Wafer Bonded Capacitive Micromachined Transducers for Underwater Applications

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We propose capacitive micromachined ultrasonic transducers (CMUTs) as a candidate for underwater acoustic applications, in this paper. We have designed and fabricated CMUT membranes by utilizing anodic bonding technology and tested them underwater. We developed a nonlinear electrical equivalent circuit for immersed CMUTs and compared the model with transient finite element analysis (FEA) and measurements. FEA reveals that the radial distribution of both the fundamental component and the harmonics in the membrane displacement can be modeled as clamped radiators. CMUTs, operating in conventional regime, are designed by deriving the force and current equations for a clamped radiator and implemented using a harmonic balance simulator. A mechanical LC section and the radiation impedance of a clamped radiator are used in the model. A 380 µm thick silicon wafer is chosen as the membrane and 3.2 mm thick glass is used as the substrate. The performance of the transducer is measured in an open water testing facility and approximately 40% bandwidth is achieved around 25 KHz with a single underwater CMUT cell.

1 Introduction

Capacitive micromachined ultrasonic transducers (CMUT) are attractive candidates for piezoelectric transducers in many application areas, such as medical imaging, intravascular ultrasound, airborne acoustics and microphones. They have been widely fabricated in the past decade using the sacrificial layer techniques or wafer bonding processes [1,2,3]. Their unique capabilities, most of which come out from the way they are built, made them promising transducers in terms of high transmission power [6], large bandwidth and high sensitivity [7]. Several advances prove that CMUTs are low cost and efficient transducers for both airborne and immersed applications around a wide frequency range [3,4].

Despite their advantages, fabrication of CMUTs involves time consuming and tedious process steps. Therefore, accurate modeling of these transducers, especially for immersed applications, is crucial. Besides, fast and intuitive models are required for taking advantage of the device properties. The equivalent circuit models of the CMUTs are extensively used for their design, which are based on Mason’s equivalent circuit developed for electro-acoustic transducers [5]. It is demonstrated that CMUTs exhibit significant nonlinear behaviour, which must be taken into account in the equivalent circuit for most operation conditions [8].

Underwater sound has been utilized in application areas like sea exploration, acoustic communications, active and passive sonar, oceanography, navigation and echo-ranging. The frequency ranges mostly lie between 1 kHz and1 MHz. In this work we designed, fabricated and examined CMUTs as candidates for underwater acoustic systems. Three single CMUT cells having different radii but same thicknesses and gap heights are modeled using the analytical equivalent circuit in [8]. Measurements are performed both in air and underwater, and compared with the results of the model.

2 CMUT Design

We designed single CMUT cells with three different radii, which are aimed to work below 50 kHz in water. The working principle of these electrostatic transducers constrains us to supply a DC bias voltage, which determines the operating point of the device. Therefore, the gap height, \( t_g \), and the membrane thickness, \( t_m \), of each CMUT cell is kept constant and the radii are chosen such that each device can be driven at acquirable DC voltage levels. The physical dimensions of the CMUTs that are decided for fabrication can be seen in Table I.

<table>
<thead>
<tr>
<th>( t_m (\mu m) )</th>
<th>( a (\mu m) )</th>
<th>( t_g (\mu m) )</th>
<th>( t_i (\mu m) )</th>
<th>( f_0 ) (in air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I 380</td>
<td>4000</td>
<td>4.5</td>
<td>0.5</td>
<td>83 kHz</td>
</tr>
<tr>
<td>II 380</td>
<td>5000</td>
<td>4.5</td>
<td>0.5</td>
<td>73 kHz</td>
</tr>
<tr>
<td>III 380</td>
<td>6000</td>
<td>4.5</td>
<td>0.5</td>
<td>40 kHz</td>
</tr>
</tbody>
</table>

Table 1. Physical parameters of the CMUT cells.

The CMUTs are analyzed by using both an FEM harmonic simulator, ANSYS (ANSYS Inc. Canonsburg, Pa), and the equivalent circuit model in [8]. The equivalent circuit model is built by utilizing the clamped velocity profile of the CMUT and it is able to predict the nonlinear behaviour. An axisymmetric model is used in the FEM analyses. In the simulations the Young’s modulus, the Poisson ratio and the density of the silicon membrane is assumed to be 169GPa, 0.28 and 2330 g/cm3, respectively. The electrical conductance of all three types of cells in water is found by
these models and shown together in Fig. 1. The resonance frequency prediction of the equivalent circuit model is consistent with the FEM results, however, it indicates a slightly larger bandwidth. Note that when an array is constructed, the bandwidth of the transducers will considerably increase due to better acoustic loading of the medium.

3 Fabrication Process

In the conventional fabrication process, first a sacrificial layer is patterned and deposited onto the substrate, which embodies the gap underneath the membrane. Then the membrane material is uniformly deposited over the sacrificial layer. A wet etch process removes the sacrificial layer through the etch holes located on the membrane and the holes are sealed to form the vacuum cavity. This process restricts building membranes with arbitrary thickness, since high stresses are usually included in the deposited membrane layer. It is also a very difficult task to release large membranes. We used anodic wafer bonding technology to form relatively large and thick membranes. This method is usually preferred for bonding a silicon wafer to a borosilicate glass wafer at appropriate electric field, pressure and temperature.

