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Dual-Electrode CMUT With Non-Uniform Membranes for High Electromechanical Coupling Coefficient and High Bandwidth Operation

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Abstract

In this paper, we report measurement results on dual-electrode CMUT demonstrating electromechanical coupling coefficient (k^2) of 0.82 at 90% of collapse voltage as well as 136% 3 dB one-way fractional bandwidth at the transducer surface around the design frequency of 8 MHz. These results are within 5% of the predictions of the finite element simulations. The large bandwidth is achieved mainly by utilizing a non-uniform membrane, introducing center mass to the design, whereas the dual-electrode structure provides high coupling coefficient in a large dc bias range without collapsing the membrane. In addition, the non-uniform membrane structure improves the transmit sensitivity of the dual-electrode CMUT by about 2dB as compared with a dual electrode CMUT with uniform membrane.

I. Introduction

Dual-electrode CMUT were shown to have higher transduction performance when compared with their conventional, single-top-electrode counterparts [1]–[3]. The frequency response of the transducer was not significantly changed because the uniform thickness membrane structure of conventional CMUT, which dominates the mechanical behavior, was not altered. Several approaches were suggested to improve the transduction performance and frequency response by changing the uniform membrane structure of the CMUT. In one case, notches were introduced in the membrane to increase the electromechanical coupling coefficient and transmit sensitivity [4]. Other studies investigated non-uniform membrane structures with mass loading. This approach increases the coupling coefficient, and more importantly, it can shape the frequency response of the device as the higher-order vibration mode frequencies can be altered [5]–[8]. One can exploit this feature to have a broader frequency band centered around the first mode of the membrane or to realize multiple frequency band transducers for harmonic signal detection. The bandwidth improvement around the first mode can also be explained by an accurate 1-D equivalent circuit model [9]. According to this model, the smaller spring constant of a mass-loaded membrane for a given center frequency reduces the lower cut-off frequency, and less mass loading of the fluid

because of the piston-like structure increases the higher cut-off frequency, hence increasing the fractional bandwidth. In this study, center mass loading is used to obtain a dual-electrode CMUT with high fractional bandwidth.

In earlier dual-electrode CMUT studies, the transformer ratio of the electrical equivalent circuit model was used to assess the performance improvement as compared with conventional CMUT, especially in the receive mode [2], [3]. However, to evaluate and compare the transduction performance across different types of ultrasonic transducers including piezoelectric transducers, the electromechanical coupling coefficient (k^2) is a more suitable metric. As is well known, k^2 is the ratio of mechanical energy delivered to the load (W_{mech}) to the total energy stored in the transducer (W_{tot}), which by definition is the sum of electrical (W_{elec}) and mechanical (W_{mech}) energy components:

$$k^2 = \frac{W_{\text{mech}}}{W_{\text{total}}} = \frac{W_{\text{mech}}}{W_{\text{mech}} + W_{\text{elec}}}. \quad (1)$$

This coefficient is an important parameter in ultrasonic transducer design because it measures the degree of energy coupling (efficiency) between electrical and mechanical domains. For piezoelectric transducers, the transducer bandwidth can be related to the coupling coefficient (k^2) [10]. This parameter was calculated and measured for conventional CMUT in previous studies using a capacitance definition [11], [12]. Here, we evaluate k^2 for dual-electrode CMUT as a figure of merit for a comprehensive comparison.

In this paper, we first calculate the coupling coefficient and fractional bandwidth of the dual-electrode CMUT with uniform and non-uniform membranes, taking a CMUT with 8 MHz center frequency as the design example. We optimize the CMUT membrane geometry in a limited parameter range for high coupling coefficient and fractional bandwidth. We then present experimental results obtained with dual-electrode CMUT which show a fractional bandwidth of 136% at the transducer surface and a coupling coefficient of 0.82. We emphasize that this performance is achieved over a broad bias voltage range. It is also shown that the transmit sensitivity of the dual-electrode CMUT is also improved with this geometrical change.

