FEM-based Study of CMUT Cell for Vacuum-Sealed and Unsealed Cavities

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Abstract. Capacitive Micromachined Ultrasonic Transducers (CMUT) superseded the piezoelectric transducers for fluid-coupled applications because of their closer impedance to the fluid. Moreover, the new era of silicon micromachining techniques provides us with the possibility to fabricate micro electro-mechanical systems (MEMS)-based electrostatic transducers such as CMUT [1, 2]. In this paper, a comparative study of vacuum-sealed and unsealed Circular Capacitive Micromachined Ultrasonic Transducers (C-CMUT) has been done using CoventorWare® tool. The comparison of various analyses such as modal, harmonic, electrostatic, damping and transient analysis has been presented and discussed in this paper. Moreover, the membrane behaviour has been studied for different values of damping ratio (0-1.1). For the computation of these structures, tetrahedron meshing has been selected except for damping analysis, in which split and merge meshing was chosen. For this device, the cavity area of 8170 μm^2 is selected. The settling time determined for the membrane is around 3 µs for both Vacuum-Sealed and Unsealed cavities.

Keywords: Resonance Frequency, CMUT, FEM, CoventorWare®.

INTRODUCTION

Nowadays, the ultrasound is widely used in many different areas, for example, non-destructive testing, direction-finding, medication, imaging, maintenance, mixing, communication, testing, etc. Furthermore, today's industry and the medical field are heavily relying on ultrasound technology [1, 3]. CMUTs provide us with the possibility of medical imaging at higher frequencies and the image quality was found to be very high due to its wide bandwidth and high resolution. This made CMUT technology pioneer in the medical field [1].

A CMUT device is usually made from a thin vibrating conductive membrane or a membrane coated with a conductive electrode, known as a top electrode, and a low-resistive silicon substrate serving as a bottom electrode. High sensitivity and large bandwidth are the key parameters for a CMUT device and can be achieved by varying the size and shape of the membrane [2, 4]. To achieve this and for improving transformation efficiency of CMUT, the gap between top and bottom electrodes is reduced and the electrode size is enlarged [2]. A large number of theoretical and experimental methods are used to understand the effect of damping on membrane behaviour in MEMS structures [2]. In this study, a finite element method (FEM) has been implemented to study the performance of a thin vibrating membrane for vacuum-sealed and unsealed cavities.

DESIGN AND MODELLING

MEMS-based electrostatic transducers play a major role in the generation of sound wave excitation and finding [1]. For this purpose, a thin membrane is allowed to vibrate under the effect of electrostatic forces in upward and downward directions above the bottom electrode forming a small gap, separated by vacuum-sealed and unsealed cavities [1]. In this paper, membrane area of 8170 μm^2 for a C-CMUT structure is selected to study the behaviour of C-CMUT cell for vacuum-sealed and unsealed cavities under the effect of different values of damping ratio. However, the resonance frequency 3.2 MHz and pull-in voltage 53.5 V for the structure are determined by using the Equations 1 and 2, respectively [5-6].

$$f_r = \frac{0.47h}{a^2}\sqrt{\frac{E}{\rho(1-\nu^2)}} \tag{1}$$

$$V_{PI} = \sqrt{\frac{\left[\frac{64D}{a^2}+\frac{4\sigma h}{a^2}\right]\left(\frac{d_0}{3}\right)+\frac{128\alpha D}{h^2a^4}\left(\frac{d_0}{3}\right)^3}{\varepsilon_0\left[\frac{1}{6d_0^2}+\frac{2}{3\pi a d_0}-\frac{1.918}{\pi a^2}\right]}} \tag{2}$$

where a is the radius of the membrane, h is the thickness of membrane, E is the Young's modulus, v is the Poisson ratio and ρ is the density of the material, d_0 is the cavity height, ε_0 is the dielectric permittivity of free space, $D = \frac{Eh^3}{12(1-v^2)}$ is the flexural rigidity, $\alpha = \frac{7505+4250v-2791v^2}{35280}$ is the empirical parameter and σ is the residual stress.

In this work, to study the membrane behaviour using (FEM) technique MEMSCAD tool CoventorWare has been chosen. The cross-sectional view of this structure has been shown in Fig. 1. Glass substrate is etched to realize the cavity of 0.3 μm, after sputtering bottom electrode (Au) of 0.2 μm. Finally, a metal (Au)-coated SiO_2 membrane is made above the glass substrate.For this design, in the preprocessor window under the mesh model section, tetrahedron meshing is implemented to compute the various simulations under different solvers such as MemMech and CoSolveEM, while split and merge meshing is employed for DampingMM module. The DC voltage of 43 V and AC voltage of 4 V is applied for various analyses for vacuum-sealed and unsealed cavities.

