Comparison of conventional and collapse-mode CMUT in 1-D array configuration

K. K. Park, O. Oralkan, and B. T. Khuri-Yakub
Edward L. Ginzton Laboratory
Center for Nanoscale Science and Engineering
Stanford University, CA 94305 U.S.A.

Abstract—**This paper presents a comparison between two types of capacitive micromachined transducers (CMUTs), one operating in the conventional mode and the other one in the collapse-mode. Both types of devices are designed to have the same membrane properties (silicon, 1-μm thick), the same peak frequency (10 MHz) and similar operating bias voltages (100 V - 130 V). In the finite element analysis (FEA) of transmit pressure, both types of devices have similar fractional bandwidth (FBW) more than 120%, whereas, the collapse-mode CMUT has higher output pressure (46.5 kPa/V) than that of the conventional CMUT (13.1 kPa/V). To validate the FEA results, these two devices are fabricated using LOCOS/wafer-bonding process. The fabricated devices have a phased array configuration with an element pitch of 75 μm. The output pressure and the FBW of the conventional CMUT is 110% and 12.7 kPa/V, respectively, which match well with FEA results. The collapse-mode CMUT has a FBW of 102.5% and output pressure of 26.4 kPa/V. With a large AC excitation and high DC bias, the conventional CMUT has an output pressure of 1.25 MPa$_{p-p}$ with 56.4-V$_{p-p}$ AC and 180-V DC. The collapse-mode CMUT has an output pressure of 2.37 MPa$_{p-p}$ with 56.2-V$_{p-p}$ AC, and 150-V DC.**

Keywords; CMUT, Collapse-mode, LOCOS, MEMS

I. INTRODUCTION

Capacitive micromachined ultrasonic transducers (CMUTs) have been investigated as an alternative technology to piezoelectric transducers. As flexural mode capacitive transducers, CMUTs have better matching to medium than the piezoelectric transducers. The CMUTs are also suitable for mass production and for integration with front-end electronics, due to the nature of microfabrication. To put these benefits to practical applications, the output pressure of the CMUT needs to be improved.
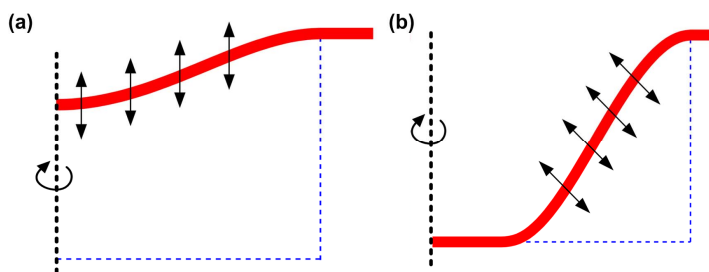
One of approaches to improve the output pressure is the collapse-mode operation. A conventional CMUT utilizes the entire area of the membrane as a transducer [Fig 1(a)]]. On the other hand, in the collapse-mode operation, the membrane is biased more than a pull-in voltage, and then the center part of the membrane contacts to a bottom electrode [Fig 1(b)]. In this mode, a CMUT cell acts as a ring-shape transducer. The electric field strength in the cavity is higher in the collapse-mode CMUT compared to the conventional CMUT, thus collapse-mode operation provides better transmit and receive efficiently.

In previous studies, the performance of a CMUT in the collapse-mode has been examined through experiments [1-2] and using finite element analysis (FEA) [3-4]. However, in the experiment, two devices with different peak frequencies were compared. In the FEA [4], several devices with the same peak frequency were compared. However, these simulations assumed infinite number of cells per transducer element.

In this work, we focus on a comparison between the conventional and the collapse-mode CMUTs. For a fair comparison, both devices should have similar operating bias voltages and operating frequencies. To consider a realistic situation, the element size is reduced to half wavelength at the peak frequency. In this comparison, we mainly focus on the output pressure as the primary figure of merit.

II. FINITE ELEMENT ANALYSIS

We used ANSYS 12 to calculate the output pressure of the CMUT. The model was developed in 2-D axisymmetric coordinates and is made of a single CMUT cell including an equivalent space between membranes. One side of the membrane (PLANE42) is linked to a substrate by capacitive transducer elements (TRANS126). The other side of the

Fig. 1. Simplified operational mode of the cell of (a) a conventional CMUT and (b) a collapse-mode CMUT.

