Experimental evaluation of CMUTs with vented cavities under varying pressure

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Abstract – We propose venting the cavities of CMUTs for environments with extreme pressure variations. The CMUT have zero differential pressure across the plate at any ambient pressure, thus ensuring a stable operating point and preventing mechanical failure. The venting vias are etched through the substrate. We observe two resonances from the vented CMUTs - the mechanical resonance of the plate and an acoustic Helmholtz resonance associated with the cavity and the venting vias. We fabricated a variety of CMUTs varying the plate radius, thickness, gap height and via arrangement to study these two resonances. A pair of CMUTs was characterized in a pitch-catch setup under varying ambient pressure. The CMUTs were successfully able to transmit and receive ultrasound under an ambient pressure of up to 20 bar. As the pressure increases, the plate resonance dominated mode becomes weaker while the Helmholtz resonance dominated mode becomes stronger. The Helmholtz resonance dominated mode maintains its frequency and bandwidth under varying ambient pressure.

Keywords: vented CMUT, varying pressure, Helmholtz resonance

I. INTRODUCTION

Capacitive Micromachined Ultrasound Transducers (CMUTs) are increasingly being considered as a better alternative to traditional piezoelectric ultrasound transducers. In airborne applications, CMUTs offer the advantage of better impedance matching to the medium than piezoelectric transducers [1]. One such application for CMUTs is in transit-time ultrasound flowmeters used for flare gas metering [2]. Flare gas metering presents unique challenges due to the large variation in the flow velocities, gas pressures and gas composition [3]. Ultrasound flowmeters are ideal for use in this application. However conventional CMUTs with vacuum backed plates cannot be used under widely varying ambient pressures. The pressure differential across the plate changes the static deflection of the plate, and as a result, the electric field through the gap. In a varying ambient pressure, the transmit and receive sensitivities and also the operating frequency would vary considerably. Beyond a certain pressure, the CMUT plates would collapse onto the substrate and would drastically change their operating frequency.

To overcome this problem, M.-C. Ho, *et. al.* proposed operating CMUTs in a permanent contact mode even under 1 atm pressure [4]. This would enable a more stable operating point over a wider operating pressure range. However, even such a CMUT would still be limited by the mechanical strength of the structure. Beyond a certain pressure, such a CMUT would fail mechanically.

We previously proposed making CMUTs which are vented to an external fluid source [5]. In its simplest form, such a CMUT cavity could simply be vented to the ambient environment thus ensuring a zero differential pressure across the plate. This will ensure a stable operating point for the CMUT under varying ambient pressure. Also, with no pressure across the plate, such a CMUT should be able to operate under any pressure condition with no risk of mechanical damage or failure.

II. DESIGN AND FABRICATION

The CMUT cavity can be vented by etching via holes through the CMUT plate or through the substrate. Since such CMUTs will be deployed in harsh and dirty environments, having via holes in the plate might pose the risk of any contaminant entering the CMUT cavity. Hence these CMUTs were fabricated with vent holes in the substrate.

The process starts with a low resistivity silicon wafer [Fig. 1(a)]. The wafer is patterned and cavities are etched in the silicon using wet TMAH (Tetra methyl Ammonium Hydroxide) [Fig. 1(b)]. The wet TMAH etch has good uniformity across the wafer and the etch depth can be controlled quite accurately after the etch rate is characterized for the setup. The wafer is patterned on the back side and through-wafer vias are etched from the back using deep reactive ion etching (DRIE) [Fig. 1(d)]. The oxide used as the masking layer is then stripped and 1.5-μm thick thermal oxide is grown again as an insulation layer as well as for oxide posts for bonding [Fig. 1(e)]. The plate SOI wafer is then bonded on top using direct fusion bonding [Fig. 1(f)] and annealed in nitrogen at 1050 °C for 4 hours. The handle layer and the buried oxide layer of the plate SOI wafer are then etched away to release the CMUT plates [Fig. 1(g)]. A 500-nm thick layer of aluminum is evaporated on the front and back of the wafer to provide better electrical contact. The aluminum and plate silicon is then patterned to define each transducer unit (element) [Fig. 1(h)].

A variety of CMUTs were fabricated using this process by varying the plate thickness, plate radius and gap height. The dimensions of the vias were kept the same for ease of fabrication however the number of vias and the arrangement of these vias were varied (Fig. 2).

