Collapsed Regime Operation of Capacitive Micromachined Ultrasonic Transducers based on Wafer-Bonding Technique

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Abstract- We report experimental results from collapsed regime operation of capacitive micromachined ultrasonic transducers (cMUTs) fabricated by a wafer bonding technique. The results show that a cMUT operating in the collapsed regime produces a maximal output pressure higher than a cMUT operating in the pre-collapse regime at 90 % of its collapse voltage, 1.79 kPa/V vs. 9.72 kPa/V at 2.3 MHz. In collapsed regime operation the fractional bandwidth (pulse echo) is increased compared to that obtained in pre-collapsed regime operation 140 % vs. 83 % with a bias 90 % of the collapse voltage. Characterization of 1-D cMUT arrays operating in oil was done by ultrasonic pulse echo and pitch catch measurements.

I. INTRODCUTION

Transducers are commonly evaluated based on their bandwidth or their sensitivity. Often these properties can be traded for each other during the design process. A figure of merit of transducers is their sensitivity bandwidth product. Transducer development effort therefore can be based on maximizing this product constrained by demands on size, cost etc. From simplified physical models of the device it is usually possible to understand what provides sensitivity or bandwidth separately. It is harder to see what optimizes the sensitivity bandwidth product.

Besides optimizing the structure and geometry of the device it is possible to operate the transducer in a non-conventional way [1] in order to obtain gains in sensitivity and bandwidth. We report on experimental results from operating a capacitive micromachined ultrasonic transducer (cMUT) [2] in collapsed regime [1] and compare them to corresponding results obtained when the transducer was operated in its conventional regime [1].

II. DEVICE DESIGN

The basic structure of a cMUT is a parallel plate capacitor with a rigid bottom electrode and a top electrode residing on a flexible membrane, which is used to transmit or detect an acoustic wave in the adjacent medium [2]. The cross-section of a cMUT cell is shown in Fig. 1. A bias voltage is applied between the electrodes to deflect the membrane for cMUT operation. During transmission an AC signal is applied to the transducer. The alternating electrostatic force between the top electrode and the bottom electrode vibrates the membrane in order to deliver acoustic energy into the medium surrounding the cMUT. During reception, the impinging acoustic wave vibrates the membrane thus changing the capacitance between two electrodes. This capacitance change is detected by an electronic circuit.

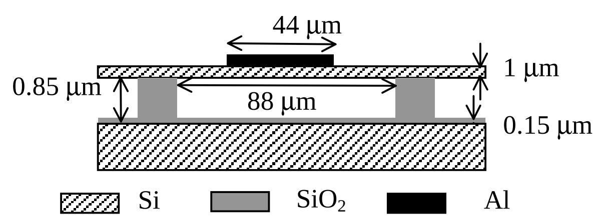

Figure. 1. The cMUT simulation used in the simulations.

The performance of the designed cMUT was simulated with a finite element software (ANSYS 7.1). A cMUT array consists of hundreds of cells as the one shown in Fig. 1. The simulated capacitance (CV) and average displacement (DV) as a function of the bias voltage are shown in Figs. 2-3. Both these curves exhibit two stable regimes of operation. One is the conventional (pre-collapsed) regime within which the bias voltage is below the collapse voltage of the cMUT. The other one is the collapsed regime above the snapback voltage and the breakdown voltage of the cMUT [1]. The simulation predicts that it would be advantageous to operate the cMUT in the collapsed regime. First, the capacitance change per applied voltage in this regime is larger than that in the pre-collapse regime, which results in higher reception sensitivity. Second, the average displacement per applied voltage in the collapsed regime is larger than that in the pre-collapsed regime. This translates into an improved capability to deliver energy into a surrounding medium. Moreover, the optimum bias voltage for collapsed regime operation can be designed further away from the collapse voltage than what is possible in conventional regime operation. This allows large AC signals to be used.

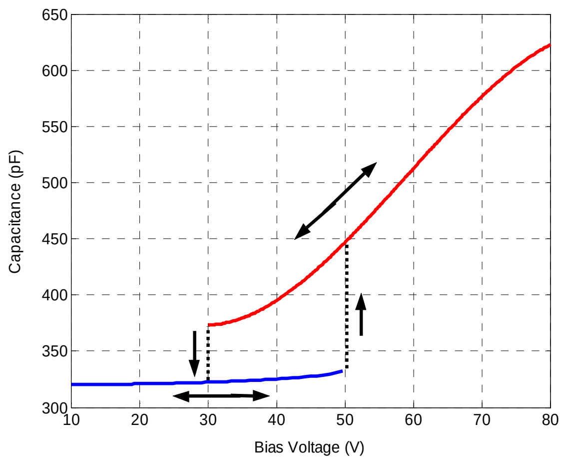

Figure 2. The simulated capacitance of the cMUT element as a function of bias.

