BROADBAND CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS RANGING FROM 10 KHZ TO 60 MHZ FOR IMAGING ARRAYS AND MORE

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Abstract — Capacitive micromachined ultrasonic transducers (CMUTs) have long been studied. Past research has shown that CMUTs indeed have remarkable features such as wide bandwidth and high efficiency. This paper introduces an inclusion to the CMUT technology that uses the wafer-bonding technique to fabricate membranes on silicon. This new technology enables the fabrication of large membranes with large gaps, and expands the frequency span of CMUTs to 10 kHz in the low end. CMUT devices with different frequency spans are fabricated using both technologies, and tested. Electromechanical coupling efficiency, k_T^2, value as high as 0.85 and fractional immersion bandwidth as wide as 175 % are measured.

I. INTRODUCTION

Electrostatic transduction mechanism has long been known as a way of generating and detecting acoustic waves. Condenser microphone is a well known example that uses electrostatic transduction. In its simplest form, a thin membrane is stretched over a conductive back-plate and supported by posts so that there is a gap between the membrane and the back-plate. The thin membrane is coated with metal to create a capacitance with respect to the back-plate and biased with a DC voltage. An acoustic wave picked up by the membrane in the form of vibrations is transformed into an electrical signal through capacitive detection. Although microphones are used only for sound reception, in principle, the membrane can be put into vibration to generate acoustic waves by utilizing the electrostatic attraction force between the two plates of the capacitor. It was shown that [1] if an electric field of the order of 10^8 V/m could be generated inside the gap between the membrane and the back-plate; electrostatic transducers could outperform piezoelectric transducers.

With the development of the MEMS technology, which allowed miniaturization and integration, researchers were able to micro-machine a plurality of small membranes (10 μm -200 μm in size) on to a conductive silicon substrate that would operate in unison. The gap between the membrane and the silicon could be made very narrow (0.05-3 μm) so that high electric fields could be generated inside the gap [2,3]. As a result, it was possible to achieve high transduction efficiency with these micromachined transducers which are also known as Capacitive Micromachined Ultrasonic Transducers (CMUTs).

After reviewing the basic operating principles of CMUTs, we will describe the fabrication process and introduce an alternate method of fabricating CMUTs that utilizes a wafer bonding technique and enables the fabrication of low frequency devices. The paper will proceed with experimental results and conclude with a discussion on the future of CMUTs.

II. PRINCIPLE OF OPERATION OF CMUTS

A. Electro-acoustics

When a voltage is applied across the plates of a capacitor an electrostatic force is generated, which is expressed as,

$$F_{elec} = \frac{\varepsilon_0 A V^2}{2d^2} \quad (1)$$

where ε_0 is the dielectric constant of free space, A is the area, d is the separation between the plates and V is the applied voltage. Assuming that one of the plates, the conductive silicon wafer in this case, is stationary, the electrostatic force pulls the membrane toward the substrate. This force is balanced by the mechanical restoring force of the membrane.

Because the electrostatic attraction force is always attractive, the AC voltage, V_{AC}, is superposed on top of a DC bias voltage, V_{DC}, for proper operation. Assuming that $V_{AC} \ll V_{DC}$, one can rewrite equation (1), and obtain the AC force on the membrane as,

$$F_{AC} = C_0 E_{DC} V_{AC} \qquad (2)$$

where C_0 is the device capacitance and E_{DC} is the electric-field inside the gap. That is, one can increase the electromechanical coupling that relates the force on the membrane to the applied voltage by increasing the DC bias voltage on the membrane. However, the collapse voltage limits the bias voltage that can be applied to the membrane. Beyond the collapse voltage the electrostatic force acting on the membrane cannot be balanced by the mechanical restoring force of the membrane and the membrane collapses to the substrate [4,5].

The electromechanical coupling efficiency, k_T^2, that is defined as the ratio of the stored mechanical energy to the total stored energy is the figure of efficiency for acoustic transducers. Hunt has shown that for electrostatic transducers, k_T^2 goes up to unity as the DC bias voltage approaches the collapse voltage, and measured k_T^2 values as high as 0.7 [1]. Finite element simulations show that k_T^2 indeed becomes unity at the collapse voltage, which is shown in the characterization section together with the measurement results.

