FEM Simulation of CMUT Cell for NDT Application

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Abstract— This paper presents the simulation of various electromechanical performance parameters for an efficient and broadband air coupled Capacitive Micromachined Ultrasonic Transducer (CMUT) for Non Destructive Testing and Evaluation (NDT/NDE) using FEM simulation tool, CoventorWare. The non contact ultrasonic inspection performed in ambient air reduces the complexity and cost. Various critical parameters like collapse voltage, resonant frequency, coupling coefficient, squeeze film damping, bandwidth, quality factor and transient response of the single cell of CMUT are discussed. We employ a hexagonal CMUT cell for the modeling, which has higher packing density.

Index Terms --- CMUT, collapse voltage, NDT/NDE, FEM

I. INTRODUCTION

Recently CMUT based on electrostatic actuation has taken over traditional piezoelectric transducers for NDT/NDE application for various aspects like enhanced sensitivity, broad bandwidth, ease of batch fabrication and have better acoustic impedance match with air [1]. Ultrasonic transducers are used to generate short pulses which propagate in a solid or liquid medium. Flaws or discontinuities in the medium cause reflected pulses which are then detected. In general, a wide bandwidth around the pulse center frequency is desirable in order to distinguish closely spaced reflections [2]. Fig.1 shows the schematic of a single cell CMUT.

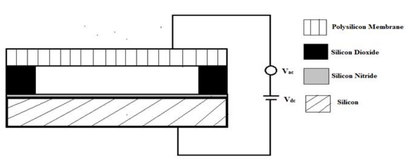

FIG.1: Schematic of a single cell of CMUT

In order to generate acoustic signal a DC bias is applied between the membrane and an AC signal is superimposed. In the receive mode, only DC bias is applied and incident acoustic pressure generates an AC detection current which is the output signal. A single cell hexagonal CMUT is designed using CoventorWare. Various electromechanical parameters which influence the operation of CMUTs are calculated. The cell acts as a parallel plate capacitor with doped polysilicon as top membrane and doped silicon as bottom electrode.

II. SIMULATION DETAILS

Various modules of CoventorWare are used for the FEM simulation. MemMech module is used for the calculation of resonant frequency and transient analysis. CoSolve module is used for the collapse voltage and coupling coefficient calculation. HarmonicEM module is used for the frequency response curve to calculate the bandwidth and quality factor. DampingMM module is used for the squeeze film damping coefficient calculation. The top membrane is clamped at the edges. The large gap size is decided to allow high transmission and reception efficiencies at higher operating voltages and also on the basis of the fabrication limitations.

TABLE 1. Device specification

Parameters	Value
Shape of the cell	Hexagonal
Membrane thickness	1 µm
Gap height (Silicon dioxide)	1 µm
Silicon nitride (Passivation)	1500 Å
Edge length of the membrane	46 µm

III. RESULTS & DISCUSSION

For NDT application one of the important factors to decide the resolution of the device is the resonant frequency. Based on the dimensional parameters listed in the TABLE.1 the resonant frequency of the cell comes to be 2.47 MHz. When a DC bias is applied on the membrane, the electrostatic force pulls the membrane down and the restoring force balances it. The voltage at which the electrostatic force exceeds the restoring force, the membrane collapses; that is known as the collapse voltage of the membrane. The collapse voltage calculated is 133.7 V as shown in Fig.2 (a).

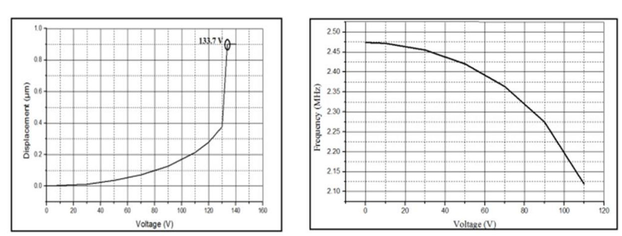

FIG.2. (a)Displacement Vs voltage (b) Frequency Vs voltage

For operation at the first harmonic, the DC bias voltage is made larger than the time varying voltage [3]. Usually the DC bias is 80% of the collapse voltage and the time varying voltage is 10% of the DC bias. So the applied DC bias on the membrane for device operation is 107 V and the AC is 10 V. When a DC bias is applied across the membrane, the resonant frequency shifts as compared to that of without DC bias. The shift in the frequency with the applied bias can be seen in Fig.2 (b).

When the CMUT operates with the electrical input, the coupling coefficient relates amount of mechanical energy delivered to the load to the total energy stored in the device. In this paper, we have used Berlincourt's [4] approach to calculate the coupling coefficient that relies on the use of the fixed (C^S) and free (C^T) capacitance of the transducer. The fixed capacitance is defined as the total capacitance of the transducer at a given DC bias:

$$C^S = \frac{Q(x)}{V}\Big|_{x_{DC}, V_{DC}}$$

The free capacitance is defined as the slope of the charge voltage curve:

$$C^T = \frac{dQ(x)}{dV}\Big|_{x_{DC}, V_{DC}}$$

and the coupling coefficient is given by: $k_T^2 = 1 - \frac{C^S}{C^T}$

The coupling coefficient calculated from Fig.3 (a), (b) comes out to be 0.13.

