CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCERS (CMUTS) WITH PISTON-SHAPED MEMBRANES

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***Abstract*—Compared to PZT transducers in medical applications, CMUTs reported on so far have broader fractional bandwidth (FBW) but lower transduction efficiency (TX and RX) [1]. Most fabricated CMUTs reported in the literature carried membranes of uniform thickness. Since there is a performance trade-off between transduction efficiency and FBW when designing CMUTs with uniform membrane thickness, there is limited room for performance improvement in these devices. However, wafer-bonding-based CMUT fabrication provides design flexibility by allowing fabrication of membranes with different thickness profiles. Herein, CMUTs featuring piston-shaped membranes are developed to improve device performance.**

According to our theoretical predictions, piston-shaped membranes should improve the CMUT performance in terms of output pressure, sensitivity, and broader fractional bandwidth. The large ratio of second resonant harmonic frequency to first resonant frequency improves FBW. Increased electrical field intensity in the CMUT cavity (due to the larger equivalent spring constant of this membrane, compared to classical membranes) improves TX and RX. The device performance also benefits from a flatter membrane shape that allows greater average membrane displacement and intra-cavity electrostatic pressure. CMUTs featuring piston-shaped membranes with different geometric shapes were designed and fabricated. In order to make a fair comparison, all designs have a similar first resonant frequency, and all devices are equal in size.

Fabricating CMUTs featuring piston-shaped membranes is a more complex process than fabricating CMUTs with uniformly thick membranes. However, no yield-loss was observed when CMUTs featuring piston-shaped membranes with different geometric shapes were fabricated.

The device characterization was carried out with both pitch-catch (PC) and pulse-echo (PE) immersion tests in oil. These devices achieved ~100% improvement in transduction performance (TX and RX) over CMUTs with uniform membrane thickness. For CMUTs with square and rectangular membranes, FBW increased from ~110% to ~150% and from ~140% to ~175%, respectively, over CMUTs with uniformly thick membranes. The new devices produced a maximum output pressure exceeding 1 MPa. Finally, performance optimization using the geometric shape was the same in both CMUTs featuring piston-shaped membranes and CMUTs with uniform membrane thickness.

I. INTRODUCTION

Typical CMUTs are made with membranes of uniform thickness [2]. In this fashion, the equivalent circuit inductance (mass) and capacitance (spring constant) of the membrane are both set, and so is the average displacement, capacitance, and all other properties of the membrane, and hence the transducer itself. This paper presents a cell configuration where a center mass is added to the membrane in order to offer some separation in the control of the mass and spring constants of the membrane, as shown in Fig. 1.

Fig. 1: Schematic diagram of a cell with a center mass.

One advantage of the addition of the center mass is the increase in the frequency of the higher order resonance mode, and hence a large increase in bandwidth. Fig. 2 shows the ratio of the second order to the first order resonance frequency for a circular membrane of the dimensions shown with a center mass of silicon.

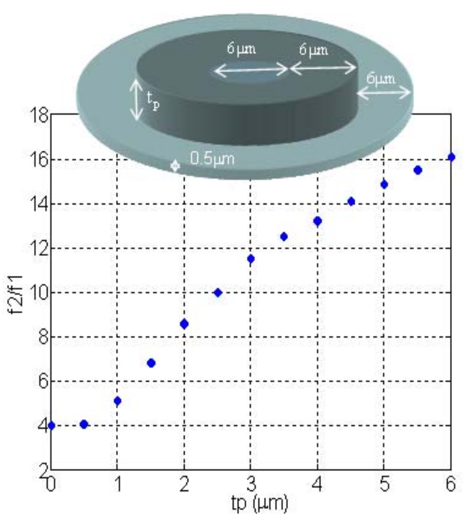
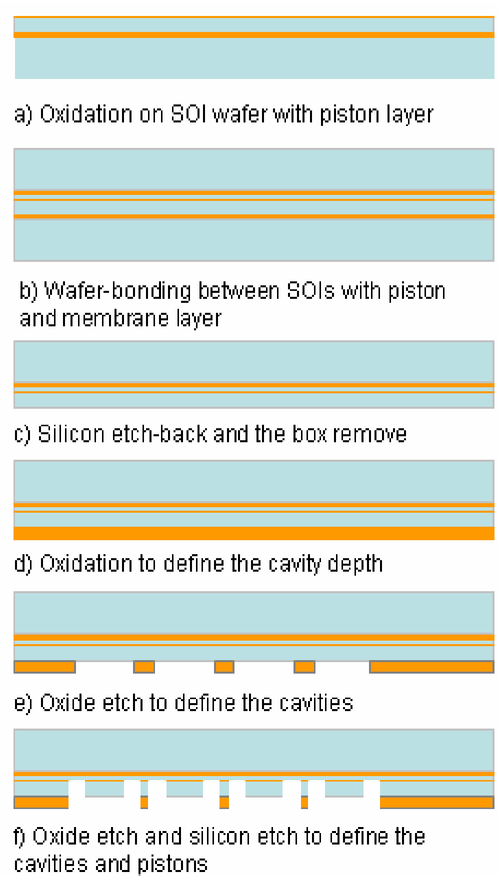


