FINITE ELEMENT ANALYSIS OF MECHANICALLY AMPLIFIED CMUTS

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***Abstract*—We introduce the possibility of improving a single-cell capacitive micromachined ultrasonic transducer (CMUT) for air-coupled ultrasound by simply adding a hollow conical-shaped structure (horn) on top of the CMUT plate. The main objective is to improve both transmit and receive sensitivity by lowering the center-to-average displacement ratio, which for bending plate operated devices inherently is limited. In addition, for receive mode the force generated from the impinging sound pressure wave is concentrated to the center of the plate, resulting in larger signals and, in contrast to piston-shaped plates, the horn has the advantage of only moderately increasing the modal mass of the structure. By using finite element analysis and first sound pressure measurements of our modified CMUT, we demonstrate that this idea is feasible and promising for air-coupled CMUTs operating at frequencies below 150 kHz, as it has been been proven to be successful for commercially available piezoelectric-driven bending plate devices as well.**

I. INTRODUCTION

A non-uniform plate shape for capacitive micromachined ultrasonic transducers (CMUTs) can be beneficial, although it requires more effort to fabricate such structures. The approach provides a larger design freedom concerning the independence between spring constant and modal mass of the entire vibrating structure. Further, the electrostatic transduction mechanism is improved due to the reduced center-to-average displacement ratio of the plate.

The first CMUT featuring plates with a piston-shape dates back to [1], [2]. In this work, however, the piston shape inherently resulted from the need to open up the typical top layers in a standard CMOS-based fabrication process to release the structure.

The first intentionally designed piston-shaped silicon nitride plates for micromachined microphones (sacrificial release process) have been introduced by [3].

Later [4]–[6] fabricated and analyzed similar device generations, which have in common that the sacrificial release fabrication method was used as well. In [7] a high-temperature assisted direct wafer bonding process was used to realize CMUTs that feature piston-shaped plates. In these devices, however, the pistons are facing towards the gap. Then [11] demonstrated a further simplification of this fabrication process by simply etching the pistons out of the front side of the plate layer, originating from a double silicon-on-insulator (SOI) wafer, i.e. having two buried oxide layers. All of these approaches have in common that the non-uniformity of the plate was realized by micro machining techniques, which for sure is required for CMUTs with many cells and which are operating in immersion or in gases at higher frequencies.

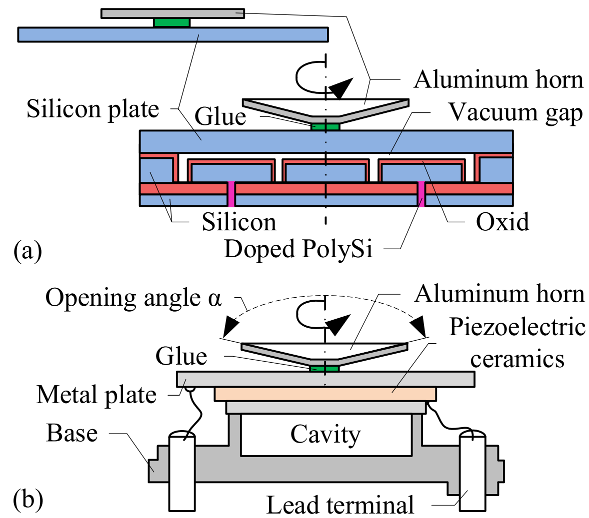

Fig. 1. Schematic of a circular single-cell air-coupled CMUT with an aluminum horn glued on top of the plate (a) and a sketch of a piezoelectric ultrasonic transducer (b), as specified in [8], [9]. For both devices the horn has an opening angle $\alpha = 156°$. The top left insert in (a) shows a "horn" with an opening angle $\alpha = 180°$, which could be fabricated with micromachining techniques [10].

In this work, however, we focus on single-cell CMUT devices for gas-coupled ultrasound at lower frequencies ranging from 20 kHz to 150 kHz. This enables us to investigate whether a better structure than just a piston shape can be used. Thus, the main idea of this paper is to add a lightweight hollow conical-shaped structure (horn, conical vibrator, mechanical amplifier), on top of the plate of a wafer-bonded single-cell CMUT [Fig. 1 (a)]. Similar to the piston-shaped plate approach, the main objective is to improve both transmit and receive sensitivity by increasing the average displacement of the plate, i.e. by lowering the center-to-average displacement ratio. Another advantage is the fact that the horn is hollow, and, thus, the modal mass does not increase as much as it does for a solid piston-shaped plate. In addition, the structure is beneficial because in receive mode the force due to the impinging sound pressure wave is concentrated to the center of the plate, resulting in larger receive signals.