II. Calculation of Electromechanical Coupling Coefficient and Fractional Bandwidth for Dual-Electrode CMUT

To calculate the electromechanical coupling coefficient (k^2), the energy definition of (1) is implemented using the coupled field electrostatic simulation capability of the commercial FEA program, ANSYS v11.0 (ANSYS Inc., Canonsburg, PA). A 2-D CMUT model (Fig. 1) with parameters given in Table I is developed. Silicon nitride with Young's modulus of 110 GPa, Poisson's ratio of 0.23, and density of 2040 kg/m³ is used as the membrane structural material. The measurement of silicon nitride material constants used in the experiments has been discussed previously [13]. When the coupled field analysis between mechanical and electrical domain is used, the electrical and mechanical energy values in (1) can be extracted at any bias value to obtain the electromechanical coupling coefficient. This is advantageous compared with capacitance-based calculations which require derivatives with small voltage steps and are thus prone to numerical errors. As in a conventional CMUT, calculation of k^2 involves determining the electrical energy, W_{elec} , associated with the center electrode at a given bias and varying that bias voltage from zero to collapse. The difference is that in the dual-electrode CMUT, a constant bias voltage applied to the side electrodes while the center electrode bias is changed. The mechanical energy, W_{mech} , is calculated over the entire membrane as the whole membrane moves with the applied electrical energy. The k^2 values

calculated with this direct energy-based finite element method have been compared with the capacitance-based calculation for several cases and its validity has been confirmed [11], [12].

To obtain the transmit sensitivity and 3 dB fractional bandwidth of CMUT with various electrode and membrane configurations, a 2-D coupled field transient model is developed. PLANE42 elements are used to model both the membrane and Parylene C layer which protects the membrane and bondpads from water exposure. The fluid medium is modeled using FLUID29 elements. Absorption is activated on the outer surface of fluid elements to extend the fluid domain. The fluid structure interaction is activated over the membrane surface. TRANS126 elements are used to model electrostatic actuation. The voltage input to the TRANS126 elements is provided via attached CIRCUI24 elements as an independent voltage source in the simulations. A 20-nsec, 10-Vp square pulse is generated by setting CIRCUI24 element real constants. To include the effect of dc bias, a static analysis is performed by turning off the transient time integration effects. The transient analysis is then performed with the initial condition observed from the previous analysis. The pressure data are averaged over the membrane surface in the time domain. Fourier transforms of the pressure data are taken to obtain the 3 dB fractional bandwidth. For transmit sensitivity calculations, CIRCUI24 element real constants are modified to generate a 5-cycle, 10-V peak tone burst signal at 8 MHz. The observed peak pressure over the membrane surface is then used to evaluate the transmit sensitivity. For fair comparison, in the conventional CMUT simulations, 50% electrode coverage is chosen, as this is close to the optimum value [12]. For both the bandwidth and the transmit sensitivity simulations, a dc bias value of 90% of the collapse voltage is used for center and side electrodes.

III. Design of Dual Electrode CMUT With Non-Uniform Membranes

The design of the non-uniform membrane CMUT is more involved than its uniform membrane counterpart because several additional center mass parameters can also be changed: namely; the center mass width, center mass thickness, and membrane thickness. Also, one can change the material selection for mass loading, however the center mass material is the same as the membrane in this study. For a fair comparison between different CMUT, the operation frequency of the transducers is kept constant [14]. The electromechanical coupling coefficient and fractional bandwidth are chosen as the main parameters for optimization.

A dual-electrode CMUT with non-uniform membrane is illustrated in Fig. 1. During the optimization, several geometrical parameters of the dual-electrode CMUT are kept constant, including the width of the central mass, to limit the design space. These are listed in Table I. Furthermore, the width of the membrane is kept constant at 48 μm . The results of simulation studies for different types of CMUT are summarized in Table II. The first 3 designs correspond to conventional CMUT with uniform membrane and 50% electrode coverage. To highlight the design variables for this particular case, the width and thickness of the membrane is varied. Increasing the membrane width and membrane thickness result in higher transformer ratio and electromechanical coupling coefficient; however, the bandwidth is significantly reduced. This illustrates a trade-off in conventional CMUT design: the efficiency and bandwidth cannot be increased at the same time [15]. Note that design 2 shows simulation results for conventional CMUT with a uniform membrane, design 4 for conventional CMUT with non-uniform membrane, while the design 5 illustrates the results for uniform membrane dual-electrode CMUT with 31% center electrode coverage, all for a constant membrane width of 48 μm . The dual-electrode structure significantly improves the electromechanical coupling coefficient and receive sensitivity, but not the transmit sensitivity or the bandwidth.