Fig. 2: A membrane with a center mass, and the ratio of the second to the first resonance mode of the structure.

Other advantages of the center mass are: more uniform displacement and hence higher output pressure, increased capacitance and hence better matching into electronic circuits and better receive sensitivity.

II. DEVICE FABRICATION AND CHARACTERIZATION

Fabricating devices with membranes as shown in Fig. 1 requires two wafer-to-wafer silicon fusion bonding steps. The details for fabricating CMUTs with membrane having a center mass are shown in Fig. 3.



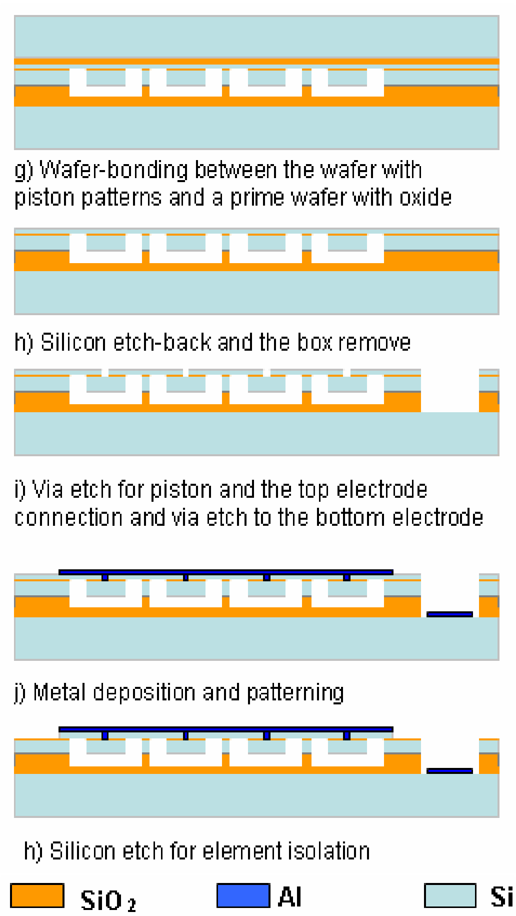


Fig. 3: Processing steps for making a CMUT with piston membranes.

For comparison purposes, and to demonstrate the validity of the proposed concept of using a center mass, square cell devices with and without a center mass were designed to have the same first order resonant frequency, and to have their pulse echo responses compared side by side. Fig. 4 shows such a comparison. Other membrane geometries with and without the center mass, such as rectangle and tent [3], were also fabricated and tested. Test results for these membrane geometries are similar to those of the square membranes.