B. Mechanical Impedance and Frequency Bandwidth

In general, CMUT membranes are resonant structures similar to a mass loaded spring. One can solve the equation of motion for the membrane to find the mechanical impedance of the membrane [5,6]. Figure 1 shows the absolute value of the mechanical impedance of a CMUT as a function of frequency. The 49 mm^2 device is made of 96 μm diameter and 0.6 μm thick membranes. For this size, air loading corresponds to an acoustic impedance of 0.02 N·s/m whereas water loading corresponds to an acoustic impedance of 73.5 N·s/m. An absolute value comparison between the mechanical impedance of the device to the acoustical loading provides us a rough estimate of the bandwidth of the CMUTs. The mechanical impedance plot in Figure 1 suggests a 3-dB bandwidth of ~5MHz at 2.5 MHz center frequency in immersion. That is, the fractional immersion bandwidth estimate for this particular device is around 200 %.

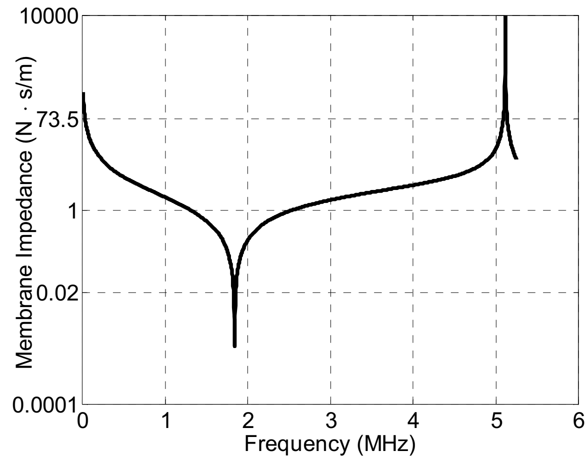

Figure 1 : Absolute value of the mechanical impedance calculated for a 49 mm^2 CMUT device that is made of 4900 membranes.

III. FABRICATION PROCESS

A. Traditional CMUT fabrication process

The traditional CMUT fabrication process uses a low resistivity silicon wafer, which will become the bottom electrode of the CMUT later. Poly-crystalline silicon is used as the sacrificial layer which is deposited by LPCVD (Liquid Phase Chemical Vapor Deposition). The sacrificial layer is patterned with photolithography and dry-etch to define the active area. The membrane is made of LPCVD Si_3N_4 which is deposited over the sacrificial layer. Small holes are dry etched in the Si_3N_4 membrane and potassium hydroxide (KOH) is used to selectively etch the sacrificial poly-silicon layer. After the release, the etch holes are sealed and the membranes are isolated from each other by another Si_3N_4 deposition at low pressure (~8 Pa). The rest of the process steps involve finalizing the membrane thickness, and making the necessary electrical connections and isolations. The details of the process can be found in [2-5].

B. CMUT Fabrication with Wafer Bonding

The process starts with a low resistivity silicon wafer and a silicon-on-insulator (SOI) wafer (Figure 2a). The first step is to grow silicon dioxide (SiO_2) on the silicon wafer prior to cavity definition. Depending on the required cavity depth for the membranes, either a dry or wet etch is employed to define the cavity (Figure 2b). Next, the silicon wafer with the cavities is bonded to the SOI wafer (Figure 2c). The thick silicon layer (also known as the handle) and the thin oxide layer are removed (Figure 2d) leaving only the active silicon layer of the SOI wafer which constitutes the membrane. The rest of the process is identical to that of the traditional CMUT process.