To optimize the CMUT design with non-uniform membrane for 8 MHz operation, the center mass and membrane thicknesses are varied for a constant 24 μm center mass width. Table II also summarizes these simulation results with varied membrane–center-mass-thickness pairs. For the center mass loaded membrane, the simulations indicate that both operation frequency and the bandwidth first increase with increasing of center mass thickness; however, after reaching a maximum value, it decreases. This behavior was also observed by others [7]. The addition of the center mass to the design plays an effective role in determining the frequency response. Decreasing the membrane thickness to 2.5 μm (from 3.5 μm) and adding 2 μm center mass results in a significant increase of the fractional bandwidth (from 107 to 145%). Moreover, the side electrode collapse voltage is reduced by nearly 20% (from 160 to 130 V). Additionally, transmit and receive figures of merit are increased with center mass addition to the CMUT design. We observe from Table II that a membrane thickness of 2.75 μm and a center mass thickness of 1.5 μm provide both high coupling coefficient (0.85) and high fractional bandwidth (137%) around 8 MHz center frequency (design 7). Compared with a uniform membrane, dual-electrode CMUT, this design improves both receive and transmit figures of merit. Moreover, the required side bias value is reduced by 15% and the fractional bandwidth is increased by 30%. Note that when the membrane thickness is further reduced and center mass thickness is increased, receive and transmit figures of merit start to degrade. Thus parameters of design 7 are chosen as an optimized design to be implemented.

IV. Fabrication of Dual Electrode CMUT With Non-Uniform Membranes

The fabrication of non-uniform membrane dual-electrode CMUT is based on the previously developed surface micromachining process [13]. For non-uniform membrane formation, first, the silicon nitride is deposited for the thickest membrane feature. An additional mask is used to protect the center mass region of the membrane and remaining membrane region is etched down to the designed membrane thickness. A scanning electron microscope image of part of a fabricated dual-electrode CMUT array with non-uniform membranes is shown in Fig. 2. Note that the center mass is discontinuous as CMUT are made of multiple rectangular membranes, each of which is loaded with a separate thick center section. The etching is performed using Vision Oxide (Advance Vacuum, Lomma, Sweden) reactive ion etch (RIE) tool, which is the same tool used to define the etch holes in the silicon nitride layer. During this dry etching of the silicon nitride layer to form the center mass, there is no etch stop in the membrane to determine the thickness of the “thin” section of the membrane. To address this issue, the etch rate of silicon nitride in the RIE tool is tested just before each etch step and a timed etch is used to determine the etch depth.

IV. Experimental Results

A. Measurement of Electromechanical Coupling Coefficient

The electromechanical coupling coefficient (k^2) can be experimentally measured by recording the device capacitance as a function of applied bias and using its capacitance based definition [12]. To obtain the capacitance between the center electrode and the bottom electrode, the electrical impedance of the CMUT is measured at this port of the device by using the network analyzer (Agilent 8753 ES, Agilent Technologies, Inc., Santa Clara, CA). The impedance is measured between 2 and 25 MHz. The first resonant frequency of the dual-electrode CMUT is found to be 15 MHz in air and the imaginary part of the impedance measured away from the resonance frequency is used to obtain capacitance of the CMUT for a given bias. This experiment is repeated while sweeping the bias voltages for both side and center electrodes. To demonstrate the independent effect of non-uniform membrane and dual-electrode implementation, the data are recorded for both uniform and non-uniform membrane dual-electrode CMUT. The experiments performed by biasing only the center

electrode and disconnecting the side electrodes are essentially conventional CMUT experiments as the advantage of having side electrodes is not utilized. Note that in this case, the electrode coverage is 31% for 15 μm wide center electrode over a 48 μm wide membrane as in Table I. Therefore, these designs are labeled as 2' and 4' in the figures. Measured capacitance as a function of the applied center electrode bias for different CMUT is illustrated in Fig. 3. The side electrode bias values used for uniform and non-uniform membrane dual-electrode CMUT experiments are 160 and 132 V, respectively, in accordance with Table II.

