Air-coupled CMUTs operating at ambient pressures ranging from 1 to 20 atm

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***Abstract*— We present impedance and pitch-catch measurements of capacitive micromachined ultrasonic transducers (CMUTs) in permanent contact mode with improved mechanical strength that demonstrate functionality up to 20 atm ambient pressure. Changes in device design and fabrication are made to improve the mechanical strength of the CMUT plates, including using smaller deflection to thickness ratio (9 – 33%), choosing better quality SOI wafers (bowing < 20 µm), and designing a much larger bonding area (300 – 700 µm overlap in radial direction) for each cell. As a result, all designs with 2000 µm radius, 65-µm-thick plates, 7.74 µm gap heights and with 300, 500, and 700 µm wide bonding area overlap for the plate, performed from 1 – 20 atm without a single failure. Despite larger bonding area, pitch-catch measurements with these CMUTs (700 µm bonding width biased at 250 V dc) still give received signal with good SNR even at 20 atm. Our results support that such CMUTs are reliable and efficient over a wide pressure range.**

***Index Terms*—**CMUT, permanent contact mode, wide pressure range, FEA, electrical impedance, pitch-catch.

I. INTRODUCTION

Many applications of gas-coupled ultrasonic devices involve extreme ambient conditions, such as chemical sensing in process industry, range finding or flow metering in harsh environments. The goal of this work is to address the challenges imposed by high and varying pressure, and to provide transducers that can efficiently receive and transmit ultrasound over a wide pressure range

In previous work, we introduced a CMUT operation mode [1,2] that features an operating frequency and coupling efficiency which are less sensitive to the change of ambient pressure. This was achieved by designing the device such that the CMUT plate is in permanent contact with the bottom of the cavity [Fig. 1(a)] independent of the applied bias voltage and for ambient pressures exceeding 1 atm. Due to the permanent contact of the plate with the bottom of the cavity, a large electric field and a large active capacitance, and thus, improved coupling efficiency can be expected. In addition, only a portion of the bottom electrode is connected to the transducer signal (Vac and Vdc), which reduces parasitic capacitance and the likelihood of electrical breakdown through the contact area [Fig. 1(b)].

We designed these devices based on finite element analysis (FEA) [1], and fabricated them [3] based on a thick-buried oxide layer process [5]. The first characterization results [3,4] proved the idea feasible.

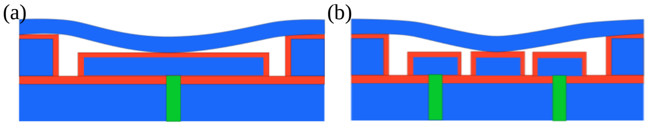

Fig. 1: Schematic cross-sectional view of a single CMUT cell as proposed in [1], where (a) is a cell in the permanent contact mode, i.e. with the plate in contact with the bottom of the cavity at 1 atm; (b) shows a cell in the same operational mode, but with a donut-shaped, partially connected backside electrode. The central island in the bottom electrode is floating.

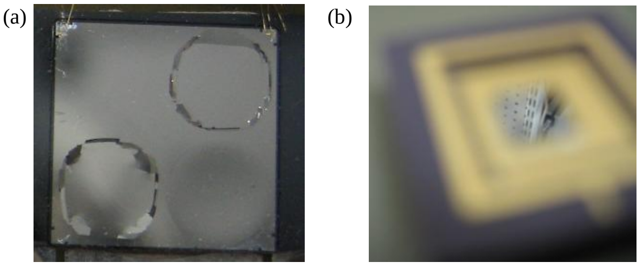

Fig. 2: Two types of failure of CMUTs from a previous fabrication: (1) Plates broken at the edge of CMUT cells, and (2) the device is vented and thus the plate becomes flat and mirror-like.

However, the first experiments at elevated ambient pressures exceeding 8 atm revealed two types of mechanical failures: some devices had broken plates at the edge of the cells [Fig. 2(a)] and others lost their vacuum cavity, i.e. they vented [Fig. 2(b)]. Because these are large devices, both failures are easily visible to the naked eyes. The broken plates result from a lack of mechanical strength, which can be attributed to the plate thickness and gap height of this design. The vented cells result from poor bonding quality in addition to a too small bonding area.

Therefore, we improved the design with a focus on mechanical strength and we present electrical input impedance and acoustic pitch-catch measurement results proving functionality up to 20 atm ambient pressure.

