m^2}{12\rho(1-\sigma^2)} \text{ and, } d = \frac{T}{\rho}$$

where T, ρ and σ are the residual stress, density, and Poisson's ratio of the membrane material respectively and A is the area of the membrane. If x denotes the membrane displacement the total restoring strain force is

$$F_S = kx$$

The electrostatic force on the membrane is given by

$$F_E = \frac{A\varepsilon^2 V^2}{2\varepsilon_0\left(t_m + \frac{\varepsilon}{\varepsilon_0}(t_a - x)\right)^2}$$

The voltage to keep the membrane at a certain deflection x can be found by equating F_E and F_S and solving for V.

The critical voltage at which the membrane become unstable can be determined by finding the displacement for which $\partial V/\partial x = 0$ Solving yields $x = \frac{1}{3}\left(t_a + \frac{\varepsilon_0}{\varepsilon} t_m\right)$ and the corresponding collapse voltage is found as

$$V_{Collapse} = \sqrt{\frac{8k\left(t_a + \frac{\varepsilon_0}{\varepsilon} t_m\right)^3}{27A\varepsilon_0}}.$$

In order to prevent the capacitor form shorting after the collapse, a thin insulating layer is provided at one of the electrode. After the membrane has collapsed it will not snap back until the voltage is reduced to below V_{collapse} to $V_{Snapback} = \sqrt{\frac{2kL^2_{insulator}(t_a - L_{insulator})}{\varepsilon_{insulator} A}}$, where k- spring constant, t_a-Separation between the plates of CMUT, $L_{\text{insulator}}$-thickness of the insulator layer, A- area of the single cell CMUT, x- collapse distance.

4. MECHANICAL IMPEDANCE OF THE SINGLE CMUT CELL

We consider a circular membrane of a radius a operating in air, the poly-silicon membrane has Young's modulus of Y_0 and a Poisson's ratio of σ. In addition membrane is in tension T in units N/m^2 the differential equation governing the normal displacement $x(r)$ of the membrane can be written as [1][7].

$$\frac{(Y_0 + T)l_t^3}{12(1-\sigma^2)}\nabla^4 x(r) - l_t T\nabla^2 x(r) - P - l_t\rho\frac{d^2x(r)}{dt^2} = 0 \tag{1}$$

where l_t is the thickness of the membrane and P is the external uniform pressure applied to the membrane. The equation is derived from an energy formulation and the critical sumption is that the tension generated by a displacement x is small compared to the tension T. Assuming a harmonic extension at an angular frequency ω, (1) is known to have solution of the form

$$x(r) = AJ_0(k_1 r) + BJ_0(k_2 r) + CK_0(k_1 r) + DK_0(k_2 r) - P/(\omega^2 \rho 1_t) \tag{2}$$

where A, B, C and D are the arbitrary constants, $J_0()$ is the zeroth order Bessel's function of first kind, and $K_0()$ is the zeroth order Bessel's function of second kind. We immediately deduced that $C = 0$ and $D = 0$ because of Bessel's function of second kind is infinite at $r = 0$ which is not physical, if we use (2) to substitute for $x(r)$ in (1), we find that k_1 and k_2 must satisfy the characteristics equations [1]

$$\frac{(Y_0 + T)l_t^2}{12(1-\sigma^2)}k_1^4 + \frac{T}{\sigma}k_1^2 - \omega^2 = 0 \tag{3}$$

$$\frac{(Y_0 + T)l_t^2}{12(1-\sigma^2)}k_2^4 + \frac{T}{\sigma}k_2^2 - \omega^2 = 0 \tag{4}$$

Following Mason's notation, we define [7] $c = \frac{(Y_0 + T)l_t^2}{12(1-\sigma^2)}$, and $d = \frac{T}{\rho}$

The quadratic formula then gives the solution

$$k_1 = \sqrt{\frac{\sqrt{d^2 + 4c\omega^2} - d}{2c}} \tag{5}$$

and

$$k_2 = j\sqrt{\frac{\sqrt{d^2 + 4c\omega^2} + d}{2c}} \tag{6}$$

In order to determine the constant A and B two boundary conditions are necessary. Physically reasonable boundary conditions at $r = a$ are that $x = 0$, which implies that the membrane undergoes no displacement at its periphery, and $(d/dr)\, x = 0$, which implies that membrane is perfectly flat at its periphery. Both conditions amount to stating that membrane is perfectly bonded to an infinitely rigid substrate. Using these conditions we determine the constant A and B and the final displacement of the membrane as [1][7]

$$x(r) = \frac{P}{\omega^2 \rho l_t} \times \left[\frac{k_2 J_0(k_1 r) J_1(k_2 a) + k_1 J_0(k_2 r) J_1(k_1 a)}{k_2 J_0(k_1 a) J_1(k_2 a) + k_1 J_0(k_1 a) J_1(k_2 a)} - 1 \right] \tag{7}$$