We observe from Fig. 3 that the capacitance of the uniform membrane conventional CMUT with no bias applied is 8 pF. However, calculated capacitance with membrane parameters listed in Table I should result in an active device capacitance of ~ 5 pF. The experimental set-up, SMA connections, wires, and overlapping top and bottom electrode regions should account for the remaining 3 pF difference. To validate this hypothesis, a dual-electrode CMUT array is diced in a way to remove all active membrane regions except for the electrical connections to bondpads. Then the wirebonded top and bottom electrode is tested in the same network analyzer setup. This test reveals a 3.1 pF parasitic capacitance value as expected. Moreover, this parasitic capacitance does not change as a function of applied bias. Hence, the parasitic capacitance value can be safely removed from experimental data of Fig. 3 to obtain the active device capacitance. The electromechanical coupling coefficient (k^2) is then calculated by using active capacitance as a function of bias voltage. To obtain the electromechanical coupling coefficient, the fixed and free capacitance-based definition of electromechanical coupling coefficient is used [11]. The fixed capacitance can be obtained directly from the experimental capacitance-voltage curve. However, to obtain the free capacitance value, a 6th-degree polynomial is fitted to the experimental data. The polynomial is fitted in several voltage intervals to increase the accuracy of derivative calculation for free capacitance. One can also observe from Fig. 3 that initial capacitance values for the dual-electrode CMUT start with higher values than with no center electrode bias applied, as the membrane is initially deflected by the presence of side electrode bias. Also, non-uniform membranes are initially deflected more under atmospheric pressure, leading to higher capacitance with no bias.

The variation of electromechanical coupling coefficient as a function of normalized center electrode bias obtained from experiments on different types of CMUT is illustrated in Fig. 4(a). We observe from this figure that the non-uniform membrane structure moderately increases the electromechanical coupling coefficient for both dual-electrode and conventional CMUT configurations as expected [5]. More importantly, Fig. 4(a) shows a dramatic improvement in coupling coefficient caused by dual-electrode structure compared with conventional CMUT, with or without non-uniform membranes. Not only are higher coupling coefficients achieved at all bias values, but the curve is more favorably shaped, especially closer to the collapse region, where $k^2 > 0.7$ is achieved for normalized bias values above 0.85. The change in k^2 after collapse is also different between the dual-electrode and conventional CMUT. While the shape of the top electrode of the conventional CMUT slowly changes after initial contact with collapse, the change in dual-electrode CMUT is more dramatic because the top electrode is more flat before the collapse, and hence nearly all of the top electrode area comes in contact at initial phases of collapse. Therefore, after this point changes in center electrode bias do not result in significant capacitance change.

For comparison with experiments, coupling coefficients obtained from finite element simulation are illustrated in Fig. 4(b). The simulations are performed until the collapse voltage because the contact analysis was not included. The agreement between the experimental and simulated curves for all cases is remarkable, indicating that the analysis

method can be used for predicting and optimizing device performance (see Table III in comparison with Table II for dual electrode CMUT, and calculated values for conventional CMUT with 31% metal coverage).

B. Transmit Mode-Bandwidth Measurements

To obtain the bandwidth and transmit mode performance improvements with non-uniform membrane structure, we use the 3 μm parylene-coated dual-electrode CMUT as transmitters and a calibrated hydrophone (GL series hydrophone, ONDA Corp., Sunnyvale, CA) at 6.75 mm away from the transducer as the receiver in a water tank [3]. In the first set of experiments, side electrodes of the uniform membrane dual-electrode CMUT with parameters given in Table I are used as a transmitter and this data serves as a reference. In the second set of experiments, the side electrodes of the non-uniform membrane dual-electrode CMUT are used as transmitter. A 20 ns, 10 V amplitude (peak) ac pulse is applied to the CMUT in both experiments. A 220 V dc bias is applied to uniform membrane dual-electrode CMUT in the first set of experiments, while a 180 V dc is applied to nonuniform membrane dual-electrode CMUT in the second set of experiments.