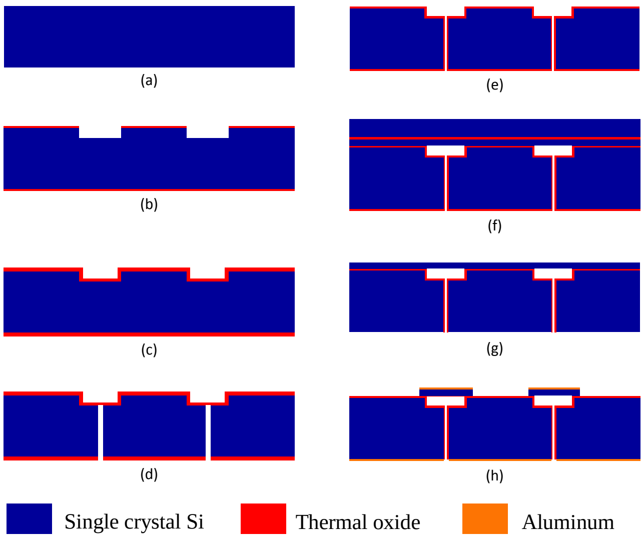

Fig. 1. Fabrication process flow for CMUTs with vented cavities

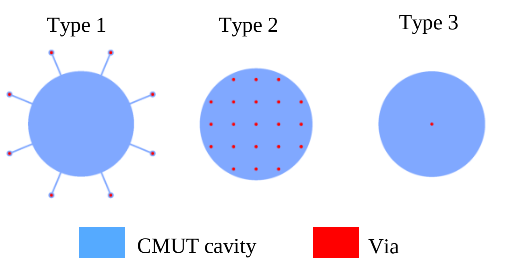

Fig. 2. Different arrangements of vias to vent CMUT cavity

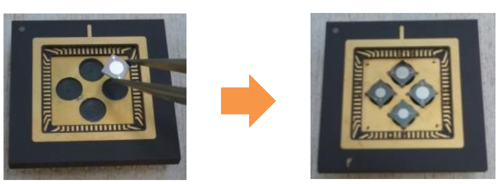

Fig. 3. Individual vented CMUT dies mounted on chip carriers with drilled recesses

III. Characterization

The fabricated CMUTs were singulated by dicing, mounted on chip carriers and wirebonded (Fig. 3). Small recesses were drilled in the chip carriers so as to connect the via holes to ambient air. The CMUTs with vented cavities inherently have two resonances. The first resonance is dominated by the CMUT plate with its associated mass and stiffness, loaded by the air medium on top and backed by a squeeze film of the gas / fluid in the cavity. The second resonance is made up of the gas / fluid inside the via and CMUT cavity which form an acoustic Helmholtz resonator-like structure. The effective response of the CMUT is a result of the interaction between these two resonances.

(i) Harmonic measurements at 1 atm pressure:

The CMUTs were initially characterized under 1 atm pressure. The CMUTs were biased with a DC voltage and excited with an AC voltage while sweeping the frequency. The displacement amplitude was measured under a laser Doppler vibrometer (LDV; OFV-511, Polytec GmbH, Waldbronn, Germany). As expected, the CMUTs exhibit two resonant modes (Fig. 4). The plate dominated resonant mode is unaffected by the number of venting vias or their arrangement. However the Helmholtz resonance dominated mode is strongly dependent on the number of vias and becomes stronger as more vias are used. The frequency of the Helmholtz mode is independent of the number of vias or their arrangement.

Keeping all other parameters the same, as the plate radius is increased, the Helmholtz dominated mode becomes stronger than the plate dominated mode (Fig. 5). Despite the decrease in the plate stiffness the frequency of the plate dominated mode increases slightly. This could be due to increased stiffness from the squeeze film.

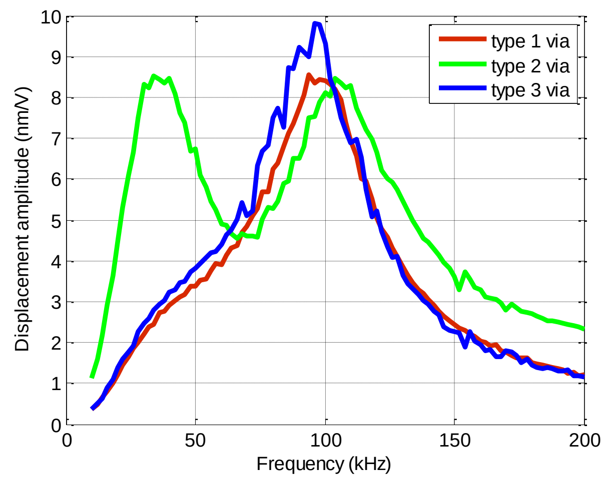

Fig. 4. Effect of via arrangement on CMUT's frequency response spectrum (Plate radius= 750 μm, plate thickness = 10 μm, gap height = 11.2 μm, via radius = 20 μm, via length = 500 μm)