TABLE I.
DIMENSIONS OF THE TWO DEVICES

	Conventional CMUT	Collapse-mode CMUT
Thickness (μm)	1	1
Radius (μm)	15	30
Gap (μm)	0.25	0.5
V$_{pull-in}$ (V)	135	71
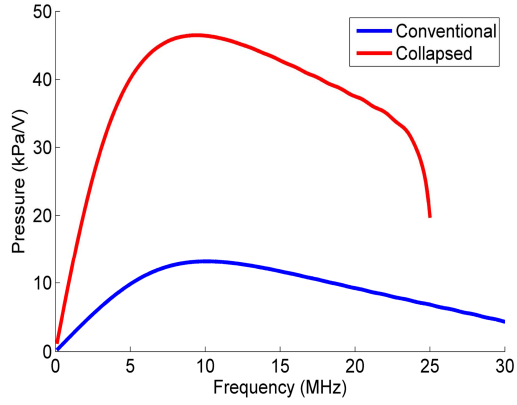
Fig 2. Calculated output pressure response of a conventional and a collapse-mode CMUT in Table I.
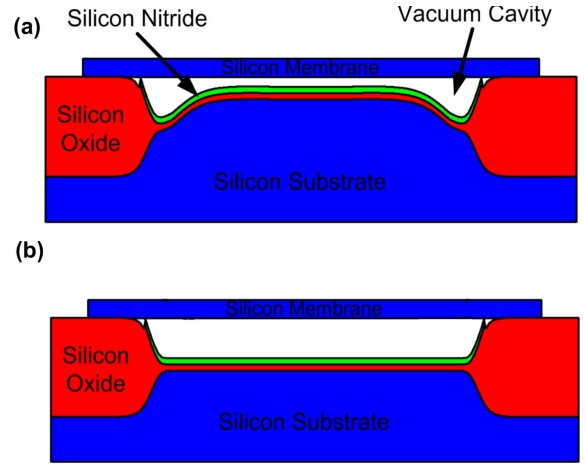

Fig 3. Cross-sectional schematic of the cell of (a) a conventional CMUT and (b) a collapse-mode CMUT. Drawing is not in scale.
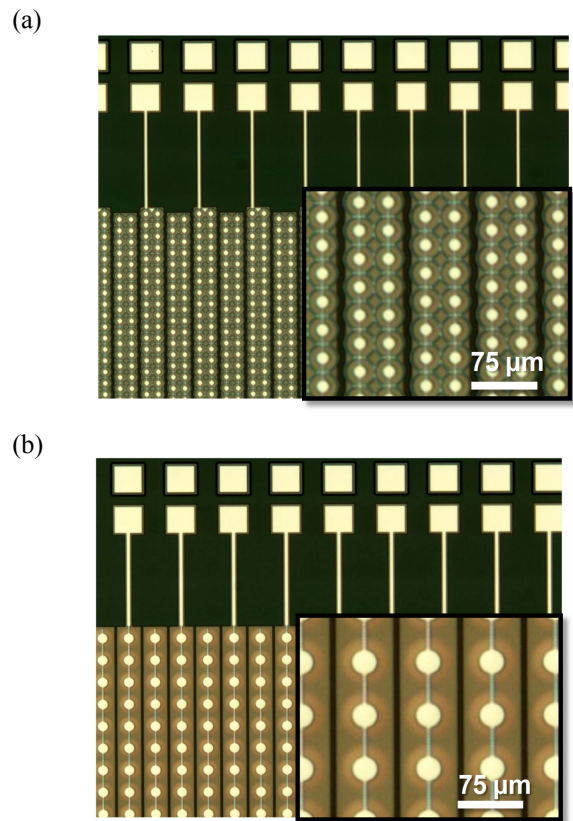

Fig 4. Optical picture of fabricated CMUTs. (a) a conventional CMUT array. (b) a collapse-mode CMUT array.

membrane faces a medium column (FLUID29) to include the effect of the acoustic impedance of the medium. We calculated the frequency response using harmonic analysis in FEA. When a DC bias voltage was applied on the transducer, the membrane was deflected down (conventional mode) or contacted the substrate (collapse mode) due to the electrostatic force. Based on this static analysis, a frequency response was calculated. At each frequency, pressure information was extracted from every node located between the medium and the membrane. The average pressure was then calculated from the pressure distribution across the cell including the space between cells. A detailed description of the FEA used in this paper was presented in [5].