II. IMPROVEMENTS IN CELL DESIGN AND FABRICATION

Several changes in the cell designs are made to overcome the mechanical failures at elevated pressure. First of all, we designed a much larger bonding area (300 – 700 µm overlap in radial direction) for each cell at the expense of increased parasitic capacitance (Table 1). This is the most important change from the 1st fabrication. As we can see from Fig. 3, a mere 100 µm overlap in the radial bonding width can hardly prevent the venting failure in presence of imperfect fusion bonding. Large bonding area (315% - 802% of the previous design) allows the devices to survive much higher pressure while the added parasitic capacitance is still small enough not to compromise the device performance much. Moreover, we used SOI wafers with flatter curvature (bowing < 20 µm) to

Improvements		1^{st} **run**	2^{nd} **run**
Better quality SOIs	Surface roughness	< 2.5 A RMS	<2.5 A RMS
	Curvature (Bowing)	~ 70 µm	2 – 40 µm Mostly < 20 µm
Thicker plate	Plate thickness	30 – 60 µm	50 – 70 µm
	Deflection to thickness ratio	17% - 120%	9% - 33%
Larger bonding area	Smallest bonding width in radial direction	100 µm wide	300-700 µm wide
More uniform gap height	Etching method	DRIE	TMAH wet etch

Table. 1 summarizes the major changes made between the two fabrication runs in terms of cell designs and fabrication processes.

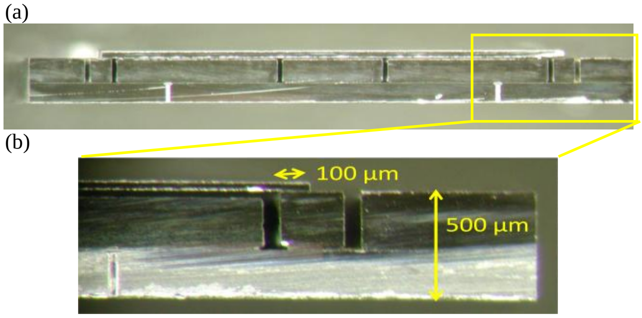

Fig. 3: Optical photos for the cross section of a device from previous fabrication, with a bonding width only 100 µm (b). Also from (a) with true aspect ratio of the device, we can see how small the bonding area is and thus the devices are prone to the venting failure in the presence of imperfect bonding.

ensure good bonding quality. These changes also increase the yield of the fabrication. The devices are also designed to have smaller deflection to thickness ratio (9 – 33%), which is equal to the ratio between gap height and plate thickness for a permanent contact device. A thicker plate and a smaller gap will give a device with frequency more sensitive to the pressure change, but the mechanical stress in the plate can be reduced.

The new fabrication still uses the processes based on a thick buried oxide layer [5]. The processes are similar to those in [3], with some changes that facilitate simpler fabrication steps and improve uniformity.

One major change in the fabrication processes is the use of tetramethylammonium hydroxide (TMAH) wet etching, instead of deep reactive ion etching (DRIE), to determine the gap height for better cross-wafer uniformity (Table 1). The SNF DRIE machine easily introduces a 5-8% larger gap around the peripheral of a wafer, which significantly impacts the static operational point of these permanent contact devices. According to [6], the concentration of TMAH solution must be > 20% to minimize the surface roughness on (100) silicon surface. Furthermore, with 25% TMAH, lowering the process temperature from 90°C to 70°C decreases the etch rate from > 0.6 µm/min to < 0.3 µm/min. We used 25% TMAH to etch at 70°C which gives ~ 0.2 µm/min etch rate; as a result, we obtained a uniformity ~ 2.5% across wafer.

In addition, the backside vias are widened to allow for BOE (buffered oxide etchant) opening up the buried box oxide, replacing a long plasma etch followed by hydrogen fluoride (HF) vapor etch. The backside vias are also elongated into short trenches to allow for more light and thus the use of optical microscope to monitor the etching process.

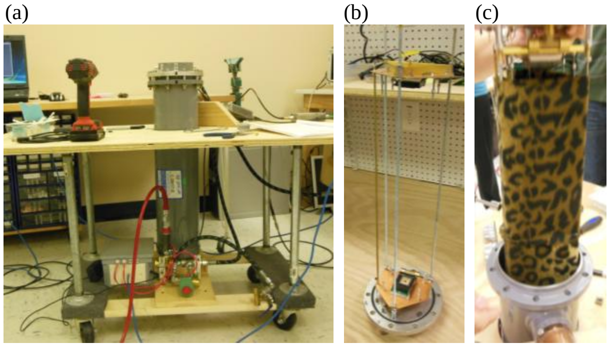

Fig. 4: The setup used for electrical impedance and pitch-catch measurements at elevated pressure: (a) the pressurized chamber with feedback control valves; (b) the fixture to mount the device in a pitch-catch configuration, which can be inserted into the pressure chamber; (c) the fixture wrapped by fabric, providing some damping to reduce reflection.