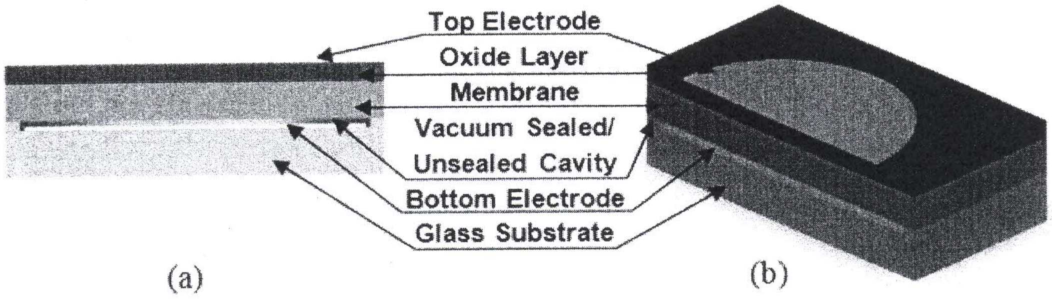


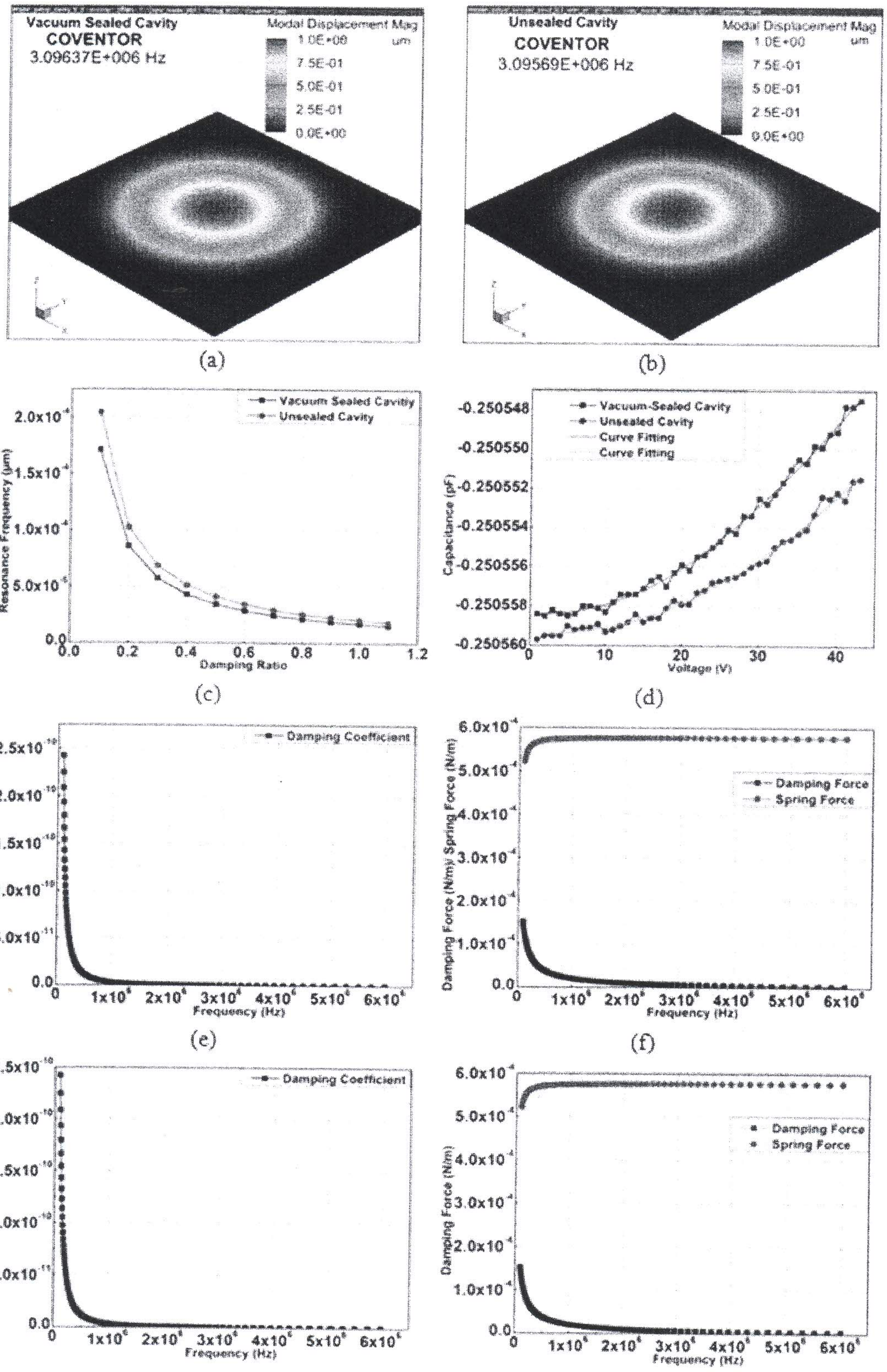
FIGURE 1. Cross-sectional view of C-CMUT cell.