In general, for larger commercially available piezoelectric-based bending plate devices [Fig. 1 (b)], this approach has been proven to be very successful [8], [9]. Note that also for these devices the conical vibrator (horn) is not fabricated by means of micromachining techniques. However, one could imagine a horn with an opening angle of 180° (mushroom-shape), as indicated in the top left insert in Fig. 1 (a). Such a structure can be fabricated with micromachining techniques. This has been demonstrated for a high-sensitive capacitive pressure sensor [10].

The geometry of an already fabricated CMUT [12] is our starting point for this work. Note that as a first step we only investigate the behavior of such a modified CMUT in transmit mode. We describe details of our finite element model (FEM), which was used to identify a range of feasible geometries of the horn, i.e. diameter and thickness. Then we describe the methods developed to fabricate and how to merge the horn with the CMUT, before we present measurement results to prove the idea and to validate our model for transmit mode.

II. Finite Element Model

We use an axially symmetric 2D finite element model (ANSYS, v14, Ansys Inc., Canonsburg, PA, USA) of the CMUT modified with a horn made out of aluminum (Fig. 2). Between the horn and the circular-shaped single-crystal silicon plate a layer of glue is added. From various gluing tests on glass plates and aluminum plates we can estimate the total area of the glue, which explains the overlap between the contact area of the horn and the glue layer in our model. The device is assumed in a rigid baffle and Fluid29 elements are used to model the surrounding air, meshed in a quarter-circle with an absorbing boundary with sufficient distance from the vibrating structure and with proper fluid-structure modifications, see [13]. The lumped transducer elements Trans126 are used to apply the electrostatic force to the plate, which is 55 µm thick and has a diameter of 4 mm. Thus, the 300 nm thick aluminum electrode on top of the silicon plate can be neglected for this large device.

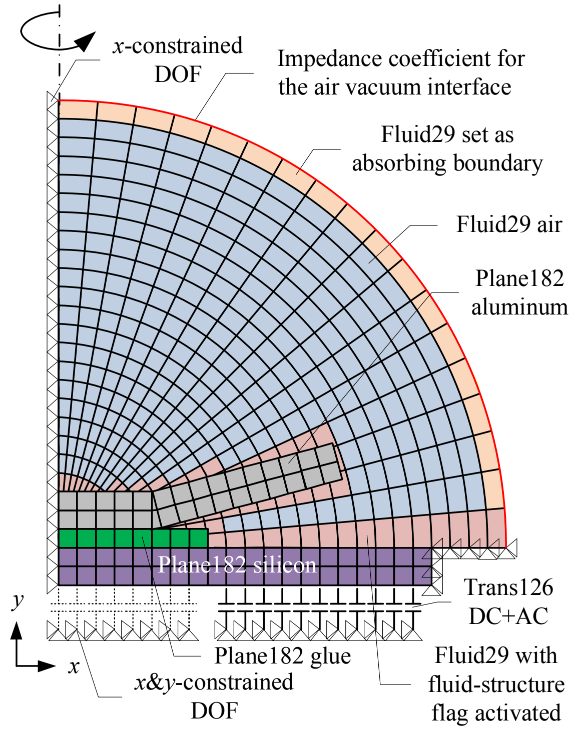

Fig. 2. Finite element model used for the calculation of the static, modal and harmonic response of a circular single-cell air-coupled CMUT with an aluminum horn glued on top of the plate.

The gap height of these device is 12.58 µm resulting in a pull-in voltage of about 225 V. Without horn the device would operate at around 55 kHz.

Note that the CMUT has an electrically floating portion of the bottom electrode [12], which explains the two groups of Trans126 elements in Fig. 2. The group in the center (dotted) only acts as a contact-target pair, i.e. this group is electrically not active.

In general, this FEM allows us to perform all calculations required to test various scenarios.

III. Horn Fabrication and Simulations Results

Based on the diameter of the circular CMUT plate (4 mm), we modified a commercially available punch pliers by making two different cutting bits for it with 2.5 mm and 3.2 mm diameter, respectively, and with the desired opening angle $\alpha = 156°$ [Fig. 1 (b)]. By using thin aluminum metal sheets we succeeded in fabricating horns with thicknesses ranging from 100 µm to 300 µm.