Because we have assumed uniform pressure P, the force on the membrane is simply PS, where S is the area of the membrane. The velocity of the membrane is $u(r) = j\omega x(r)$, and we take v as a lumped velocity parameter [1]

$$\nu = \frac{1}{\pi a^2} \int_0^a \int_0^{2\pi} u(r) r\, d\theta\, dr \tag{8}$$

$$\nu = \frac{jP}{\omega \rho l_t} \times \left[\frac{2(k_1^2 + k_2^2) J_1(k_1 a) J_1(k_2 a)}{a k_1 k_2 (k_2 J_0(k_1 a) J_1(k_2 a) + k_1 J_1(k_1 a) J_0(k_2 a))} - 1 \right] \tag{9}$$

Mechanical impedance is defined as the ratio of pressure to velocity. Hence the mechanical impedance of the membrane Z_m can be written as [1] [7]

$$Z_m = \frac{P}{\nu} \tag{10}$$

Let us consider

$$A_1 = 1_t\, a k_1 k_2 (k_2 J_0 (k_1 a) J_1 (k_2 a) + 1_t k_1 J_1 (k_1 a) J_0 (k_2 a)) \tag{11}$$

$$A_2 = a k_1 k_2 (k_2 J_0 (k_1 a) J_1 (k_2 a) + k_1 J_1 (k_1 a) J_0 (k_2 a)) \tag{12}$$

$$A_3 = 2(k_1^2 + k_2^2) J_1(k_1 a) J_1(k_2 a) \tag{13}$$

$$Z_m = j\omega \rho l_t \left[\frac{A_1}{A_2 - A_3} \right] \tag{14}$$

the ultrasound waves. So the central frequency of the transducer is one of the prime factors to decide about the minimum AW size to be detected [4]. The simulated resonance frequency of mode-1, for the device given in this paper is 2.06 MHz.

Figure 2 shows the relation between the frequency and the mechanical impedance for 1 micron thick hexagonal poly-silicon membrane.

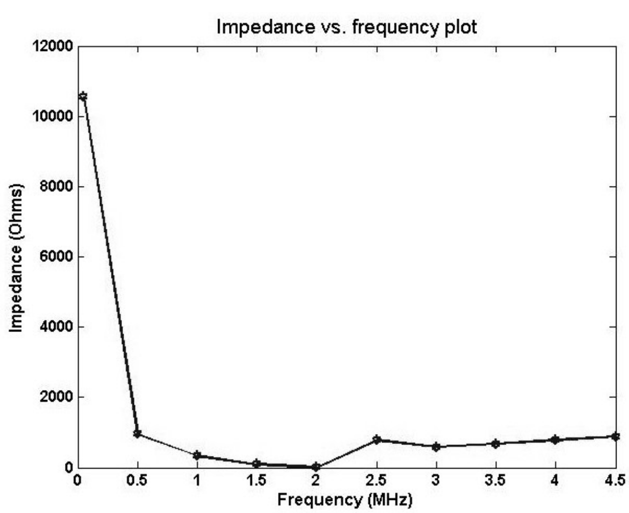

Figure 2: Plot of Mechanical Impedance Versus Natural Frequency

The collapse voltage is used to determine the applied voltage limit of the capacitive micromachined ultrasonic transducers for proper operation of the device.

Figure 3 shows the displacement pattern of the poly-Si membrane due to the DC bias voltage of 150 V between the membrane and silicon substrate. Figure 4 shows the stress distribution on the membrane due to applied voltage of 150 V.

From figure 5 it is observed that if voltage across the capacitor is increased the capacitance is increasing nonlinearly and after the collapse voltage there is a sudden rise in capacitance.

Ultrasonic waves were generated and received by two identical transducers. The signal was transmitted by biasing the transmitter transducer with a 50V DC bias as well as 10 V of AC signal.

