Modeling and Analysis of Rectangular Structure Based Micromachined Ultrasonic Sensor

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Abstract: - In this paper a rectangular silicon nitride membrane capacitive micromachined ultrasonic transducer (CMUT) has been proposed to suit best for medical imaging applications. Investigations have been brought up using single cell rectangular architecture as well as array of the cells through three dimensional finite element method (FEM) model. The maximum and minimum displacements result with single cell and array of cells have been measured. The force is evaluated as 16.894 µN. The relative investigation of membrane displacements of array rectangular geometries on a lone substrate accumulated with dissimilar distances (1 µm, 2 µm, 5 µm, and 8 µm) between each other is also carried out.

Key-Words: - Sensor, CMUT, Ultrasonic, Medical Imaging, FEM, MEMS

1 Introduction

CMUT devices are a very attractive technology today due to its various benefits over traditional ultrasonic sensors. Conventional ultrasonic sensors are characteristically resonant devices prepared from piezoelectric materials. As a prospective alternative technology for piezo-based sensor microelectromechanical system (MEMS)/ nanoelectromechanical system (NEMS) based micromachined ultrasonic transducer is comprehensively studied [1]-[3]. Microsensors are greatest extensively used MEMS devices nowadays. Nearly all MEMS and microsystem devices consist of complex three dimensional geometries. CMUTs are a favourable substitute to piezoelectric transducers and obtain significant consideration owing to their many benefits [4]-[8]. CMUT is a micromachined architecture and useful for producing and sensing acoustic signal. This signal is in the ultrasonic range. It is the topic in which broad research is carried out for approximately previous two and a half decades. Even though it was developed for air coupled applications, nowadays it is mainly used for the medical ultrasonic applications and therapy. In modern technology microsystem nanodevices and integrated circuits (ICs) have excessive potential for medical sensor applications. These devices are helping to attain higher resolution and greater sensitivity. MEMS/NEMS in overall has established commercial accomplishment in sensor technology. The key application area of MEMS includes industrial, automotive and biomedical applications. Nowadays, the applications includes in wireless communication technology and gamming industries. It has a great base on automotive and industrial industry. CMUTs using dimensions of below 100 µm are manufactured on the barriers of the fluidic channels. It functions in the range of 1-100 MHz. The CMUT devices are surface micromachined to have a small surface profile, allowing uninterrupted liquid movement. Nowadays capacitive microphones have restricted bandwidth owing to their membrane resonance. CMUT is the so-called radio frequency (RF) recognition technique to engage as microphone. The RF detection technique practices the sequential assembly of membrane of one corresponding CMUT as transmission line for an RF signal.

As the essential element to accomplish the transformation among acoustic and electrical energy, ultrasonic transducers are extensively applied in medical imaging system, nondestructive evaluation, flow measurement, environmental chemical detection. Related to the previous transducers, micromachined ultrasonic transducer (MUT) fabricated by MEMS technology has countless benefits in integration, which can construct system on chip (SoC) technologies [1]. In addition, the MEMS technology switches the truthfulness in micrometer (μm) magnitude, which essentially decreases the manufacturing errors and increases the dependability. Presently, the MUT device comprises CMUTs based on flexural vibrations initiated through desirability force among suspended membrane and the substrate [9]. CMUT is fundamentally a parallel plate capacitor, voltage is applied on one electrode and another is grounded. The thickness of plate is generally few microns only [10]-[12]. Movement of the plates produces ultrasonic waves during transmission and modification in capacitance is perceived during reaction [13]. One of the major benefits is the lesser impedance for ultra thin membrane [14] hence CMUT eradicates the requirement of using similar layers [15]. CMUT devices are functioning on the design of front–end electronics, packaging and modular association of greater capacity. As well fine-pitch two dimensional CMUT arrays are also in development [16]-[19]. CMUT technology negotiates a number of modelling and fabrication autonomy which letting to convention ultrasonic devices. Nonetheless CMUT device competences are determined by on model parameters and material choice. Nowadays a lot of high-k materials for nanodevice applications are in investigation [20]-[23]. Gurum et al., also proposes lone chip CMUT-on-CMOS for real-time medical imaging applications [24].

In this work we have modeled the CMUT device consisting of rectangular membrane structure. Section 2 discusses the architecture of a CMUT device and the FEM modelling methodology of CMUT. Section 3 comprises the outcomes of investigation and discussion on membrane displacements for single cell rectangular geometries as well as its array of cells. Section 4 concludes the significant findings and investigations of the work.

2 Modeling of Rectangular CMUT Structure

Maximum devices manufactured as CMUT have membranes that faithfully estimated circles. Analytical investigations for these membranes are comparatively easily established. It is applied to corresponding circuits that fitted with experimental consequences [25]. In this modeling methodology the region of the membrane profiles are preserved constant. The design parameters are listed in Table 1. The basic structure of a CMUT cell is presented in Fig. 1.