For a reasonable comparison between the conventional CMUT and the collapse-mode CMUT, we chose dimensions of two devices to meet the following criteria. First, their membranes have same thickness (1 µm) and the same material properties (single crystal silicon). Second, their DC bias voltages should be similar to each other. In this case, we chose a bias voltage around 100 V. Therefore the pull-in voltage (collapse voltage) of the conventional CMUT should be higher than 100 V, whereas that of the collapse-mode CMUT is lower than 100 V. In addition to these criteria, the dimensions of the two CMUTs should be in the reasonable range for fabrication feasibility. Table I shows dimension of CMUTs in the FEA.

Fig. 2 shows frequency response of the output pressure of the two devices in Table I. Both devices were biased at 100 V and the output pressure was calculated based on small signal excitation. As shown in Table II, the collapse-mode CMUT has 3.5 times higher output pressure compared to the conventional CMUT, while maintaining similar peak

TABLE II.
CALCULATED PERFORMANCE OF DEVICES IN TABLE 1.

	Conventional CMUT	Collapse-mode CMUT
Peak Frequency (MHz)	10.1	9.4
Fractional Bandwidth (%)	124	147
Output Pressure (kPa/V)	13.1	46.5

frequency. The collapse-mode CMUT has slightly wider fractional bandwidth (FBW) compared to the conventional CMUT, but both devices have a FBW exceeding 120%. These results agree with the previous experimental work [2].

Please note that the model simulates a single cell and assumes that 1) the size of an element (a unit transducer) is infinite and 2) all the cells in the elements are moving with the same amplitude and phase. However, both assumptions are not valid in reality.
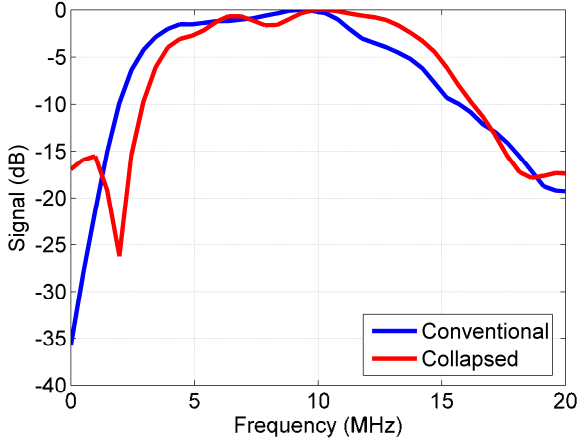
Fig. 5. Frequency response of the output pressure of a conventional CMUT and a collapse-mode CMUT.

III. DEVICE FABRICATION

In order to validate the FEA results and to perform a fair comparison, the two types of devices described in Table I were fabricated. We chose the LOCOS/wafer-bonding process for fabrication [6], because of its precise dimension controllability and good uniformity. In addition, this fabrication process enables to fabricate the two types of devices, *i.e.* conventional CMUTs and collapse-mode CMUTs, in a single wafer. By locating a silicon step inside a cavity, one can design a "thin gap" [Fig. 3(a)] device and a "thick gap" [Fig. 3(b)] device in a single wafer. In this fabrication run, the height of the thick gap is 500 nm and the height of the silicon step is 250 nm.

We chose a 1-D phased array configuration for both devices. Each device (4 mm x 6 mm) has 64 elements (Fig. 4). As shown in Table II and the peak frequency is 10 MHz in immersion; therefore the element-to-element pitch was set to 75 μm, which was half of the wavelength. Based on the element pitch and the membrane radius (Table I), it turned out that the element of the conventional CMUT is made of two columns of cells and that of the collapse-mode CMUT is made of a single column of cells as shown in Fig. 2.

IV. RESULTS

The output pressure of the fabricated devices as a function of frequency was measured using a calibrated hydrophone (Onda, HNP0400). The devices were immersed in vegetable oil and a single element was biased at 100 V. Then a 33-ns