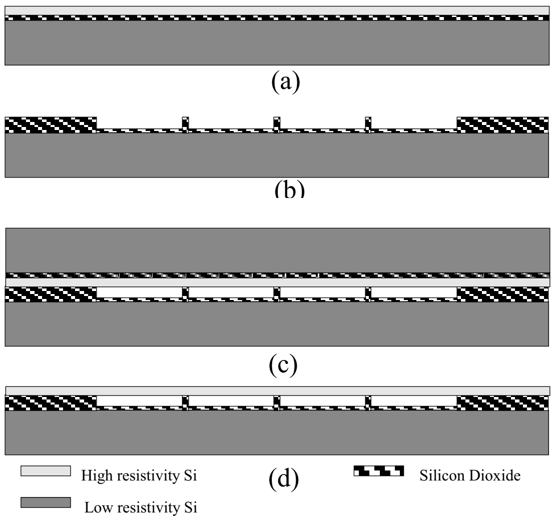

Figure 2: Simplified process flow of CMUT fabrication with wafer-bonding technique, (a) SOI wafer (b) low resistivity silicon wafer: oxidized and patterned for cavity definition, (c) wafer bonding, (d) grinding and etching the handle of the SOI wafer.

The wet sacrificial release in the traditional CMUT process is the most critical step. The high stress values in the sacrificial layer and the membrane, and large capillary forces during the drying step [7,8], limit the realizable membrane size to 180 μm (this value is obtained empirically and does not reflect the absolute limit). The wafer bonding technique, on the other hand, eliminates the wet release process and the associated limitations on the membrane size. In addition, the new process reduces the number of process steps and decreases the device turnaround time. Figure 3 is an optical picture of such a device fabricated for low frequency applications.

IV. CMUT FABRICATION

As mentioned previously, CMUT membranes are resonant structures. The resonance frequency is determined by the size and the thickness of the membranes. The resonant behavior is over-damped in immersion applications, but the frequency band in which the device operates is still determined by the membrane parameters. By altering these parameters, CMUT devices have been built whose frequency band ranges anywhere from 10 kHz to 60 MHz. In this section, we will show examples of CMUT devices for various applications at different frequency bands.

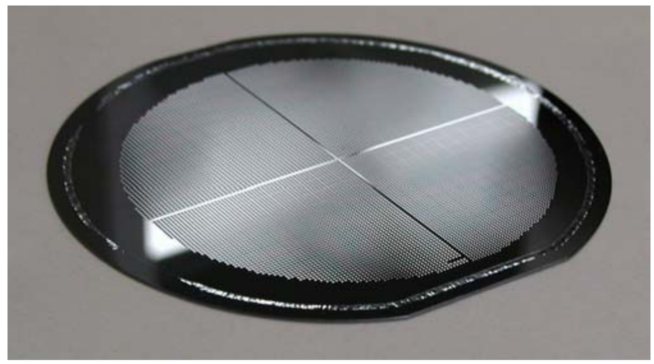

Figure 3: An optical picture of a 7.5 cm diameter single element CMUT device which is made of 650 μm wide square membranes.

A. k_T^2 Measurements

The electromechanical coupling efficiency can be measured in two ways. One of them uses the resonance and anti-resonance frequencies to calculate k_T^2 [1]. This measurement technique becomes troublesome when the DC bias voltage is close to the collapse voltage because of the large membrane swing at resonance. The second method uses the capacitance variation as a function of DC bias voltage [9,10]. Figure 4 is a plot of the measured k_T^2 as a function of the increasing DC bias voltage (blue solid line) in comparison with the finite element simulation results (red dotted line), using the capacitance approach.

B. Bandwidth Measurements

We fabricated CMUT devices for various applications ranging from sonar to intravascular imaging, each working at different frequency spans. Figure 5 shows the measured frequency response of three CMUT devices. Device 1, which is designed to work in the 10-150 kHz range for sonar applications, (dash-dotted line) is made of 650 μm wide square and 4.5 μm thick silicon membranes. Traditional CMUT process is not capable of producing such large membranes; therefore the wafer-bonding technique is used to fabricate this low-frequency device. Device 2 (solid line) and device 3 (dashed line) are fabricated using the traditional CMUT process, where the former one is made of 96 µm diameter circular and 0.6 µm thick Si_3N_4 membranes. The latter one, which is an annular array element designed for intravascular imaging, is made of 0.88 µm thick Si_3N_4 tent membranes with posts at 24 µm periodicity.