III. MEASUREMENTS AT ELEVATED PRESSURE

A new pressurized chamber [Fig. 4(a)] with a pre-aligned fixture, which arranges one pair of devices at a distance of 42 cm [Fig. 4(b)], was built to perform measurements at elevated pressure. An air compressor pumped air into the chamber, and silicone grease was applied between the lid and the chamber to provide better sealing. The maximum pressure possible for this setup is 20 atm. Bias-T's for each CMUT were connected from outside the chamber. Before inserted into the chamber, the fixture was wrapped by a fabric [Fig. 4(c)] that is proved to reduce reflections from the side wall during pitch-catch measurements.

In order to evaluate the electrical and acoustic behavior of these devices, we performed both the electrical input impedance and acoustic pitch-catch measurements in ambient pressure from 1 to 20 atm.

i. ELECTRICAL IMPEDANCE MEASUREMENTS

The electrical impedance is measured by an impedance analyzer HP 4192A (now Agilent Technologies Inc., Palo Alto, CA, USA). Due to the limited processing power of HP 4192A, the calibration of the raw impedance data was done in MATLAB, which considers all cables and connectors, the bias-T, the printed circuit board, the socket, and the chip carrier that the device is mounted on. Consequently, we can measure the impedance without undesired additional parasitic capacitance.

All three CMUTs measured survived the highest pressure of 20 atm (Fig. 5). These devices have the same cell radius (2000 µm), plate thickness (65 µm), gap height (7.74 µm), and partial electrode (60%, the definition was described in [3]), but different bonding widths, which are 700 µm [Fig. 5(a)], 500 µm [Fig. 5(b)], and 300 µm [Fig. 5(c)], respectively. The corresponding device capacitances, calculated from the

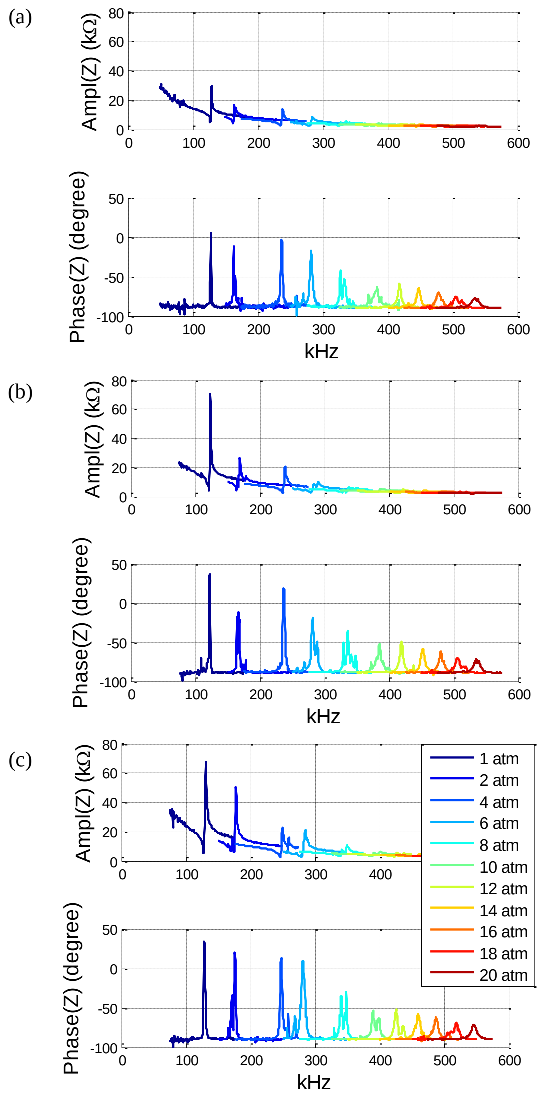

Fig. 5: Electrical input impedance for 3 devices, all with cell radius 2000 μm, plate thickness 65 μm, 7.74 μm gap height, 60% partial electrode, but with different bonding areas. (a) has bonding width of 700 μm, (b) has 500 μm, and (c) has 300 μm.

impedance at 75 kHz, are 111.7 pF, 92.3 pF, and 64.3 pF. Essentially, the larger bonding width implies more parasitic capacitance, but the larger bonding area also ensures a mechanically stronger device. Based on the measurement, the 300 μm bonding width should be sufficient for our pressure range of interest.

