Characterisation and Modelling of MEMS Ultrasonic Transducers

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Abstract. Silicon ultrasonic transducer micro arrays based on micro-electro-mechanical-system (MEMS) technologies are gaining popularity for applications in sonar sensing and excitation [1]. A current challenge for many researchers is modelling the dynamic performance of these and other micro-mechanical devices to ascertain their performance and explain experimental observations reported [2]. In this work, the performance simulation of a MEMS ultrasonic transducer array made from silicon nitride has been successfully carried out using CoventorWare package. The dynamic response of the entire transducer array was characterised, and the results were compared with theoretical predictions. Individual elements were found to vibrate with Bessel-like displacement patterns, and they were resonant at approximately 3 MHz, depending on thickness and lateral dimensions [3]. The frequency shows a linear dependence around the common thickness of 2 μm. Peak displacement levels were examined as a function of frequency, DC bias voltage, and AC drive voltage. Accounting for fabrication variations, and uniformity variations across the wafer, the full array showed minimal variations in peak out-of-plane displacement levels across the device, and isolated elements that were over-responsive and under-responsive. Presently, the effect of observed variations across the array on the performance of the transducers and their radiated fields are being examined.

1. Introduction
An ultrasonic wave refers to any sound wave above the frequencies of audible sound, which is about 20 kHz. Ultrasonic waves are used in a wide variety of applications, for instance, non-destructive evaluation, medical diagnostic applications and imaging, and also applications in sonar sensing and excitation. The first MEMS-based ultrasonic transducers were originally fabricated at Stanford University during 1990s [5]. The concept of the ultrasonic transducer is similar to the condenser microphone (an electrostatic transducer). The MEMS-based ultrasonic transducer consists of a suspended membrane, which is used to generate and detect the ultrasonic wave. The advantages of making the ultrasonic transducer in MEMS scale are the ability to generate and detect acoustic wave...
using only a single membrane structure [6], improvements in cost, and the high degree of reliability and performance.

1.1. Types of MEMS Based Ultrasonic Transducer
Three different types of MEMS ultrasonic transducers are presented in published research works: The electrostatic ultrasonic transducer, the electrostatic with V-grooved backplates transducer, and the piezoelectric ultrasonic transducer.

The electrostatic MEMS-based ultrasonic transducer is a micro-capacitive structure. This type of transducer is also known as the capacity-micromachined ultrasonic transducers (cMUTs) [7]. The cMUTs used a suspended membrane to generate ultrasonic waves. The cMUTs consists of a top electrode, a suspended membrane over a micro-cavity and a silicon substrate as the bottom electrode. The V-grooved backplate cMUT is another type of electrostatic MEMS ultrasonic transducer [8]. The only difference is the bottom silicon substrate (backplate) is V-grooved. Therefore, bulk micromachining process is used in this type of transducer. The suspended membrane is a capacitive structure that operates under an electrostatic field. A DC bias voltage is applied across the top and bottom electrodes to generate an electrostatic field, and an AC voltage is applied across the membrane using the same electrodes to force the micro-capacitor to cause the membrane to generate an ultrasonic wave.

The piezoelectric MEMS-based ultrasonic transducer consists of a square membrane made of silicon nitride and silicon oxide suspended on a back-side bulk-micromachined silicon substrate. Four piezoresistors, thermopiles and a heating resistor are placed on the membrane [9]. The piezoresistors and thermopiles are used to measure the membrane temperature, whereas the heating resistor is used to heat up the membrane to generate ultrasonic waves. The disadvantages of this transducer are the design and fabrication complexity.

2. Theory of Operation

The cMUT is the main focus in this characterisation and modeling study. A single electrostatic cell of the MEMS based ultrasonic transducer is shown in figure 1 below.

During transmission (wave generation), a DC bias voltage and an AC alternating voltage are supplied across the top and bottom electrodes (connected to switch pin 2 in the figure). During reception (detection wave), the transducer is connected to a DC bias voltage and a resistor (connected to switch pin 3 in the figure). The membrane is stretched with a tensile force, \( \tau \) by the DC voltage supply. In the figure, \( a \) is the membrane radius, \( d_m \) is the membrane thickness and \( d_g \) is the membrane cavity gap.

2.1. The Electrostatic Capacitance in the MEMS Ultrasonic Transducer
The electrostatic capacitance, \( C \) of the cMUT is defined as \( C = \varepsilon_0 \left( \frac{A}{d_g} \right) \). Where, \( \varepsilon_0 \) is the dielectric constant of the air and \( A \) is the surface area of the membrane. When the DC voltage, \( V_{DC} \) is applied
across the top and bottom electrodes, an electric charge, $Q_{DC}$ appears on the surface of the membrane [6]. The electric charge is defined as $Q_{DC} = C \cdot V_{DC}$. Where, $C = \epsilon_0 \frac{A}{d_g - x_{DC}}$, and $C_0$ is the capacitance value according to the gap height variation due to the applied DC bias voltage. $x_{DC}$ is the static average displacement due to the DC applied electrostatic force.

2.2. Output Resonance Frequency of the MEMS cMUT
The membrane density $\rho$, the radius of the membrane $a$, and the thickness of the membrane $d_m$, are the critical parameters in determining the resonance frequency of the MEMS-based ultrasonic transducers [2][8]. With the membrane thickness taken into account, the resonance frequency of a cMUT is:

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

Where $d_m$ is the membrane thickness, $E$ is the Young’s modulus and $\sigma$ is the Poisson’s ratio.