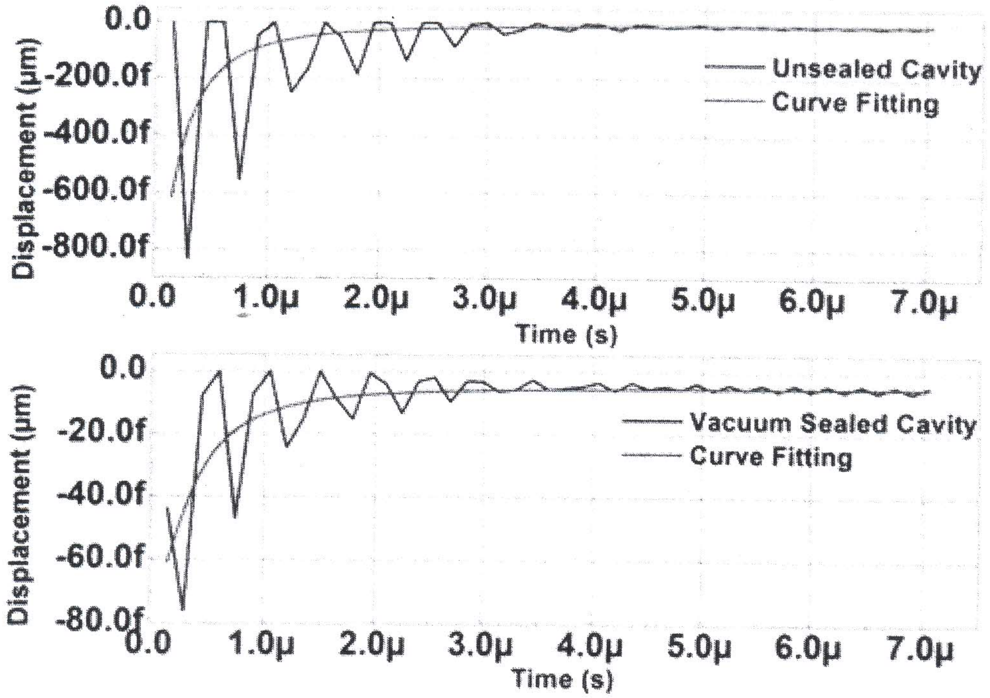
RESULTS AND DISCUSSION

The natural frequency of 3.09637 MHz and 3.09569 MHz for both vacuum-sealed and unsealed CMUT cells is calculated by using FEM technique, respectively. It purely depends upon the mass and spring constant of the membrane, shown in Fig. 2 (a) and (b). When a DC voltage is applied along to the top and bottom electrodes, the membrane starts to bend towards the bottom electrode because of electrostatic force. However, the internal stress force within the membrane resists the membrane displacement by the electrostatic force. Finally, membrane starts to vibrate at the resonance frequency on superimposing the AC voltage. The maximum displacement of 1.71331E-4 μm and 2.04722E-4 μm has been calculated for vacuum-sealed and unsealed cavities for the damping ratio 0.1. However, it is noted that as the value of damping ratio increases, the membrane displacement decreases in an exponential order, shown in Fig. 2 (c).The variation in capacitance on applying variable DC voltage is depicted in Fig. 2 (d). It is clear from the graph that the value of capacitance increases as the applied DC voltage increases because of a decrease in the gap between the plates of capacitor described as $C=\varepsilon A/d$. The value of damping coefficient is 3.0497E-11 N/(m/s) and 3.39182E-13 N/(m/s), damping force is 5.85311E-5 N/m and 5.85651E-5 N/m, and spring force is 5.6469E-4 N/m and 5.64762E-4 N/m. These values are calculated at the resonance frequency for vacuum-sealed and unsealed cavities, respectively with the help of DampingMM module, and presented in Fig 2 (e), (f), (g) and (h). Finally, the time required for the membranes to become stable has been computed using transient study, and it is found that after 3 μs, both the vacuum-sealed and unsealed membranes get stable, as shown in Fig. 2 (i).