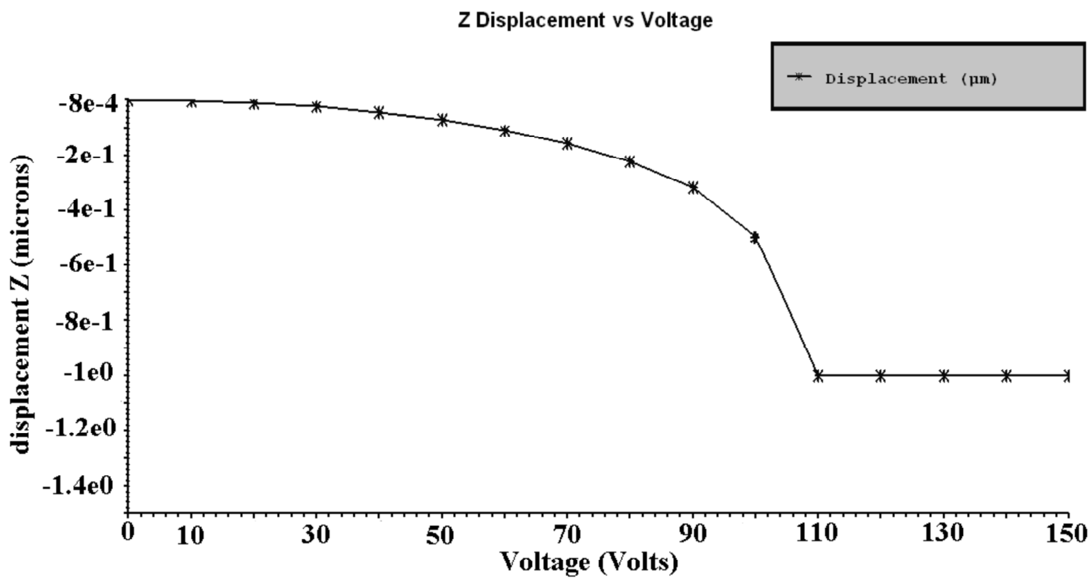

Figure 3: Plot of Displacement versus Voltage

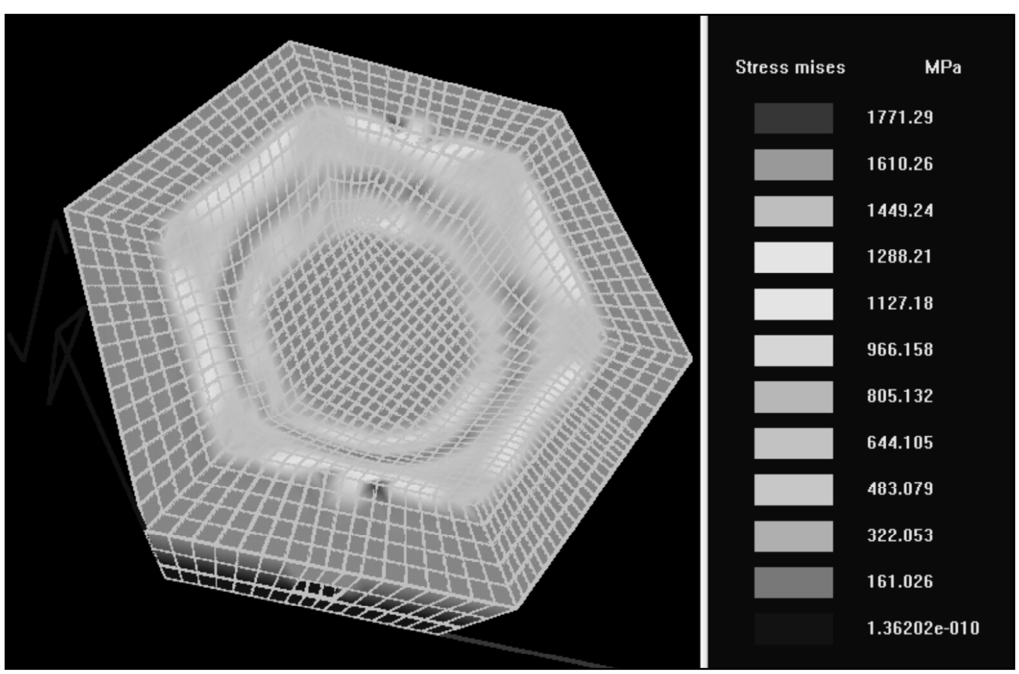

Figure 4: Displacement of the Membrane at 150V

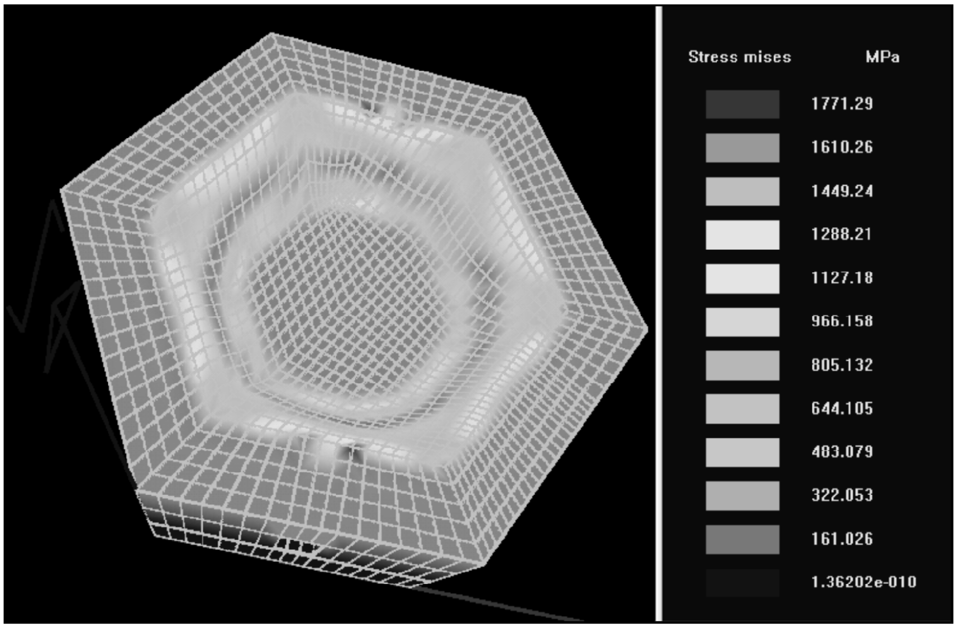

Figure 5. Stress Distribution in Membrane at 150V

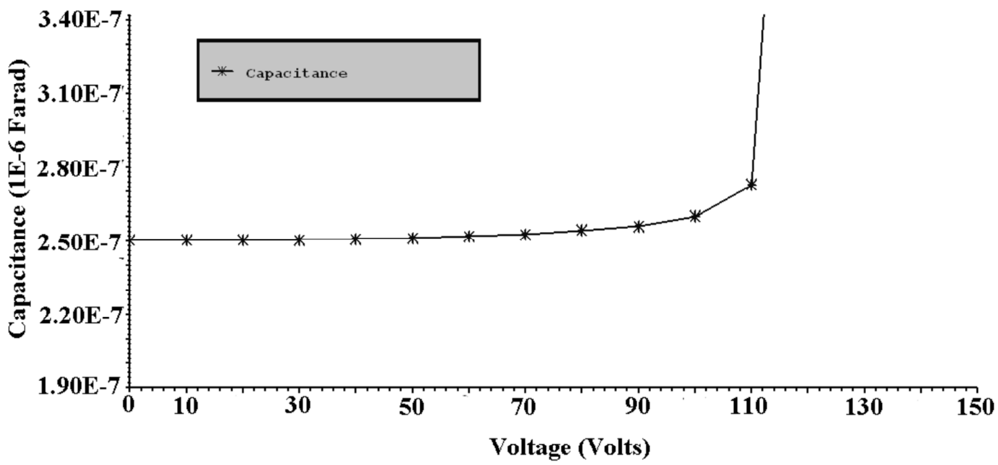

Figure 6: Capacitance versus Voltage Plot

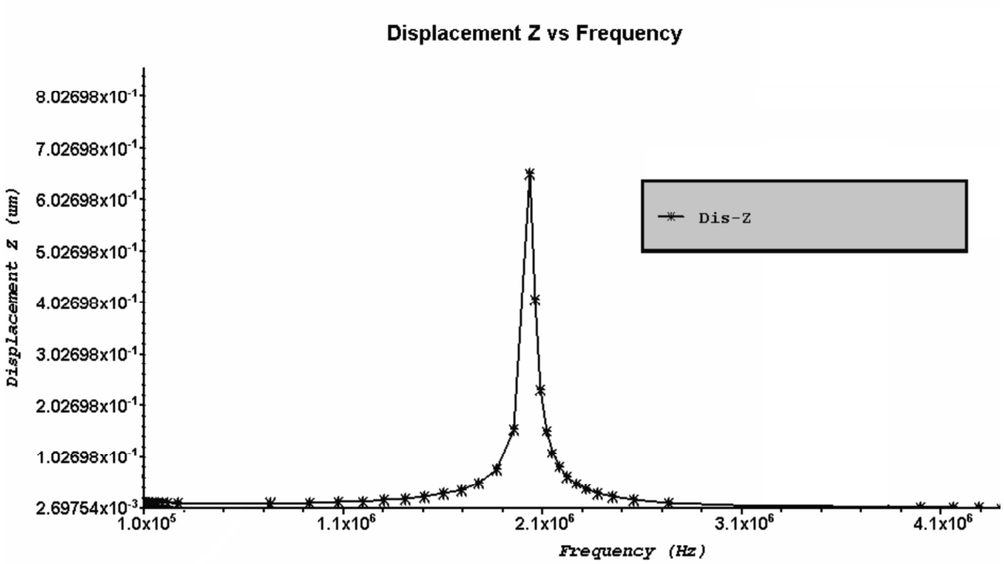

Figure 7: Frequency versus Displacement Plot

Figure 7 shows the displacement of the membrane at resonant frequency of 2.06 MHz due to the applied voltage.

5. CONCLUSION

The packaging densities of the hexagonal shaped devices are maximum and the best performance of the device is achieved at 2.06 MHz frequency. It is also observed that the thickness of membrane affects collapse voltage, snapback voltage, natural frequency of the CMUT. The CV characterstics and the collapse voltage analysis of the device is also reported.

References

[1] Igal Ladabaum, Hyongsok T. Soh, Butrus T. Khuri-Yakub "Surface Micromachined Capacitive Ultrasonic Transducer" *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, **45**(3), 1998.