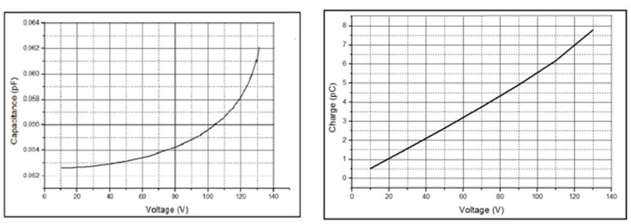

FIG.3. (a) Capacitance Vs voltage (b) Charge Vs voltage

As the medium is air, the air film acts as a damper and this damping is called squeeze-film damping. The damping force is dependent on gap height; smaller the gap results into larger damping force. When the gap is large, the pressure build up is negligible and at higher frequencies spring force is dominant over damping force as shown in Fig.4 (a). The damping coefficient (c) calculated comes out to be 1.96 N/ (m/s), as shown in Fig. 4 (b).

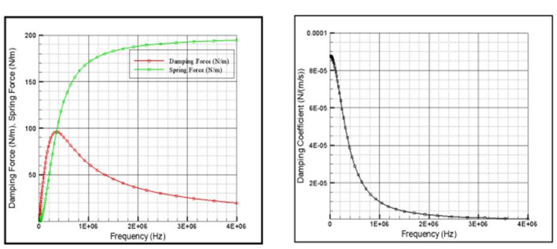

FIG.4. (a) Damping and spring forces Vs frequency
(b) Damping coefficient Vs frequency

The damping ratio is then calculated using formula:

$$\zeta = \frac{c}{c_0} = \frac{c}{2m\omega_0},$$

where, ζ is the damping ratio, c_0 is the critical damping and ω_0 is the free vibration frequency of the system. The damping ratio comes as 0.18. By using the damping ratio harmonic analysis is done to calculate the bandwidth and the quality factor of the device. Fig.5 (a) shows the frequency response when squeeze film damping is not considered. The applied bias is 107 V DC and 10 V AC. Fig.5 (b) gives the frequency response when the damping ratio is 0.18, due to the squeeze film effect. The bandwidth of the transducer comes to be 1MHz and the quality factor 2.15. The maximum displacement of the membrane is 0.126 µm.

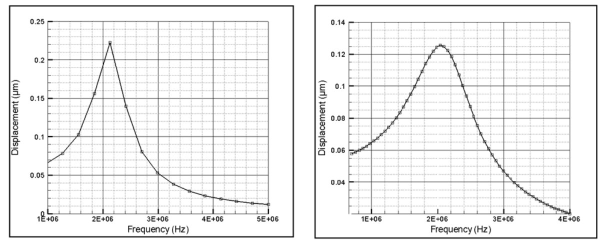

FIG.5. (a) Displacement Vs frequency when $\zeta = 0.1$
(b) Displacement Vs frequency when $\zeta = 0.18$

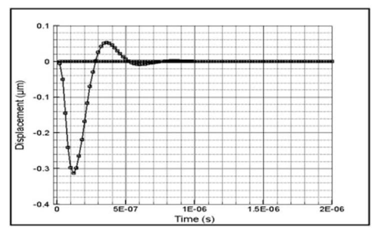

FIG.6. Displacement Vs time

Fig.6 shows the transient response of the transducer when a DC bias of 80 V and a pulse of amplitude 5 V for duration of 50 ns is applied. The pulse length generated by the device is small which gives higher resolution.

IV. CONCLUSIONS

An air coupled CMUT cell design was accomplished which has significant implications in non-destructive evaluation. A broadband transducer is achieved which is suitable for detecting cracks in the near field region. Hexagonal membrane was used as it has high packing density and fabrication is easy than the circular one, which has slightly better response. Further array design optimization of the CMUT is to be done to get high power.

V. REFERENCES

[1] Babar Ahmad and Rudra Pratap, IEEE Sensors Journal, vol. 10, no. 11, November 2010.
[2] D.W. Greve, I.J. Oppenheim, Sensors, Proceedings of IEEE, vol.2, pp.814-819, Oct.2003.
[3] M.I. Haller, B.T. Khuri-Yakub, Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions , vol.43, no.1, pp.1-6, Jan 1996.
[4] G.G. Yaralioglu, A.S. Ergun, B. Bayram, E. Haeggstrom, B.T. Khuri-Yakub, Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transaction, vol.50, no.4, pp.449-456, April 2003.