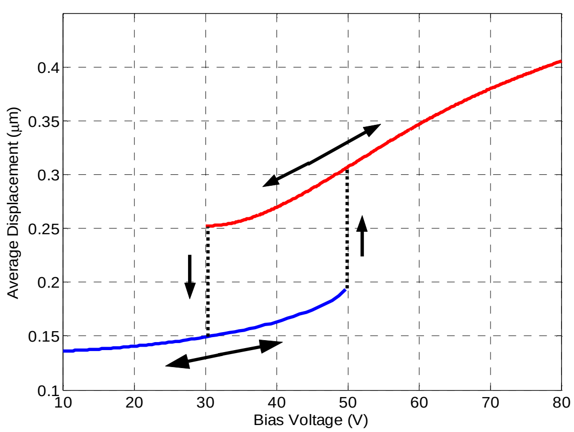

Figure 3. The simulated static membrane displacement .

The cMUT arrays were fabricated by a wafer bonding technique [2]. In this bonding technique the transducer membrane and cavity were defined on an SOI wafer and on a prime wafer, respectively. Then, using silicon direct bonding in a vacuum, the two wafers were bonded together to form a transducer. The advantages of this bonding technique allow for repeatable fabrication of cMUTs featuring predictable center frequency, bandwidth, collapse voltage and electromechanical coupling coefficient.

III. DEVICE CHARACTERIZATION

The devices were characterized in vegetable oil by means of a capacitance measurement and by means of MHz ultrasonic pitch-catch and pulse-echo measurements. In pitch-catch both transmission properties (TX), and receive properties (RX), of the device operation were obtained.

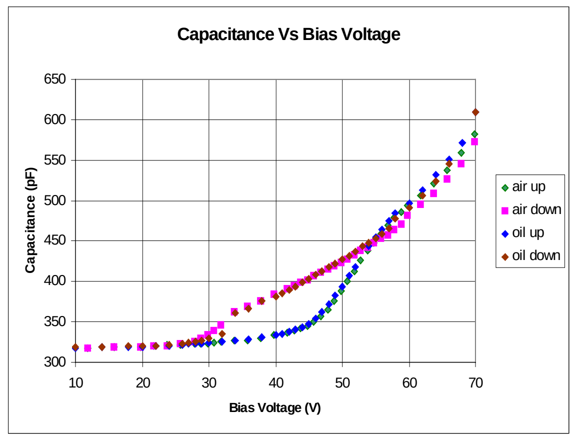

Figure 4. The capacitance of the cMUT element as a function of bias, measured.

In the capacitance measurements, we used a negative DC bias source and a signal generator to generate a 5 kHz, 60 mVp.p., AC signal. An oscilloscope digitized the signal obtained by a voltage divider consisting of a 130 kΩ resistor and the cMUT, the results are shown in fig 4.

In the TX measurements, the distance between the hydrophone and the cMUT transmitter was 10.96 mm, and a 2.3 MHz sinusoidal wave train with 10-35 cycles and an amplitude of 0.5 V - 2.5 V was applied to the cMUT. The hydrophone (PZT-Z44-0400, Specialty Engineering Associates) was positioned by an Aerotech HDZ2 linear translation stage, which had accuracy of 1 µm. The signal from the hydrophone was amplified by a 17 dB, 10 kHz-25 MHz, 50 Ω pre-amplifier before it was read into the oscilloscope. The transducers were aligned so that a maximum reception voltage was obtained. In the RX measurements the distance between the hydrophone and the cMUT was 86.1 mm and a 1.3 MHz, 0.5 Vp-p sinusoidal 35-50 cycles wave train was applied to the transmitting 12.5 mm diameter Panametrics V109 circular flat focus transducer. We measured the amplitude, bandwidth and nonlinear distortion of the received signal as a function of bias voltage and received signal amplitude as a function of applied AC amplitude. A reception calibration experiment was carried out to calculate the sensitivity of the cMUT. Here the cMUT was exchanged for the hydrophone in order to determine the acoustic pressure generated by the PZT onto the cMUT surface.