CONCLUSIONS

The study of the membrane behaviour of C-CMUT cell has been successfully conducted using MEMSCAD tool, CoventorWare®for vacuum-sealed and unsealed cavities. The effect of DC voltage on the capacitance and, damping ratio on the resonance frequency and displacement of C-CMUT cell are also studied. Moreover, damping and transient study has also been done to calculate damping coefficient, damping and spring force, and time required by the membrane to become stable is determined to be 3 μs for both C-CMUT cell. It is concluded that the resonance frequency response decreases exponentially for both cavities but the response of vacuum-sealed cavity is lower than the unsealed cavity. However, in the case of capacitance, a higher capacitance is determined for vacuum-sealed cavity compared to the


Vacuum Sealed Cavity
COVENTOR
3.09637E+006 Hz
Modal Displacement Mag
um
1.0E+00
7.5E-01
5.0E-01
2.5E-01
0.0E+00
(a)
Unsealed Cavity
COVENTOR
3.09569E+006 Hz
Modal Displacement Mag
um
1.0E+00
7.5E-01
5.0E-01
2.5E-01
0.0E+00
(b)
Vacuum Sealed Cavity
Unsealed Cavity
Maximum Displacement at Resonance Frequency (μm)
Damping Ratio
(c)
Vacuum-Sealed Cavity
Unsealed Cavity
Curve Fitting
Curve Fitting
Capacitance (pF)
Voltage (V)
(d)
Damping Coefficient
Damping Coefficient (N/(m/s))
Frequency (Hz)
(e)
Damping Force
Spring Force
Damping Force (N/m)/ Spring Force (N/m)
Frequency (Hz)
(f)
Damping Coefficient
Damping Coefficient (N/(m/s))
Frequency (Hz)
(g)
Damping Force
Spring Force
Damping Force (N/m)
Frequency (Hz)
(h)



(i)

FIGURE 1.(a)and (b) Modal analysis for vacuum-sealed and unsealed cavity, (c) Harmonic study with varying damping ratio, (d) Capacitance plot on applying DC voltage sweep, (e) and (f) Damping coefficient, damping force and spring force study for vacuum-sealed cavity, (g) and (h) Damping coefficient and, damping force and spring force study for unsealed cavity, (i) Transient analysis.

unsealed cavity and the value of capacitance increases with increasing value of applied DC voltage.

ACKNOWLEDGEMENTS

The authors thank Prof. Santanu Chaudhury, the Director CSIR-CEERI, for encouragement. They wish to thank all members of Smart Sensors Area at CSIR-CEERI, and V. K. Khanna is thankful to CSIR for grant under emeritus scientist scheme.

REFERENCES

1. Dongqing Li, "Encyclopaedia of Microfluidics and Nanofluidics," Springer, 2008.
2. Bu-Sang Cha, Takeshi Kanashima, Seung-Mok Lee and Masanori Okuyama, "Air Damping Effect on Air-based CMUT operation," Journal of the Korean Physical Society, 2015, Vol. 67, No. 3, pp. 486-495.
3. R Mukhiya, Aditi, K. Prabakar, M. Raghuramaiah, J. Jayapandian, R. Gopal, V. K. Khanna and C. Shekhar, "Fabrication of Capacitive Micromachined Ultrasonic Transducer Array with isolation trenches using anodic wafer bonding," IEEE Sensors Journal, 2015, Vol. 15, No. 19, pp. 5177-5184.
4. Arif S. Ergun, Goksen G. Yaralioglu and Butrus T. Khuri-Yakub, "Capacitive Micromachined Ultrasonic Transducers: Theory and Technology," J. Aerosp. Eng., 2013, Vol. 16, No. 2, pp. 76-84.
5. Kwan Kyu Park, Hyunjoo Lee, Mario Kupnil, Omer Oralkan, Jean-Pierre Ramseyer, Hans Peter Lang, Martin Hegner, Christoph Gerber, Butrus T. Khuri-Yakub, "Capacitive micromachined ultrasonic transducer (CMUT) as a chemical sensor for DMMP detection," Sensor and Actuators B, 2011, Vol. 160, pp. 1120-1127.
6. M.Rahman, S.Chowdhury, "An Accurate Model for Pull-in Voltage of Circular Diaphragm Capacitive Micromachined Ultrasonic Transducers (CMUT)," MEMS LAB report, Department of Electrical and Computer Engineering, University of Windsor, Ontario, Canada.