A FEA modal simulation was performed for the CMUT design with 700 μm bonding width [Fig. 6(a)]. The modal frequency is not as sensitive to the dc bias voltage, but it strongly depends on ambient pressure. For comparison, the short circuit resonant frequencies at 250 Vdc are extracted from the impedance measurement. As the pressure rises and the plate is pushed more against the bottom of the cavity, the actual vibrating portion of the plate decreases, and thus the frequency increases monotonically from 127 kHz at 1 atm to 525 kHz at 20 atm, which is in excellent agreement to our FEA results (< 4.5%) [Fig. 6(b)].

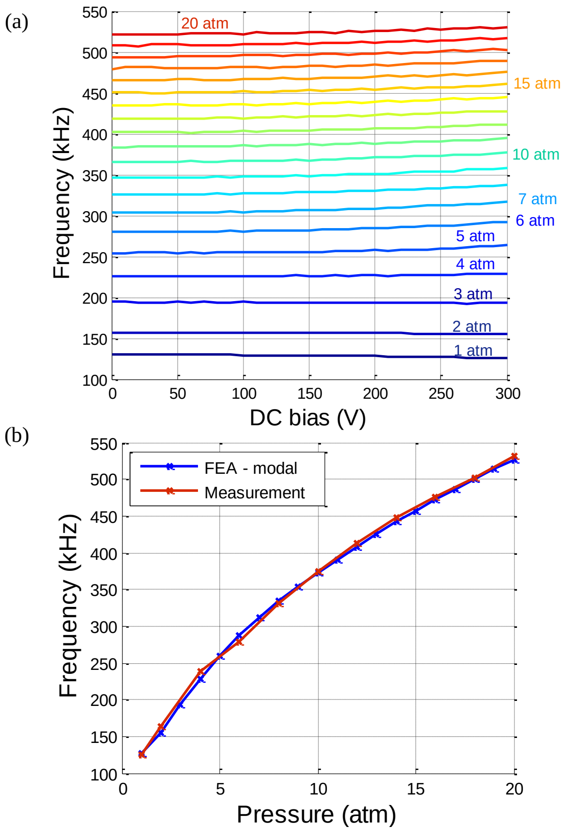

Fig. 6: (a) modal frequency from FEA of a device with cell radius 2000 μm, plate thickness 65 μm, 7.74 μm gap height, 60% partial electrode, and 700 μm bonding width. (b) compares the FEA modal frequency to that extracted from the impedance measurement at 250 Vdc.

ii. PITCH-CATCH MEASUREMENTS

Pitch-catch measurements were performed to assess the acoustic performance of the transducers. In our setup, the two devices are separated by 42 cm. A function generator (HP33120A) drives the transmit device (TX) with 20-cycle, 8 Vpp sinusoidal burst signal. The signal from the receiving device (RX) was amplified by external low-noise amplifiers (Burel & Kjaer 2636 and 2639 amplifiers) with a total dc gain of ~ 26 dB (20x). The time domain signals (Fig. 7) demonstrates that both TX & RX devices are operational in various ambient pressures up to 20 atm. Please note that the gain of the amplifiers can be much larger, but with < 26 dB gain, the amplitude of RX signal is already sufficiently large to conduct signal processing for ultrasound flow measurement.

At lower pressure, we can also see a 2^{nd} RX signal due to the reflected ultrasound between RX and TX transducers. Since the alignment between the two devices is not perfect, however, as the pressure increases and thus the frequency, beam width becomes smaller and 2^{nd} reflection disappears.

The pitch catch results with frequency and pressure sweeping are summarized in Fig. 8. The RX peak to peak signal is extracted from time domain results similar to Fig. 7, and then further compensated by the amplifier frequency response, the diffraction loss and attenuation, which is equivalent to when the two transducers facing each other at zero distance and with a unity gain amplifier. Note that the