TABLE III.
DEVICE PERFORMANCES FROM FIG. 5 AND FIG 6

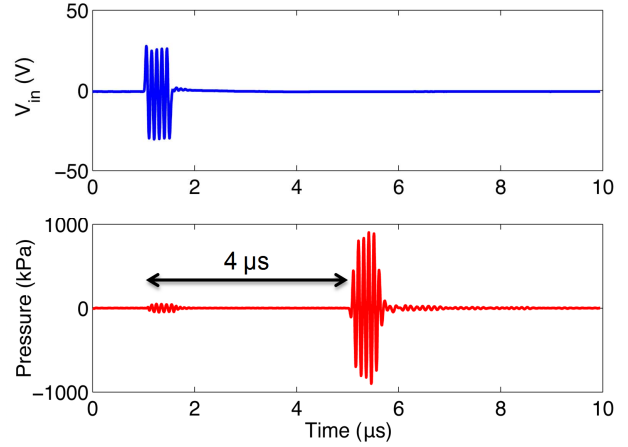|	Conventional CMUT	Collapse-mode CMUT
Peak Frequency (MHz)	9.3	10.3
Fractional Bandwidth (%)	110.6	102.5
Output Pressure (kPa/V)	12.7	26.4

Fig. 6. Measured waveform of output pressure measurement. 5 to 10 cycles of sinusoidal waves are applied on the CMUT (top) and a hydrophone receives a propagated sound wave (bottom). The time delay between the transmit signal and the receive signal, 4 μs, corresponds to the distance between the CMUT and the hydrophone.
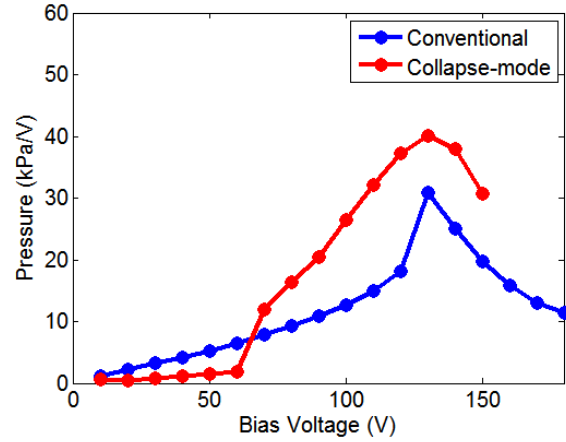

Fig. 7. Measured and calculated output pressure per unit input in various bias voltages of a conventional CMUT and a collapse-mode CMUT.

unipolar pulse was applied on the element. The acoustic impulse response is measured using the hydrophone located on axis and the frequency response was calculated by calculating the FFT of the received signal (Fig. 5). As shown in Table III, the measured peak frequency and the FBW match well with the FEA results presented in Table I.

The output pressures of the two types of devices were measured with various combinations of DC and AC voltages. In order to remove the interference from a reflected signal from the surface of the medium and from any surface wave on the device, we used a tone burst excitation, with 5-10 cycles. The hydrophone was placed on the axis of a single element. Based on the received signal by the hydrophone, the attenuation loss of the medium and the diffraction loss, the average output pressure on the element surface can be calculated as shown in Fig 6.

As a standard characterization, pressure per unit input voltage was measured using a small AC signal applied at various DC bias points. Fig. 7 presents the output pressure per
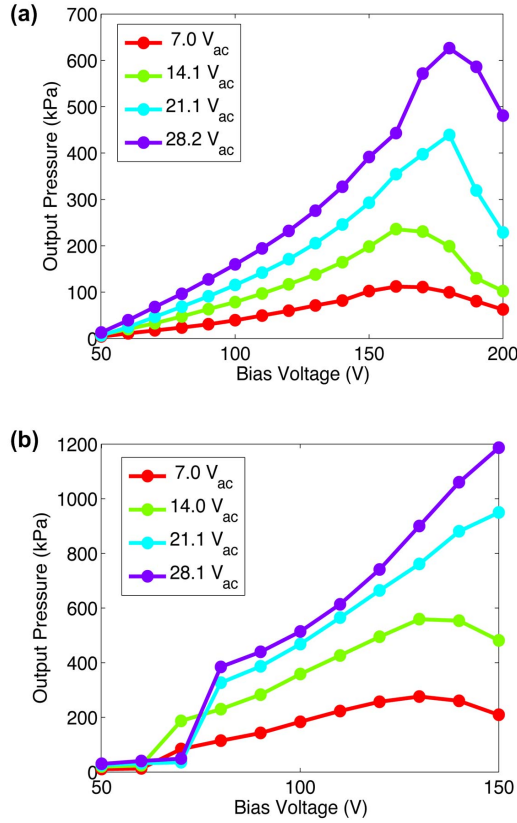
Fig. 8. Measured output pressure in various dc and ac voltage. (a) A conventional CMUT. (b) A collapse-mode CMUT.