A single CMUT is designed layer by layer. The entire arrangement comprises on silicon substrate. The top of the structure is extremely doped. Vibrating Si_3N_4 membrane is maintained by SiO_2 stands. Aluminium is used as a metal. The tinny Si_3N_4 membrane is separated through a small vacuum cavity from the substrate. It is due to avoid short circuits among the electrodes as soon as membrane collapses.

Table 1. Design parameters for Rectangular CMUT

Parameters	Values
Thickness of the membrane	0.75 μm
Length of membrane	50 μm
Width of membrane	39.27 μm
Thickness of the gap	0.50 μm
Force	16.894 μN
Pressure	8603.98 N/m^2

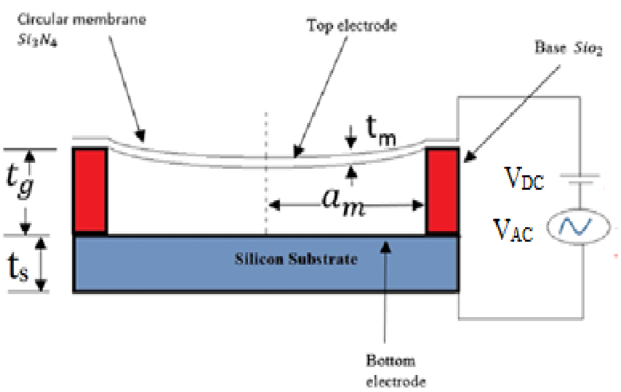


Fig. 1. Architecture of CMUT cell

The CMUTs are considered agreeing to the subsequent necessities. Meanwhile a constant membrane area is preferred, the pitches grows with circle, hexagonal and rectangular. Here we have considered rectangular structure for the investigation. Area of rectangular can be written as, a = l × b, where l is the length, and b is width, giving a length value of 50 μm and width value of 39.27 μm.

PZFlex offers the original release of SolidWorks modeling interfaces. This interface is intended with complex architectures. As

SolidWorks tends to build models in arbitrary space and the origin is not necessarily assigned to a convenient point in the model, it is needed to translate the model to a known reference point. This will allow easy access to the node and elemental locations generated within the model. Fig. 2 depicts the rectangular assembly architecture with single cell CMUT. For the frequency of interest for the model and the number of elements per wavelength, the mesher calculates the element size required and displays the number of elements that will be created in each direction.

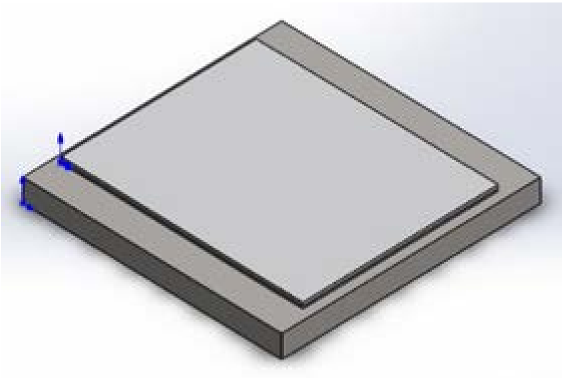


Fig. 2. Model name: rectangular assembly with single cell

2 Results and Discussion

2.1 Membrane Displacement for Single Cell Rectangular Geometry

The model of CMUT is fabricated using a thin rectangular membrane of silicon nitride (0.75 µm). The meshed modeled structure for rectangular membrane CMUT is presented in Fig. 3. The physical properties of the proposed structure are presented in Table 2 (Appendix-1). The loads, pressure and force is applied consistently in the direction of the membrane as shown in Table 3 (Appendix-2).

The pressure is applied on the membrane as providing a value of 8603.98 N/m^2. Here the applied static bias considered is 40 V in addition to a signal of 100 mV. The force is estimated as 16.894 µN. Completely the faces of the models are constant excluding the face 1 which is membrane. A meshed arrangement of a rectangular CMUT including 16148 nodes and 9227 elements is presented in Fig. 3. Subsequently applying the loads, membrane twitches distorting with extreme displacement at the middle of the membrane as in Fig. 4.