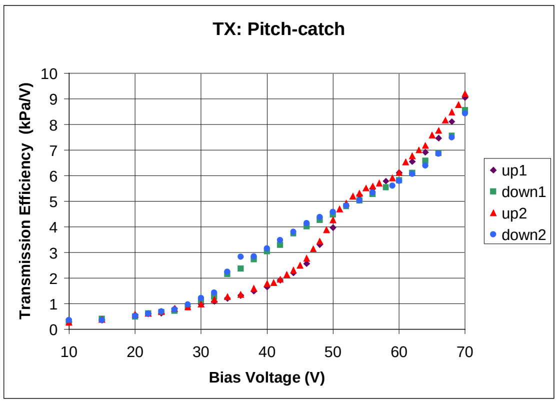

Figure 5. The transmission efficiency of the cMUT element as a function of bias.

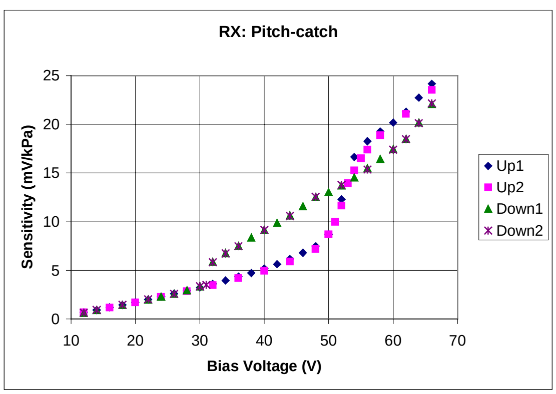

Figure 6. The receive sensitivity of the cMUT element as a function of bias.

In the pulse-echo measurement (PE), the negative spike from the Panametrics 5058 PR pulse generator was attenuated 29 dB by two HP 355C and 355D attenuators to -10 V. A polished aluminum block, at 50.8 mm from the cMUT, was used as reflector, and the output signal from the cMUT was fed into the oscilloscope.

The two loops of the capacitance-bias voltage (CV) curve, Fig. 4, in air/oil show two regions of operation: the conventional regime, and the collapsed regime. It also shows a steeper slope in the collapse regime than in the conventional regime. The transition region in the CV curve shows the steepest slope. This slope is not infinite due to the fact that the membranes collapse at slightly different voltages. Generally the difference between the experimental and the simulation results is the abrupt change in capacitance and average displacement in the simulations at collapse and snapback, whereas the experimental results indicated a change with a finite slope at these voltages.

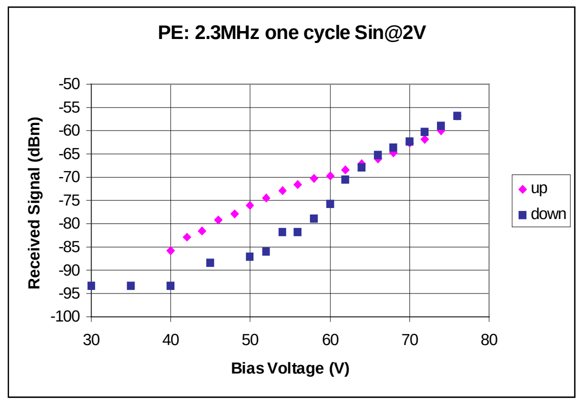

Figure 7. The pulse echo signal received by the cMUT element as a function of bias.

The two loops of the pitch-catch (TX, RX) curves obtained with the cMUT transmitting and listening, Fig.5., and *vice versa* in Fig.6. show the repeatability of the device. These curves, again, show two regimes of operation. They show larger TX and RX signals when the device was operated in the collapsed regime compared to when it was operated in the conventional regime.

The collapse and snapback regions are visible. The slopes of the curve in these regions are, again, not infinite. The TX curve is a result of an AC test, which means that it can not directly be compared to the derivative of the DV curve. The reason is that the membrane in the quasi-static DV case does not feel the reactive load of the immersion liquid. This load makes it, however, possible to apply larger AC signal close to collapse voltage than the quasi-static modeling predicts. To make the comparison between collapsed regime operation and conventional regime operation fair, the transmitted or received signal should be normalized by the bias voltage at least if different voltages are used.

The similarity in shape of the PE curve, Fig. 7 to the TX and RX curves is expected since PE is TX times RX, at least in principle.