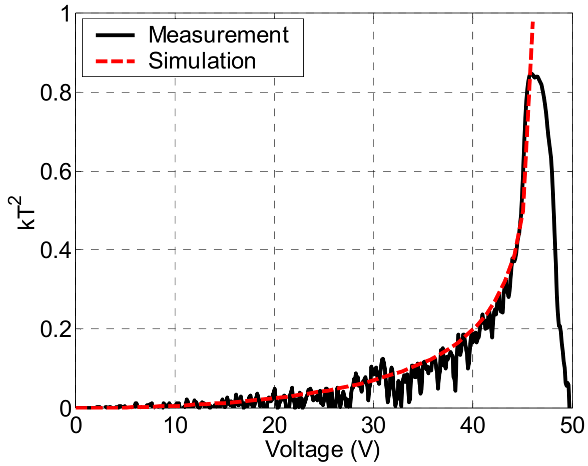

Figure 4 : Electromechanical coupling efficiency of a CMUT device: measurement results in comparison to simulation result.

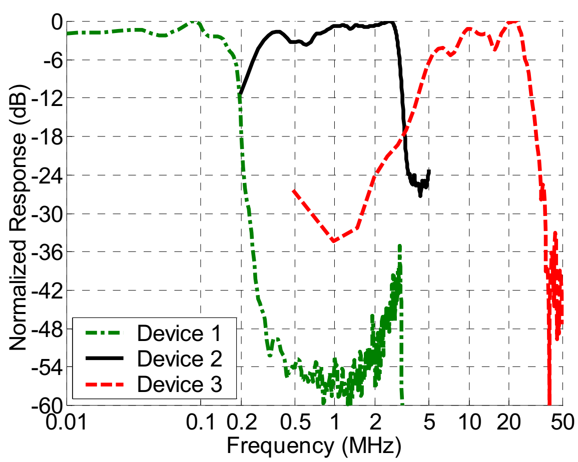

Figure 5: Frequency response of three different CMUTs designed for different applications: obtained with pulse-echo experiments and corrected for diffraction and attenuation.

The frequency response plots of Figure 5 were obtained by performing a pulse-echo experiment, where the CMUT devices were excited with a short pulse. The echo from a plane reflector was detected by the same device. We obtained the frequency response by taking the Fourier transform of the echo signal and correcting it for diffraction and attenuation. Figure 5 shows the two-way frequency response of the devices; therefore 6-dB points are used to find the bandwidth. These devices all have fractional bandwidths that are larger than 100 %; 175 % for device 1 and 2, and 135 % for device 3.

V. Discussion

This paper describes two alternate methods of fabricating CMUTs. The traditional method utilizes a wet sacrificial release process, and therefore is limited in realizable membrane size. The alternate method avoids the complicated sacrificial release and sealing processes by using a wafer bonding technique to make the membranes. This new method is capable of producing large membranes that are suitable for low frequency applications. In addition, it utilizes the surface area more efficiently than the traditional CMUT process which is a critical issue for high frequency devices that are made of small membranes. In between these two extremes, the traditional CMUT process has been very successful in producing high yield, high efficiency and wideband immersion transducers as the reported results also suggest. However, with its simplicity and fast turnaround time wafer bonding technique is a strong alternative to the traditional CMUT process.

Figure 5 demonstrates that CMUTs have wide bandwidth in immersion applications, and the frequency band of operation can be designed and fabricated by changing the size of the membranes that make up the transducer. It also shows that the shape of the membrane is not critical in immersion applications where the acoustic loading of the medium dominates the mechanical impedance of the membranes.

VI. Conclusion

Capacitive micromachined ultrasonic transducers, also known as CMUTs, have been shown to perform comparably to its piezoelectric counterparts in various aspects. One-dimensional linear and annular and two-dimensional CMUT arrays with element count as large as 16000 have been built. 2-D and volumetric imaging results have also been reported. In this paper we reviewed the fabrication process of CMUTs and briefly described the new wafer-bonding technique that allowed the fabrication of low-frequency devices.

The experimental results reported in this paper show that the current CMUT process is capable of producing wideband (over 100 % fractional bandwidth in immersion) and efficient (k_T^2 of 0.85) ultrasonic transducers within a frequency range of 10 kHz to 60 MHz. This frequency range of CMUTs covers various application areas from sonar, and underwater imaging to intravascular imaging and fluidic applications.

ACKNOWLEDGMENT

This research has been supported by US Office of Naval Research and DARPA.

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