We used a highly doped, low resistivity, double side polished, 380 µm thick silicon wafer as the membrane. This wafer has more reliable mechanical properties than the deposited thin films. The thickness of the silicon wafer determines the membrane thickness. A commercially available glass wafer, Borofloat, is preferred as the substrate. This wafer is desired to be much thicker than the membrane side so that it can act like a rigid substrate. The process steps are summarized in Fig. 2. First, the cavity is patterned and a 4.5 µm gap height is obtained by etching the silicon wafer using a reactive ion etching reactor (Fig. 2b). A 250 nm of chromium layer is used as the etch mask. For the electrical isolation of the 3” silicon surface, 500 nm of silicon oxide is thermally grown in a diffusion furnace at 1050°C (Fig. 2c). During the oxidation process water vapor is supplied into the furnace. Since both sides of the wafer are oxidized, the top surface of the membrane is etched by a reactive ion etching process (Fig. 2d).

The glass substrate is a 3.2 mm thick borosilicate wafer (Fig. 2e). In order to maintain surface smoothness to enable a successful anodic bonding process, the electrodes are buried into the glass as shown in Fig. 2f. Therefore, the glass is etched approximately to the same thickness of electrode layer to be evaporated. As the substrate electrode, 5 nm of chromium and 45 nm of gold are deposited by thermal evaporation. Finally, the borosilicate and the silicon wafers are cleaned at 120°C in a Piranha etch for about 15 minutes.

We had several trials to bond the two wafers together by using the anodic bonder, EVG 501 Universal Bonder [9]. We applied the process at 450°C at a pressure of 0.1 µbar. In order to prevent the thin oxide layer from breakdown, the bonding voltage is increased up to 1000V with 100V steps in every 10 minutes. Although we observed that applying incremental voltage steps improves the bonding quality, we still had some small areas on the wafers that are not bonded very well. The details of the process and the problems are discussed in [9]. The wafer bonded CMUTs are shown in Fig. 3. After the bonding process a chromium layer is sputtered on top of the active area as the top electrode of the membrane. The most recent bonding processes took place in Applied Micromachining Ltd. (AML), which achieved 100% bond success.

After the completion of the microfabrication steps, electrical contacts to the electrodes are obtained by a commercially available silver conductive epoxy, Eccobond 83C. A 6 mm thick rigid foam disk is fixed inside a circular holder that is just a little larger than the glass wafer. Then, the transducers are mounted inside the holder.
and embedded into the epoxy, Eccobond 45. This way the transducers are terminated by a medium having very low acoustic impedance at the rear termination. Finally, the device is cured and the active region of the transducer is varnished in order to provide electrical isolation for immersion experiments.

4 Measurements

The fabricated CMUTs are measured both in air and in water. The electrical admittances of the transducers are measured by an impedance analyzer (HP4194A). The measurements are made with 10V bias steps up to 200V DC. The conductance of cell III is depicted in Fig. 4. Note that the calculated conductance in water (Fig. 1) is consistent with the measured one, but there is an important loss factor. The calculations were made assuming lossless electroacoustic transduction.

Underwater performances of the transducers are tested in an open water test facility located at Bilkent University Lake. CMUTs are driven with multiple bursts of sinusoids generated from a signal source and amplified by a power amplifier. A 50V DC bias voltage is applied and the amplitude of the AC signal is kept at 100Vpp, while the frequency is swept. The radiated sound energy is received by a calibrated hydrophone located at 1 m away from the CMUTs. The test environment is supported by the Labview program, where the calibration data of the hydrophone is utilized to compensate the received signals. The resulting root mean square pressure spectra of the CMUTs are depicted in Fig. 5. This part of the measurements was made with the transducers that were fabricated during the early trials of the bonding process, which were not 100% successfully bonded [9]. As a result, the measured resonance frequency of the smallest cell (type I) is not as predicted in Fig. 1, which might be due to poor bonding. However, the resonance frequencies of the other two cells are as expected. The inequality of the peak values observed from each size of transducer results from the difference between their collapse voltages, which increases as the radius is decreased when other dimensions are fixed. Therefore, the smaller cells (type I and II) are not driven as efficiently as the largest one with 50V DC bias. CMUTs are conventionally operated close to their collapse voltage for higher efficiency.

Although, the theoretical breakdown limit is 500V for a 500 nm silicon oxide layer, if we apply more than 200V DC all devices fail without even collapsing. This can be accounted for the reduction of breakdown voltage due to passing ions from the oxide layer during the anodic bonding process [10].

From the immersion experiments of all three cells, we observed small peaks at half the resonance frequency, as seen from Fig. 5. These peaks can be explained with the nonlinear behavior of CMUT, since the driving AC voltage is reasonably high [8]. When the frequency is at half the resonance frequency of the device, the second harmonic falls onto the resonance frequency giving rise to significant membrane velocity. This peak increases with respect to the
peak at the resonance when the AC to DC voltage ratio increases.

![Figure 5. RMS pressure generated by the single cells at 1m away from the hydrophone. 100V pp AC signal is applied to each cell at 50V DC bias voltage.](image)

5 Conclusions

In this work we fabricated single CMUT cells for use in underwater applications by using the wafer bonding technology. Underwater experiments show that approximately 40% bandwidth is achieved from a single cell. However, much larger bandwidth will be obtained when the radiation impedance of the transducers will be increased with an array configuration.

A major problem with this process is the amount of loss we encountered. The baseline of the conductance measurements begins from approximately 18µS and increases linearly with frequency. Another problem is the low breakdown voltage, which limits us to drive the CMUTs more efficiently near the collapse voltage. For favorable usage of the CMUTs in underwater and airborne applications further improvements are needed.

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References