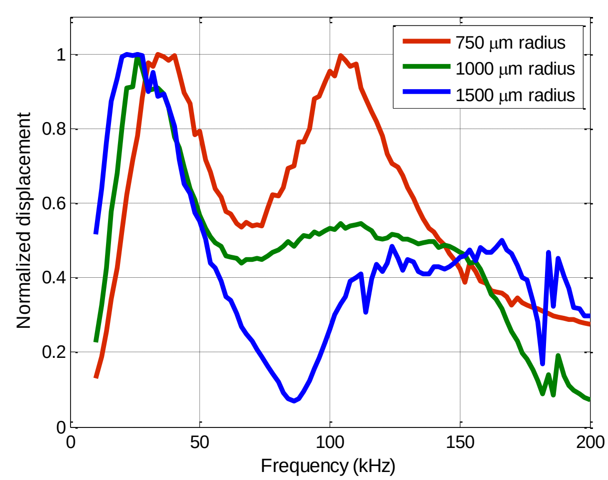

Fig. 5. Effect of plate radius on CMUT's frequency response spectrum (Plate thickness = 10 μm, gap height = 11.2 μm, via radius = 20 μm, via length = 500 μm, vias in type-2 arrangement)

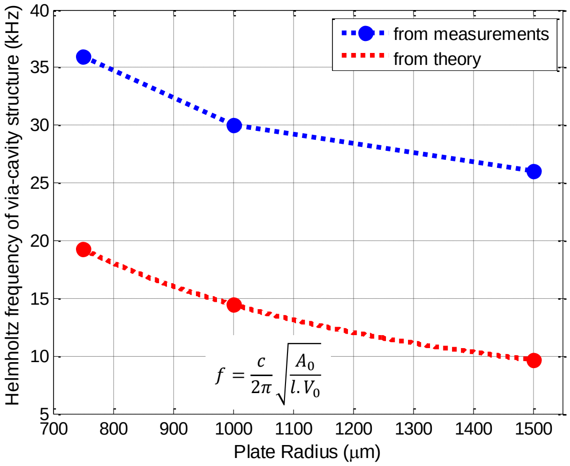

Fig. 6. Effect of plate radius on the Helmholtz mode frequency (Plate thickness = 10 μm, gap height = 11.2 μm, via radius = 20 μm, via length = 500 μm)

The frequency of the Helmholtz dominated mode decreases as the plate radius is increased. This trend conforms to the theoretical frequency [6] for a pure Helmholtz resonator of similar dimensions (Fig. 6).

(ii) Pitch-catch measurements under varying pressure:

A pair of identical devices was arranged in a pitch-catch setup in a pressure chamber at a distance of 7 cm from each other. Since these CMUTs have a relatively large bandwidth, the short circuit resonance frequency of the transmitting CMUT and the open circuit resonance frequency of the receiving CMUT need not be matched perfectly by adjusting the bias voltage.

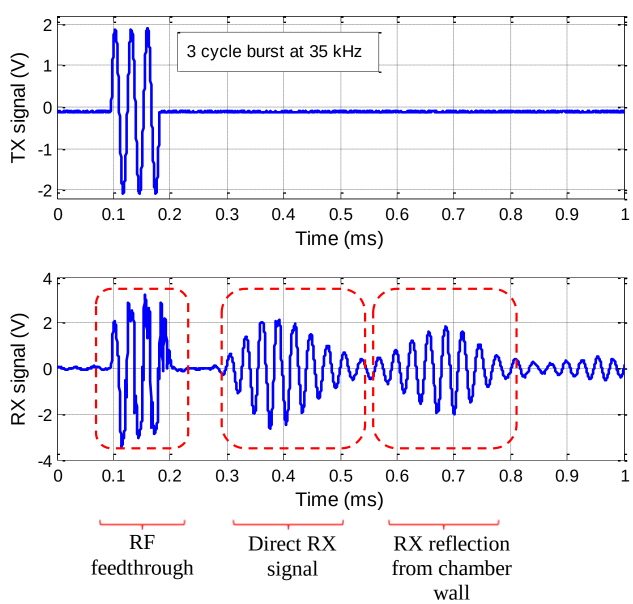

Fig. 7. Pitch-catch signal (Plate radius = 750 μm, plate thickness = 20 μm, gap height = 5.6 μm, via radius = 20 μm, via length = 500 μm, pressure = 15 bar, DC bias = 300 V)