3. Design of A MEMS based Capacitive Ultrasonic Transducer
The chosen materials used in fabricating the MEMS based ultrasonic transducer are CMOS compatible. This is because any additional control circuitry for the transducer can easily be fabricated on the same wafer. A Highly doped P-type silicon wafer is used as a base material and as a bottom electrode. CMOS compatible materials: LPVCD silicon nitride is chosen as the protection layer and the membrane structure, where as the sputtered aluminium metallisation is used as the top electrode.

There are different types of membrane geometries used in the design of the MEMS based ultrasonic transducer, which wave reported in past research studies. The hexagonal shaped membrane is the most common geometry. In this study, a circular shaped membrane is chosen in the design, which helps reduce the design complexity. The radius of the membrane is 30 μm. Two design variations are used in the study to obtain the transducer resonant frequency figure.

| Membrane parameters | Type1 | Type2 |
|---------------------|-------|-------|
| Radius of membrane, $a$ | 30μm | 30μm |
| Thickness of the membrane, $d_m$ | 1μm | 0.5μm |
| Cavity gap, $d_g$ | 1μm | 1μm |

Table 1 Transducer membrane parameters.

Using CoventorWare, a MEMS design and simulation package, a model of the MEMS based ultrasonic transducer is generated. Figure 2 shows a single membrane cell MEMS based ultrasonic transducer and the cross sectional view of the transducer. The complete MEMS ultrasonic transducer array is shown in figure 3.

Figure 2 A single cell MEMS based cMUT with circular membrane.
4. Computational and Simulation Results
Firstly, a computational prediction of the resonant frequency of the transducer is calculated. The predicted resonant frequency of the transducer is shown in table 2. Only the resonant frequency of the transducer is calculated in this study to compare with the software simulation results. From the calculation the results, suggest that a membrane thickness of 1μm produces a higher resonant frequency than the 0.5μm-thick membrane, and that in general the frequency is proportional to the thickness.

| Membrane parameters          | Type1  | Type2  |
|------------------------------|--------|--------|
| Radius of membrane, \(a\)    | 30μm   | 30μm   |
| Thickness of the membrane, \(d_m\) | 1μm   | 0.5μm |
| Resonant frequency, \(f\)    | 5.2MHz | 2.6MHz |

Table 2 Calculated resonant frequency of the transducer with different membrane thickness.

The computer simulation model shown in figure 2 is meshed using the mesh and analysis function in the CoventorWare package. The meshed model of a single cell transducer is shown in figure 4. A 10VDC bias voltage is applied across the top and bottom electrodes in the simulation to investigate the designed MEMS cMUT characteristics. The simulated results which include the capacitance generated between the membrane and the substrate, maximum membrane displacement and the resonant frequency are shown in table 3.

|                              | Model 1 | Model2 | Model 3 | Model 4 |
|------------------------------|---------|--------|---------|---------|
| Membrane Radius, \(a\) (μm) | 30      | 30     | 30      | 30      |
| Membrane Thickness, \(d_m\) (μm) | 1      | 1      | 0.5     | 0.5     |
| Cavity Height, \(d_g\) (μm) | 1       | 0.5    | 1       | 0.5     |
| Capacitance (Metal to Substrate), \(c\) (pF) | 2.90×10^{-2} | 3.07×10^{-2} | 2.00×10^{-2} | 3.03×10^{-2} |
| Maximum Membrane Displacement, \(D\) (μm) | 1.59×10^{-4} | 4.14×10^{-4} | 1.07×10^{-4} | 2.89×10^{-3} |
| Resonant Frequency, \(f\) (MHz) | 4.51    | 4.53   | 2.43    | 2.43    |

Table 3 Computer model simulation results.
5. Observations, Discussion and Future Works

The computer simulation results indicated that the resonant frequency of the transducer is in agreement with the calculated results discussed in table 2. Clearly, from the simulation results observed, when a $10\text{V}_\text{DC}$ bias voltage is applied, the electrostatic pull in force in the 0.5μm cavity height transducer is greater than the 1μm cavity-height transducer. Therefore, larger membrane displacement occurred in the 0.5μm cavity gap transducer.

The MEMS-based capacitive ultrasonic transducer characterisation and modelling is carried out successfully. However, the design procedures and modelling techniques can be improved. The shape of the transducer cell, material used in fabricating the membrane and the thickness of the membrane can be improved in future designs and study to obtain more efficiency in operating the transducer. In future works, better understanding of the transducer behaviour is required in order to provide an accurate modelling of the transducer and generate an accurate equivalent circuit of the transducer.
6. Conclusion
In conclusion, the design of the MEMS based ultrasonic transducer is successfully carried out. The complete prototype of the MEMS based ultrasonic transducer consists of a series of ultrasonic cell arrays, which are capable of generating a 3MHz ultrasonic wave using a 0.5μm-thick membrane. A highly doped silicon wafer is used as the substrate material and as a bottom electrode. The transducer membrane is fabricated using silicon nitride with a circular shape pattern. The computational and computer software simulations of the modelled transducer were also successfully carried out in this project. The simulation results based on the design show the transducer output resonant frequency in good agreement with the calculated values in the theoretical analysis of the transducer.

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