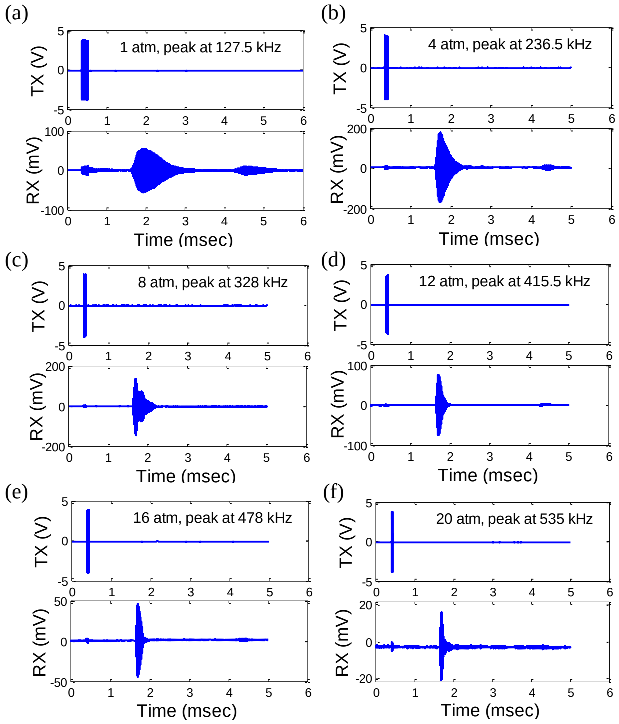

Fig. 7: Pitch-catch transmitting and received signals in time domain for the two devices with 700 µm bonding width, at pressures: (a) 1 atm, (b) 4 atm, (c) 8 atm, (d) 12 atm, (e) 16 atm, and (f) 20 atm.

attenuation at 20 atm is not significantly higher than that at 1 atm, since the effect of high attenuation at higher frequency is offset by the effect of pressure on lowering the attenuation. The amplitude fluctuation can possibly be attributed to the partial side wall reflection and frequency mismatch between the transducers. The calculated insertion loss is -13.4 dB and -30.6 dB at 3 atm and 20 atm, respectively; the bandwidth increased from 8 kHz at 1 atm to 35 kHz at 20 atm, while the fractional bandwidth stayed constant at ~ 7% from 1 to 20 atm. Note that we are able to obtain a received signal with good signal-to-noise ratio (SNR), and decent signal level with only 26 dB of amplification, over the entire pressure range.

IV. CONCLUSION

We successfully demonstrated that our CMUTs with improved mechanical strength (bonding width > 300 µm) can handle elevated pressures of at least 20 atm, while the increased parasitic capacitance does not sacrifice the acoustic performance - the received signal in the pitch-catch measurements shows good signal level and good SNR across the entire pressure range of interest.

For future work, we plan to further investigate the physics and behavior of these CMUTs in the permanent contact mode, including saturation in output level at higher ac excitation, the pressure measurements, the plate movement profiles at different ac and dc combinations, and effect of housing or baffles around the transducers.

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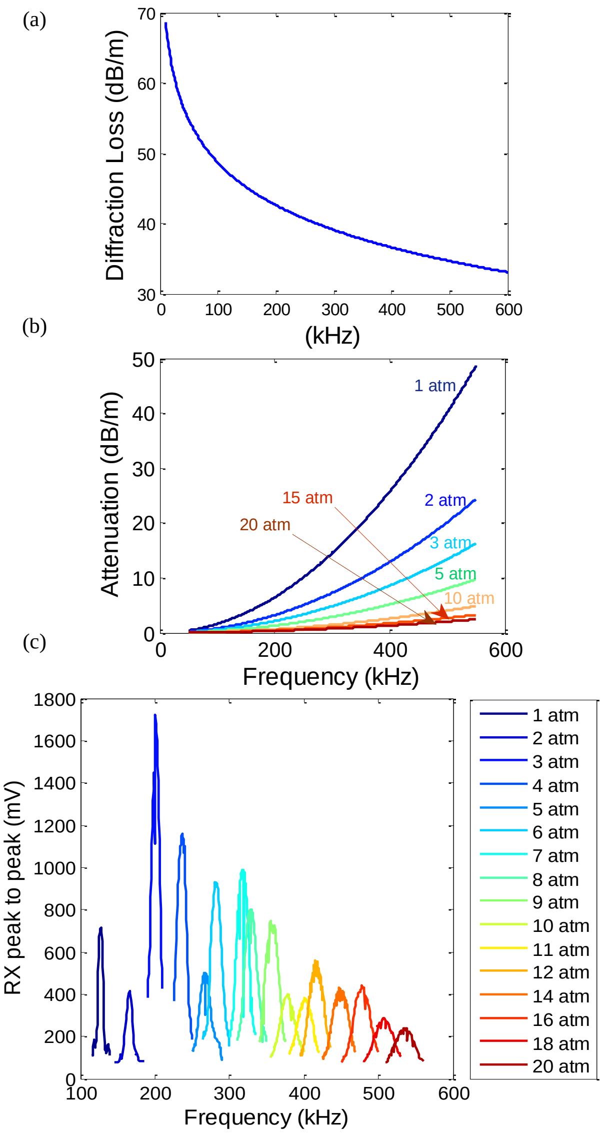

Fig. 8 summarizes the frequency and pressure sweeping results and compensation factors from the pitch-catch measurements: (c) is the signal we would get if the two devices face each other at zero distance, compensated by the amplifier frequency response, the diffraction loss (a) and attenuation in air at 23°C and zero humidity (b).

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