unit input AC voltage, when applying a 10-MHz burst input signal. The output pressure of the collapse-mode device linearly increases with bias voltages until membranes collapse at 130 V. After the pull-in, the output pressure decreases because its fundamental frequency shifts to a higher frequency than the excitation frequency, 10 MHz. On the other hand, the output pressure of the collapse-mode device, after collapsed at 70 V, increases with the bias voltage up to 130 V, after which the fundamental frequency started to change dramatically. The output pressure at 100-V bias, is listed in Table III. Note that the output pressure ratio between the collapse-mode and the conventional CMUT under proper operating conditions (80-120 V) is approximately 2, which is 33% smaller than the calculated ratio using FEA [5].

Due to the non-linear response of the cell, the results in Fig. 7 may not be valid with higher AC voltages. In order to investigate the maximum output pressure, we measured output pressure of the two devices with various DC and AC combinations as shown in Fig. 8. The conventional CMUT [Fig. 7(a)] had linear response to the AC excitation up to 56.4 V_{pp}. However, the output sensitivity of the collapse-mode device decreases with more AC voltage. In this experiment, the maximum pressure from the conventional CMUT is 1.25 MPa_{p-p} with 56.4 V_{p-p} AC. The collapse-mode CMUT has much higher maximum pressure, 2.37 MPa_{p-p} with 56.2 V_{p-p} AC.

V. CONCLUSION

We presented the comparison between a conventional CMUT and a collapse-mode CMUT. Both devices were designed to have the same membrane thickness, peak frequency and DC bias voltage. Both devices were fabricated in a 1-D phased array configuration. The transmit characteristics of the two designs were calculated using FEA and also experimentally measured.

The calculated output pressure per unit input voltage of the collapse-mode CMUT is 3.5 times of that of the conventional CMUT in FEA. However, the ratio reduced to 2 in the measurement. For the given peak frequency of 10 MHz and the membrane thickness of 1 μm, both designs presented wide fractional bandwidth, both in FEA results and in measurements. The fabricated conventional CMUT and the collapse-mode CMUT presented a maximum output pressure of 1.25 MPa_{p-p} and 2.37 MPa_{p-p} respectively.

In addition, this work presented that the collapse-mode CMUT element in 1-D phased array configuration, *i.e.* the element pitch is limited to half wavelength, still presented wide bandwidth, which is comparable to the simulation.

In this paper, we have only considered the transmit characteristics of two specific designs. Therefore, additional consideration is required for various applications. Therefore additional optimization and comparison are the subjects of future research.

VI. ACKNOWLEDGMENT

REFERENCES

[1] O. Oralkan, B. Bayram, G.G. Yaralioglu, A.S. Ergun, M. Kupnik, D.T. Yeh, I.O. Wygant and B.T. Khuri-Yakub, "Experimental characterization of collapse-mode CMUT operation," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, vol. 53, no. 8, pp. 1513- 1523, Aug. 2006.
[2] Y.L. Huang, E. Haeggstrom, B. Bayram,X.F. Zhuang, A. S. Ergun, C.H. Cheng, B. T. Khuri-Yakub, "Comparison of conventional and collapsed region operation of capacitive micromachined ultrasonic transducers," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, vol. 53, no. 10, pp. 1918- 1932, Oct. 2006.
[3] B. Bayram, E. Haeggstrom, G.G. Yaralioglu, and B.T. Khuri-Yakub, "A new regime for operating capacitive micromachined ultrasonic transducers," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on , vol. 50, no. 9, pp. 1184- 1190, Sept. 2003.
[4] G. G. Yaralioglu, B. Bayram, and B. T. Khuri-Yakub, "Finite Element Analysis of CMUTS: Conventional vs. Collapse Operation Modes," in Proc. IEEE Ultrason. Symp., Vancouver, Canada, pp. 586-589, 2006.
[5] G.G. Yaralioglu, S.A. Ergun, and B.T. Khuri-Yakub, "Finite-element analysis of capacitive micromachined ultrasonic transducers," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, vol. 52, no. 12, pp. 2185- 2198, Dec. 2005
[6] K. K. Park, H. Lee, M. Kupnik, and B. T. Khuri-Yakub, "Fabrication of capacitive micromachined ultrasonic transducers via local oxidation and direct wafer bonding," Microelectromechanical Systems, Journal of, vol. 20, no. 2, pp. 95-103, Feb. 2011.