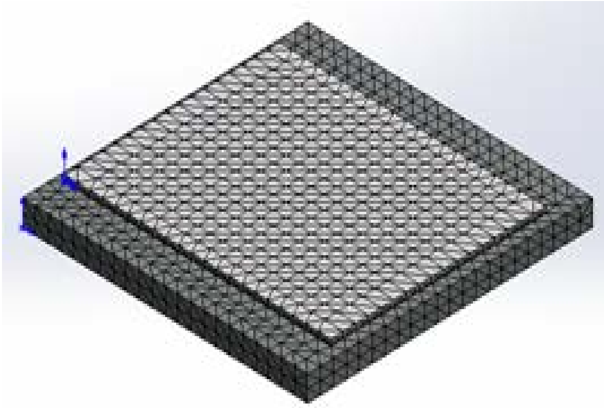


Fig. 3. A meshed structure of rectangular CMUT cells

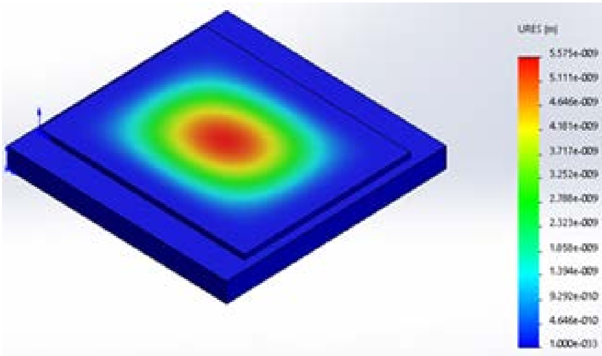


Fig. 4. Three dimensional CMUT cell with rectangular membrane having maximum displacement at the middle of the membrane

The displacement result of rectangular membrane with single cell structure is shown in Table 4. The huge displacement agrees to a strain of 2.7816 × 10^{-5} as in Fig. 5. The fracture strain for Si_3N_4 is 3.6 × 10^{-2}. As a result the CMUT is functioned fine lower the fracture boundary and fatigue would not be an important problem.

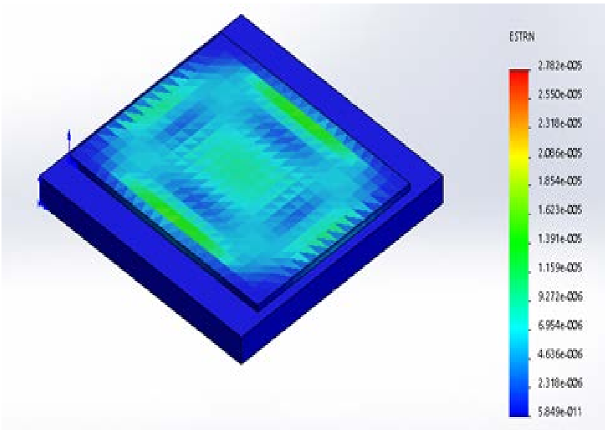


Fig. 5. Strain limit explanation of a rectangular CMUT at 40 V

Table 4. Displacement result of rectangular membrane with single cell

Name	Type	Min	Max
Displace-ment 1	URES: Resultant Displacement	0 m Node: 1	5.57521e-9 m Node: 1822

2.2 Membrane Displacement for Array of Cells Rectangular Geometries

The modelled structure for array of four rectangular membrane cells CMUT is presented in Fig. 6. The physical properties of the particular architecture are presented in Table 5 (Appendix-3). The loads, pressure and force is applied consistently in the direction of the membrane, which is shown in Table 6 (Appendix-4).

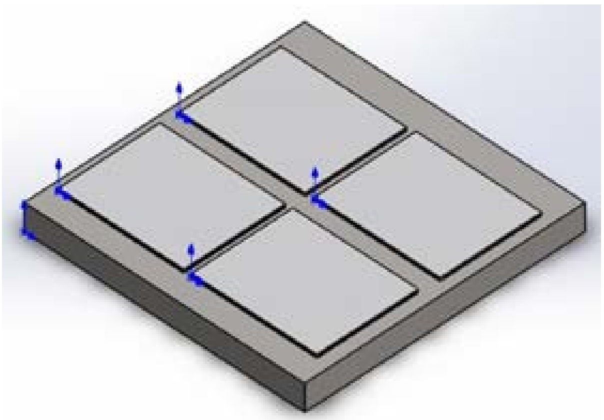


Fig. 6. Model name: rectangular assembly with array of cells

In the similar way the pressure is applied on the membrane by providing a value of 8603.98 N/m^2. Here also is considered an applied static bias of 40 V in addition to a signal of 100 mV. The force is estimated here 16.894 µN. Completely the faces of the models are constant excluding the face 1 which is membrane. A meshed structure of an array of rectangular CMUT with 18305 nodes and 10381 elements is presented in Fig. 7. Subsequently applying the loads in this array structure, membrane twitches distorting with extreme displacement at the middle of the membrane as in Fig. 8.