Ideally both the CMUTs can be biased closer to their collapse voltage to optimize the transmitting and receiving sensitivity. For this experiment, both the transmitting and receiving CMUT were biased at 300 V (~65% of collapse). The bias voltage was limited to protect the devices against any dielectric breakdown. The wider bandwidth of these CMUTs allows for a shorter transmit burst signal. In this case, the transmitting CMUT was excited by a 3 cycle AC burst and the signal from the receiving CMUT was recorded (Fig. 7). The frequency of the transmit burst signal was varied to get the frequency spectrum of the pitch-catch measurement.

The pressure in the chamber was varied from 1.01 bar (1 atm) up to 20 bar and the frequency spectrum of the pitch-catch signal was studied (Fig. 8). At lower pressure the devices show a stronger signal at the plate dominated mode (at ~130 kHz for this design). However as the pressure is increased, the plate dominated mode loses strength. Also its frequency and bandwidth decrease. On the contrary the Helmholtz resonance dominated mode (at ~35 kHz for this design) becomes stronger with increasing pressure. Also, it maintains its frequency and bandwidth over the varying pressure.

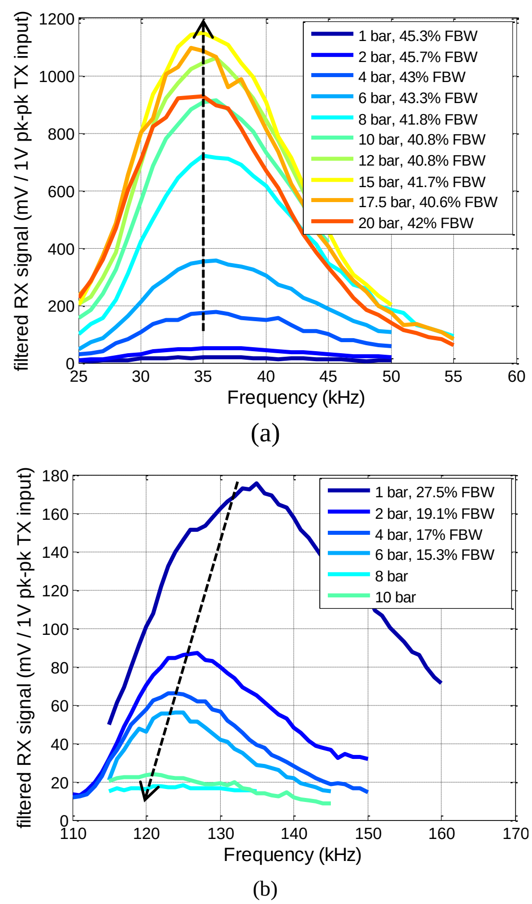

Fig. 8. Pitch-catch measurements under varying pressure: (a) Helmholtz resonance dominated mode (b) Plate resonance dominated mode (Plate radius = 750 μm, plate thickness = 20 μm, gap height = 5.6 μm, via radius = 20 μm, via length = 500 μm, DC bias = 300 V)

IV. CONCLUSION AND FUTURE WORK

We fabricated CMUTs with cavities vented to the ambient atmosphere. Such CMUTs exhibit two peaks in their harmonic response, owing to the resonance of the plate and the acoustic Helmholtz resonance of the gas / fluid in the cavity and the venting via holes. The strength of the Helmholtz resonance peak strongly depends on the number of vias venting the CMUT cavity. The relative strength of the two modes also depends on the ambient pressure. With an increase in ambient pressure, the Helmholtz resonance mode becomes stronger while the plate resonance dominated mode weakens. Although its strength varies with the ambient pressure, the Helmholtz resonance mode maintains its frequency and bandwidth under varying pressure. This makes it quite attractive for use in transit-time flowmeters under varying pressure.

We are currently developing models to accurately predict the behavior of such CMUTs with vented cavities. Further we will optimize the CMUT design for operation in the Helmholtz resonance mode.

ACKNOWLEDGMENT

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