[2] E. Cianci, V. Foglietti, G. Caliano, M. Pappalardo 2002 "Micromachined Capacitive Ultrasonic Transducer Fabricated using Silicon on Insulator Wafers" *Microelectronic Engineering*, 61-62, 1025-1029.

[3] G. Caliano, F. Galanello, A. Caronti, R. Carotenuto, M. Pappalardo "Micromachined Ultrasonic Transducers Using Silicon Nitride Membrane Fabricated in PECVD Technology".

[4] Igal Ladabaum, B. T. Khuri-Yakub 1 January 1998. "Micromachined Ultrasonic Transducers: 11.4 MHz Transmission in Air and More" *Appl. Phy. Lett.* **68**(1).

[5] Yongli Huang, A. Sanli Ergun, Edward Haeggstrom, Mohammad H. Badi and B. T. Khuri Yakub April 2003 "Fabricating Capacitive Micromachined Ultrasonic Transducers With Wafer-Bonding Technology" *Journal of Microelectromechinacal Systems*, **12**(2), 128-136.

[6] Omer Oralkan, Baris Bayram, Gosken G. Yaralioglu, Sanli Ergun, Mario Kupnik, Devid T. Yeh, Ira O. Wygant, B. T. Khuri Yakub August 2008 "Experimental Characterization of Collapse Mode CMUT Operation" *IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control*, **53**(8), 1513-1523.

[7] W. P. Mason 1942 "Electromechanical Transducers and Wave Filters " New York, Van Nostrand.

[8] Ayhan Bozkurt, Igal Ladabaum, Abdullah Atalar, B. T. Khuri-Yakub November 1999 "Theory and Analysis of Electrode Size Optimization for Capacitive Microfabricated Ultrasonic Transducers" *IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control*, **46**(6), 1364-1374.

[9] Shailendra Kumar Tiwari, A. Gopalkrishna Pai, Anil Arora, B. S. Satyanarayan, V. K. Dwivedi 2007 "Influence of Hexagonal Shaped Membrane Thickness on the Performance of Capacitive Micromachined Ultrasonic Transducers " 2nd Institute of Smart Structure and Systems National Conference-, CEERI, Pilani.

[10] Goksen G. Yaralioglu, Arif Sanli Ergun, Baris Bayram and B. T. Khuri Yakub "Calculation and Measurement of Electromechanical Coupling Coefficient of a Capacitive Micromachined Ultrasonic Transducers" *IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control*, **50**(4), 449-456, 2003.