The waveforms received by the hydrophone and the corresponding frequency spectra for uniform and nonuniform membrane dual-electrode CMUT are illustrated in Fig. 5(a) and (b), respectively. In Fig. 5(b), 0 dB corresponds to the peak value of the measured frequency response for the uniform membrane dual-electrode CMUT, and all other curves are normalized to the same reference. Both time signals in Fig. 5(a) show similar characteristics including the long tail caused by ringing in the un-backed silicon substrate which can be eliminated by placing matched and lossy backing material in contact with the silicon substrate [16]. This resonance causes a dip in the frequency response at around 7.8 MHz for both uniform and non-uniform membrane dual-electrode CMUT. This is expected, because at this frequency the thickness of the silicon substrate (530 μm) corresponds to half a wavelength of longitudinal waves in silicon ($V_1 = 8430 \text{ m/s}$). With the low impedance on the backside of the silicon presented at the front surface, on the bottom electrode, this effectively creates another non-rigid mechanical port and reduces the power radiated into the fluid medium. The simulated frequency response for both uniform and non-uniform dual-electrode CMUT with 3 μm parylene layer are also shown in Fig. 5(b) as dashed lines. Note that simulations compensate the diffraction for the 6.75 mm distance between the transducer and hydrophone surface, and the input pulse shape. The simulations do not include the effect of the silicon substrate which is replaced by a perfectly rigid surface; hence the resonance dip is not present in the simulation results. We observe from Fig. 5(b) that simulation and experimental results agree very well for both cases. After undoing the diffraction effects, we obtain the experimental 3-dB one-way fractional bandwidth of 136% on the surface of the transducer for non-uniform dual-electrode CMUT, which is agreement with the corresponding result in Table II. This increase in fractional bandwidth is very significant for imaging performance.

V. Discussion

The results presented in this paper point out several features of CMUT. With the available microfabrication tools, one can precisely control the CMUT membrane geometry in both lateral and vertical dimensions. In addition, the electrode structure can be patterned to build devices such as dual-electrode CMUT. This combination in turn provides an effective means to adjust the frequency response of the CMUT and its electromechanical coupling coefficient nearly independently. While a CMUT with uniform membrane provides a broad bandwidth, this comes at the cost of reduced coupling coefficient. This trade-off is partially remedied by including a center mass, however the coupling coefficient is still low compared with piezoelectric transducers except at bias voltages too close to the collapse voltage,

limiting the CMUT sensitivity and dynamic range. Dual-electrode structure provides a higher coupling coefficient at a broader range of bias values with a uniform membrane, and increases the maximum output pressure because of large membrane swing, but with limited bandwidth. Ultimately, the use of the non-uniform membrane with a dual-electrode CMUT provides higher bandwidth while providing coupling coefficients rivaling those of pillar-type single-crystal piezoelectric arrays [17].

The shape of the coupling coefficient curves presented in Fig. 4 also show features with practical significance. With the dual-electrode CMUT, not only are high coupling coefficients achieved at about 90% of the normalized bias, but the slope of the curves is much less compared with conventional CMUT. This provides a higher tolerance to non-uniformity of transducer elements in an array caused by geometrical variations or issues like charging. Note that not only the normalized bias range, but also the absolute voltage range for high coupling coefficient is improved. For example, in Fig. 4(a) a dual-electrode CMUT with nonuniform membrane with 132 V side electrode bias achieves $k^2 > 0.7$ in a center electrode bias range of 61 to 74 V, whereas a conventional CMUT with nonuniform membrane has a corresponding dc bias range of only 3 V (119 to 122V).

In addition to coupling coefficient and bandwidth, the non-uniform membrane improves the transmission sensitivity of the dual-electrode CMUT in pascals per volt. This is important, as the higher maximum pressure levels achieved by the dual-electrode structure are obtained with less voltage swing. In terms of dual-electrode CMUT bias voltage requirements, nonuniform membrane structure is also favorable. As observed from Table III, a conventional CMUT with uniform membrane requires 122 V bias for 90% whereas the maximum voltage required for dual-electrode CMUT with non-uniform membrane requires a maximum bias of 132 V on the side electrode and 74 V bias on the center electrode. This particular design of dual-electrode CMUT with non-uniform membrane addresses the performance gap of CMUT and piezoelectric transducers both in terms of coupling coefficient and output pressure levels while providing a larger bandwidth [18]. It is also interesting that a CMUT with high coupling coefficient (such as dual-electrode CMUT with uniform membrane) may not provide a broad bandwidth unless the membrane geometry is specifically designed. This reveals the fact that the mechanical impedance of the CMUT membrane plays a significant role in achieving high bandwidth and high sensitivity simultaneously.