The following results summarize the gains obtained when using the collapsed regime of operation compared to using the conventional regime of operation. In TX the amplitude of the transmitted 50 cycles 2.3 MHz uncorrected signal increased by 91 %, at 40 Vdc (1.79 kPa to 3.42 kPa). Maximally 9.72 kPa/Vac was transmitted, at 70 Vdc. The uncorrected bandwidth of the received one-cycle signal increased by 78 %, at 35 Vdc becoming 2.01 MHz at 35 Vdc.

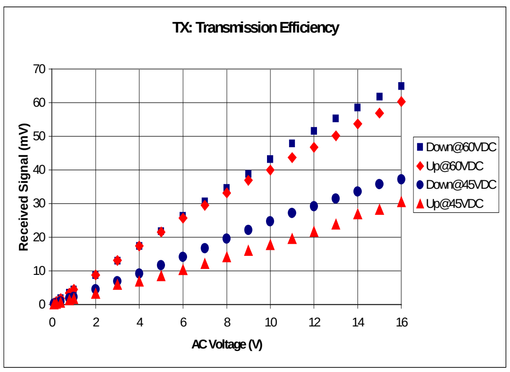

Figure 8. The signal transmitted by the cMUT element as a function of applied AC signal.

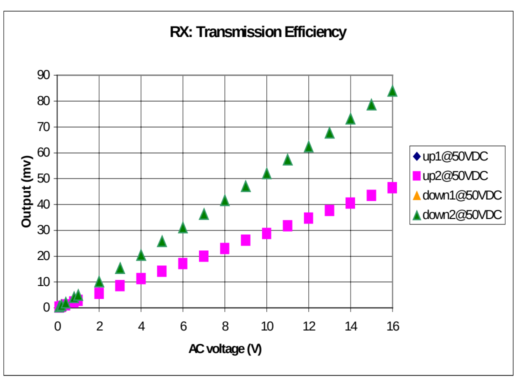

Figure 9. The signal received by the cMUT as a function of AC signal applied to a PZT transmitter.

In RX the amplitude of the received 50 cycles 1.3 MHz signal increased by 75 %, at 56 Vdc. Maximally 24.16 mV/kPa was received at 74 Vdc. This corresponds to 14.01 dB/kPa/Hz$^{0.5}$ into 58 kHz when the noise level was 20 μVpp. The uncorrected bandwidth of the received one-cycle signal increased by 13 % at 54 Vdc becoming 1.06 MHz (82% fractional bandwidth) at 54 Vdc.

In PE the amplitude of the received 50 cycles 2.3 MHz signal increased by 255 %, at 50 Vdc. Maximally 0.4 mV/Vac was received, at 76 Vdc. This corresponds to 34.35 dB/Hz$^{0.5}$ into 1.22 kHz when the noise level was 0.22 μVpp. The bandwidth of the received one-cycle signal increased by 236 %, at 50 Vdc. The largest bandwidth measured was 4.2 MHz, at 70 Vdc.

The nonlinearity of the device is less than 4.5 % in both transmission and reception, Fig. 8 and Fig.9. Moreover, it is seen that the efficiency of the device both in transmission and in reception is higher in collapsed regime operation than it is in operation in the conventional regime. The gains in transduction efficiency and fractional bandwidth, come at the expense of a 5 dB increased harmonic distortion in TX. The overall nonlinear content is, however, below –40 dB.

IV. CONCLUSION

The experimental results from collapsed regime operation showed that this mode of operation provides gains in maximum output pressure and reception sensitivity compared to a cMUT operating in the conventional regime. In collapsed regime operation the fractional bandwidth was increased compared to that obtained in conventional regime operation. The cMUTs were fabricated by a wafer bonding technique. The characterization of the 1-D cMUT arrays operating in oil was done by ultrasonic pulse echo and pitch catch measurements.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

[1] Bayram, B., Hæggström, E., Yaralioglu, G.G., and Khuri-Yakub, B.T., "A New Regime for Operating Capacitive Micromachined Ultrasonic Transducers", IEEE Trans. Ultrason. Ferroelect., Freq. Contr. 50(9), p. 1184-1190, Sept. 2003.

[2] Huang, Y., Ergun, A.S., Hæggström, E., Badi, M.H.,and Khuri-Yakub, B.T., "Fabricating capacitive micromachined ultrasonic transducers with wafer-bonding technology" , JMEMS 12(2) , p. 128 –137, April 2003