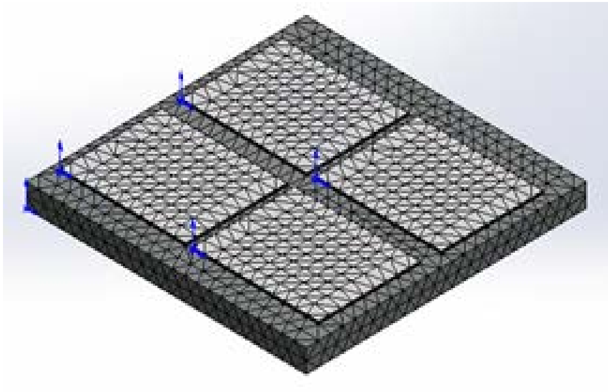


Fig. 7. A meshed architecture of array of a rectangular CMUT cell

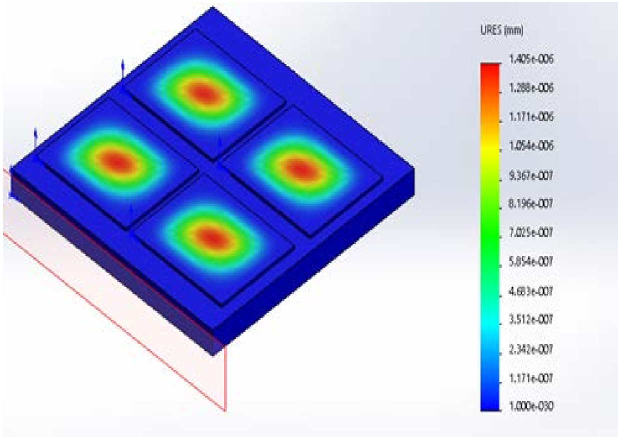


Fig. 8. 3-D CMUT cells with rectangular membrane having maximum displacement at middle of the each membrane

The displacement result of rectangular membrane with single cell structure is shown in Table 4. Here the maximum displacement achieved is 1.40499 × 10^{-6} mm. The enormous displacement agrees to a strain value of 2.447 × 10^{-5}. The fracture strain for Si_3N_4 is 3.6 × 10^{-2}. As a consequence the CMUT is functioned very fine lower than the fracture boundary and fatigue would not be an important problem.

Table 7. Displacement result of rectangular membrane with array of cells

Name	Type	Min	Max
Displace-ment1	URES: Resultant Displace-ment	0 mm Node: 1	1.40499e-6 mm Node: 3996

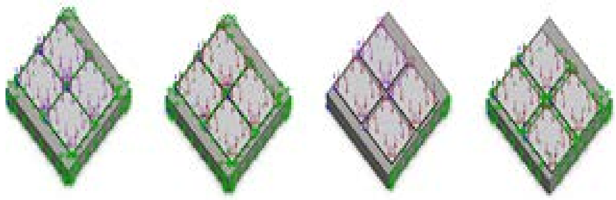
2.3 Comparative Analysis of Membrane Displacement for Array of Cells Rectangular Geometries on a Single Substrate

The four rectangular membranes assembled with different distances between each other are presented in Fig. 9. Loads, pressure and force is applied to each membranes face 1. Simulation study of membrane displacement is as shown in Table 8. It shows the maximum displacement occur at the 1 µm distance between the rectangular membranes. The value is 1.406 nm.

In the Fig. 9 the green arrows represent the boundary condition of fixed edges. However the other appearances indicate consistency and the trend of the electrostatic force applied. The length and width of rectangular shaped membrane is taken as 50 µm and 39.27 µm respectively with a thickness of 0.75 µm.

Table 8. FEM model study of membrane displacement

Name	Type	Minimum at the edges (nm)	Maximum at the centre (nm)
CMUT with rectangular membrane with 1 µm	Resultant Static Displacement	0	1.406
CMUT with rectangular membrane with 2 µm	Resultant Static Displacement	0	1.401
CMUT with rectangular membrane with 5 µm	Resultant Static Displacement	0	1.402
CMUT with rectangular membrane with 8 µm	Resultant Static Displacement	0	1.403



(a) (b) (c) (d)

Fig. 9. The distance between the rectangular membranes are as follows: (a) 1 µm (b) 2 µm (c) 5 µm (d) 8 µm

4 Conclusion

This paper explains the modeling techniques of CMUT of rectangular membrane structure. However to arrive at a full proof structure, array and parameter design optimization technique more research is needed. This work analysed a comparison between the three dimensional array structure having different distances between the membranes at each instant. Rectangular CMUT elements are validated through FEM simulations and attempted to arrive at a conclusion for choosing the best peak displacement. Three dimensional modeling of the proposed structure is investigated by SolidWorks simulation tool. It has proved that the CMUT cell and array of the cells are function very fine lower than the fracture boundary and fatigue would not be an important problem.

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