VI. Conclusions

In this paper, dual-electrode CMUT with nonuniform membranes achieving high coupling coefficient, high fractional bandwidth, and high pressure output are reported. The electromechanical coupling coefficient (k^2) for these transducers is simulated and experimentally verified. Experimental results indicate that dual-electrode CMUT with non-uniform membranes provide k^2 of 0.82 at 90% of the collapse, whereas the required maximum dc bias is slightly increased to 132 from 122V as compared with optimized conventional CMUT with uniform membrane. Moreover, a substantial increase in the fractional bandwidth (136 vs. 82%) is demonstrated. These results indicate that CMUT may deliver high performance in a large bias range, without collapse, improving its reliability and tolerance for non-uniformity in array applications. The analysis and measurements reported here show that by careful design of membrane geometry and electrode structure, CMUT can achieve the coupling coefficient and bandwidth of state-of-the-art piezoelectric transducers while retaining the manufacturing and electronics integration advantages offered by microfabrication techniques.

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References

1. Guldiken RO, Balantekin M, Degertekin FL. Analysis and design of dual-electrode CMUTs. *Proc IEEE Int Ultrasonics Symp* 2005:581–584.
2. Guldiken RO, McLean J, Degertekin FL. CMUTs with dual-electrode structure for improved transmit and receive performance. *IEEE Trans Ultrason Ferroelectr Freq Control* Feb;2006 53:483–491. [PubMed: 16529124]
3. Guldiken RO, Zahorian J, Balantekin M, Degertekin FL. Characterization of dual-electrode CMUTs: Demonstration of improved receive performance and pulse echo operation with dynamic membrane shaping. *IEEE Trans Ultrason Ferroelectr Freq Control* Oct;2008 55(10):2336–2344. [PubMed: 18986882]
4. Zhou S, Reynolds P, Hossack JA. Improving the performance of capacitive micromachined ultrasound transducers using modified membrane and support structures. *Proc IEEE Int Ultrasonics Symp* 2005:1925–1928.
5. Knight J, Degertekin FL. Capacitive micromachined ultrasonic transducers for forward looking intravascular imaging. *Proc IEEE Int Ultrasonics Symp* 2002:1052–1055.
6. Hall NA, Guldiken R, McLean J, Degertekin FL. Modeling and design of CMUTs using higher order vibration modes for harmonic imaging. *Proc IEEE Int Ultrasonics Symp* 2004:260–263.
7. Senlik MN, Olcum S, Atalar A. Improved performance of CMUT with nonuniform membranes. *Proc IEEE Int Ultrasonics Symp* 2005:597–600.
8. Huang Y, Hægström E, Zhuang X, Ergun AS, Khuri-Yakub BT. Capacitive micromachined ultrasonic transducers (CMUTs) with piston shaped membranes. *Proc IEEE Int Ultrasonics Symp* 2005:589–592.
9. Lohfink A, Eccardt PC. Linear and nonlinear equivalent circuit modeling of CMUTs. *IEEE Trans Ultrason Ferroelectr Freq Control* Dec;2005 52:2163–2172. [PubMed: 16463483]
10. Kino, GS. *Acoustic Waves: Devices, Imaging and Analog Signal Processing*. Englewood Cliffs, NJ: Prentice-Hall; 1987.
11. Fraser, J.; Reynolds, P. Finite-element method for determination of electromechanical coupling coefficient for piezoelectric and capacitive micromachined ultrasonic transducers. presented at the Joint 140th Meeting of ASA/NOISE-CON; 2000.
12. Yaralioglu GG, Ergun AS, Bayram B, Haeggstrom E, Khuri-Yakub BT. Calculation and measurement of electromechanical coupling coefficient of capacitive micromachined ultrasonic transducers. *IEEE Trans Ultrason Ferroelectr Freq Control* Apr;2003 50:449–456. [PubMed: 12744401]
13. Knight J, McLean J, Degertekin FL. Low temperature fabrication of immersion capacitive micromachined ultrasonic transducers on silicon and dielectric substrates. *IEEE Trans Ultrason Ferroelectr Freq Control* Oct;2004 51:1324–1333.
14. Huang Y, Hægström E, Zhuang X, Ergun AS, Khuri-Yakub BT. Optimized membrane configuration improves the CMUT performance. *Proc IEEE Int Ultrasonics Symp* 2004:505–508.
15. Olcum S, Senlik MN, Atalar A. Optimization of the gain-bandwidth product of capacitive micromachined ultrasonic transducers. *IEEE Trans Ultrason Ferroelectr Freq Control* Dec;2005 52:2211–2219. [PubMed: 16463487]
16. Ladabaum I, Wagner P, Zanelli C, Mould J, Reynolds P, Wojcik G. Silicon substrate ringing in microfabricated ultrasonic transducers. *Proc IEEE Int Ultrasonics Symp* 2000:943–946.
17. Lim LC, Rajan KK, Jin J. Characterization of flux-grown PZN-PT single crystals for high-performance piezo device. *IEEE Trans Ultrason Ferroelectr Freq Control* Nov;2007 54:2474–2478. [PubMed: 18276540]