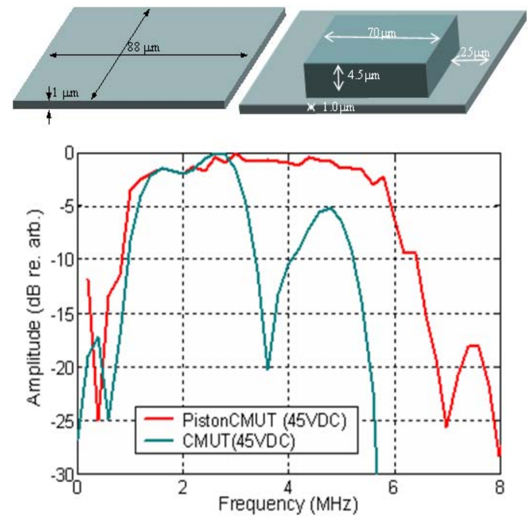
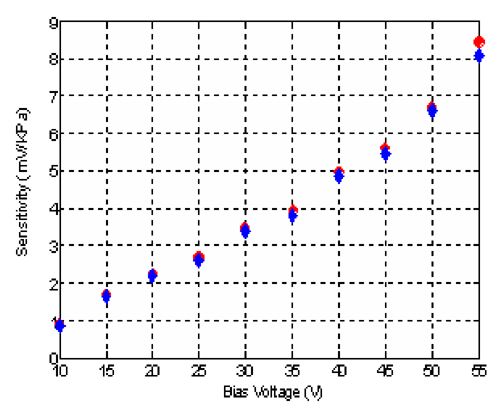


Fig. 4: Comparison of the band shape of two CMUTs with the same first resonance frequency, but one without and one with a center mass.

It is clear from Fig. 4 that the device with a center mass has a higher order resonance that is around 7 MHz while the uniform membrane device has a higher order resonance at around 3.5 MHz. This results in a tremendous advantage in bandwidth for the device with the center mass.

The transmit and receive characteristics of the device (with center mass) of Fig. 4 were also measured and are shown in Fig. 5.



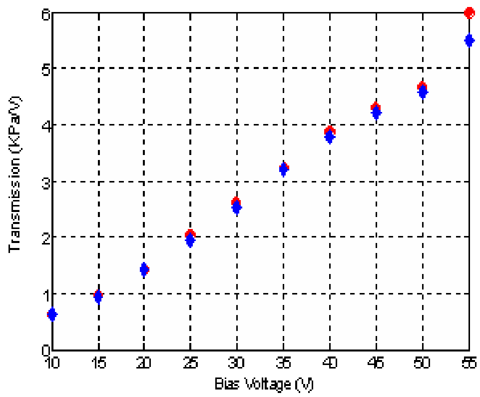


Fig. 5: The transmit and receive characteristics of a CMUT with a center mass are shown. Both are twice as large as the same characteristics for the conventional uniform membrane device.

We also tested the CMUT with center mass in a novel fashion where an electrical excitation pulse is applied without the benefit of DC bias. In this mode, we expect to get maximum output pressure out of the device as the excursion of the membrane is maximum, and because the membrane motion is damped by the fluid, there is not ringing expected. This approach teaches that it is probably more profitable to operate CMUTs without DC bias on transmit and to then switch on the DC bias on receive to enhance the signal to noise ratio of the received signal. Fig. 6 shows the result of this test.

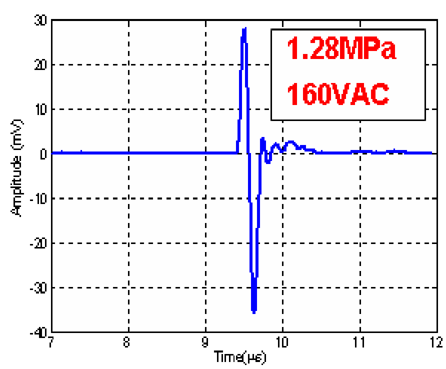


Fig. 6: Hydrophone measurement of the output pressure of a CMUT. The CMUT of Fig. 4 has a center mass and with an excitation that consists of a pulse without a DC bias.

III. CONCLUSION

The addition of a center mass to a membrane provides a piston-like motion to the membrane which has advantages of improved bandwidth, increased device capacitance, increased output pressure, increased sensitivity, increased average displacement on the surface and therefore enhancement in the fill factor. The same approach has been tested with square cells, rectangular cells, and with tented devices, and in all cases all the above mentioned improvements have been obtained.

It is important to note that the ability to add a center mass is not restricted to CMUTs made with wafer bonding. Rather, a mass can be deposited on the top side of a membrane and the same improvements demonstrated above can be attained.

Another point this paper makes is that the most output pressure is obtained when transmitting with a pulse without a DC bias. In this case, the AC signal with amplitude much higher than the collapse voltage can be applied on the membrane and thus higher output pressure can be obtained.

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