18. Mills DM, Smith LS. Real-time in-vivo imaging with capacitive micromachined ultrasound transducer (cMUT) linear arrays. Proc IEEE Int Ultrasonics Symp 2003:568–571.

Fig. 1. Rendering of a non-uniform membrane dual-electrode CMUT with thicker center mass section.

Fig. 2. Scanning electron microscope image of a fabricated non-uniform membrane dual-electrode CMUT. This particular CMUT has a 30 μm wide membrane with a 10 μm wide, 1.5 μm thick center mass.

Fig. 3. Measured center electrode capacitance as a function of applied dc bias for uniform/non-uniform membrane conventional and dual-electrode CMUT. Corresponding design parameters are given in Table II.

Fig. 4.

(a) Calculated electromechanical coupling coefficient based on experimentally measured capacitance data after removing parasitic capacitance; (b) simulated electromechanical coupling coefficients (no parasitic capacitance considered in simulations). Corresponding design parameters are given in Table II.

Fig. 5.

(a) Waveforms measured by a hydrophone in water when dual-electrode CMUT with uniform and non-uniform membranes are used as transmitters and excited by short pulses; (b) frequency spectra of the signals in (a). Solid and dashed lines show experimental and finite element simulation results, respectively. Corresponding design parameters are given in Table II.

Table I

Physical Parameters of Dual-Electrode CMUT with Uniform and Non-Uniform Membranes Used in the Simulations. This Set of Parameters is Kept Constant During Design Optimization.

Center mass width	24 μm
Gap/isolation thickness	0.12 μm /0.25 μm
Center/side electrode width	15 μm /10 μm
Center to side electrode separation	4.5 μm

Table II

Simulated Results Comparing Transducer Performance Metrics for CMUT with Different Membrane Geometry, Electrode Structure and Corresponding Operation Parameters.

Design	Membrane width/thickness (μm)	Center mass thickness (μm)	Bandwidth (FBW %)	Side/center bias (V)	Transformer ratio (n) (N/V·m)	Coupling coefficient (k^2)	Side/center collapse voltage (V)	Side/center transmit sensitivity (kPa/V)
1	100/6.5	0	60	NA/144	0.29	0.38	NA/160	NA/26.6
2	48/3.5	0	107	NA/92	0.19	0.26	NA/102	NA/26
3	20/1	0	113	NA/130	0.14	0.15	NA/157	NA/34.5
4	48/2.75	1.5	137	NA/93	0.20	0.44	NA/103	NA/27
5	48/3.5	0	107	160/76	0.42	0.73	240/121	16.6/22
6	48/3	1	128	146/72	0.48	0.79	219/123	17.3/22.8
7	48/2.75	1.5	137	132/74	0.52	0.85	207/122	17.7/23.2
8	48/2.5	2	145	130/71	0.49	0.82	194/122	18.5/22.6

Table III

Summary of Coupling Coefficient and Applied Bias Values for Uniform/Non-Uniform Membrane Conventional and Dual-Electrode CMUT (Obtained from Fig. 4). The Calculated Coupling Coefficients are Shown in Parentheses.

	Center electrode bias (V)	Side electrode bias (V)	Coupling coefficient (90% of collapse)
Uniform membrane conventional CMUT (31% electrode coverage)	122	0	0.28 (0.24)
Non-uniform membrane conventional CMUT (31% electrode coverage)	116	0	0.40 (0.42)
Uniform membrane dual-electrode CMUT (Design 5)	76	160	0.72 (0.73)
Non-uniform membrane dual-electrode CMUT (Design 7)	74	132	0.82 (0.85)