In a large number of gluing tests of horns on top of a glass substrate we identified a proper glue and activator combination (Loctite 480 and activator 7455, Henkel AG, Düsseldorf, Germany). The color of this glue is black, which allowed us to accurately determine the glue layer diameter (about 1.3 mm) below the horn by looking

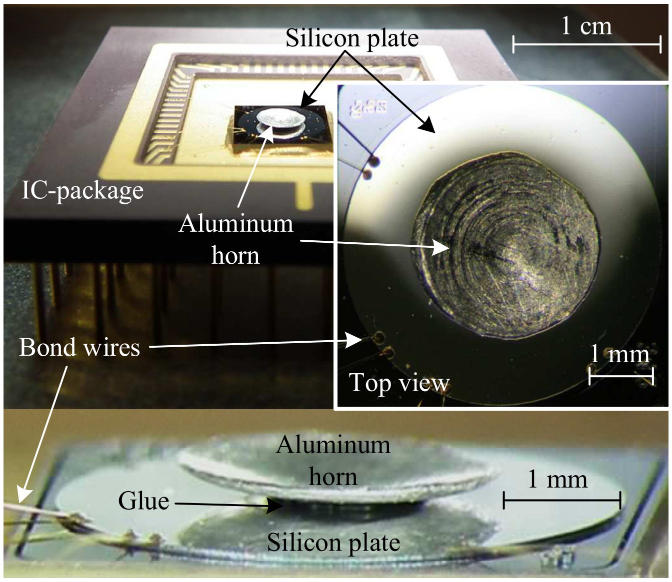

Fig. 3. Photographs of a 4-mm diameter single-cell air-coupled CMUT with an aluminum horn glued on top of the plate. The thickness of the horn is 100 µm and the diameter is 2.5 mm. The device is glued and wire-bonded to a standard IC-package for electrical connection.

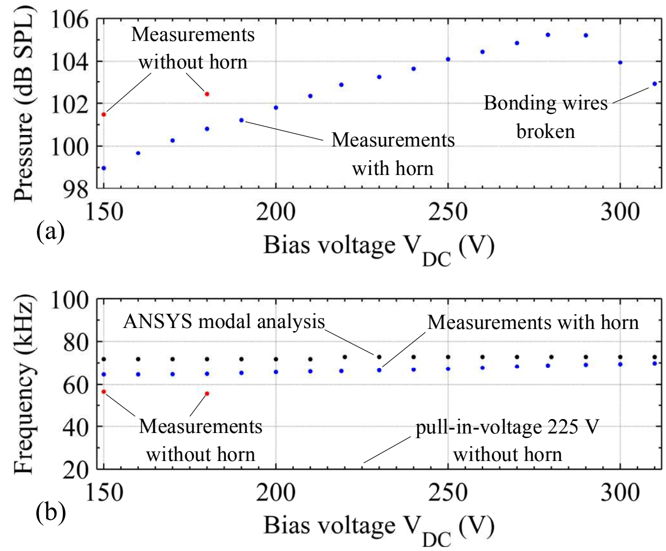

Fig. 4. Sound pressure levels (a) measured at a distance of 2.6 cm in front of the device with a calibrated microphone (B&K Type 4138, Skodsborgvej, Denmark) and a direct comparison of measured and calculated frequencies (b), all before and after gluing the horn at various d.c. bias voltages. The a.c. excitation signal was 10 V_{pp} and the pull-in voltage of the CMUT without horn is 225 V.

through the glass substrate with a standard microscope. The thickness (about 150 µm) was measured by using a caliper.

In a first step we performed a non-linear pre-stressed modal analysis [13] for all of these various types of horn geometries in terms of thickness and diameters. This delivers all relevant mode-shapes of the entire structure with the corresponding frequencies and values for the effective modal mass for each mode. The finding of this first analysis was that the horn with a thickness of 100 µm and a diameter 2.5 mm should be used. Such a horn is sufficiently stiff to avoid any higher mode in the horn itself and for a thicker horn the frequency would drop below 20 kHz due its larger mass.

In a subsequent step we performed a pre-stressed harmonic analysis to estimate the performance improvement caused by the horn. The FEM predicted that the frequency reduces from 55 kHz down to 27 kHz. The center displacement improved by a factor of 5.5 from 360 nm to 1.97 µm. The average displacement improved by a factor of 9 from 110 nm to 1 µm.

IV. First Measurements for Validation

Encouraged by these first calculations and before gluing the horn on top of the CMUT plate (Fig. 3), we characterized the CMUT without horn at two different d.c. bias voltages, i.e. 150 V and 180 V. For all measurements we used a calibrated microphone in front of the device (for details see [14]). As expected, we observed that the sound pressure increases when the d.c. bias voltage is increased and that the frequency decreases from 56.4 kHz down to 55.5 kHz due to the spring-softening effect (Fig. 4).

After gluing the horn, the device was characterized again. We started with a d.c. bias voltage of 150 V and, surprisingly, instead of a drop in operation frequency, due to the increased modal mass, down to the predicted 27 kHz, we observed a higher frequency of 64 kHz. Further, the measured sound pressure level was 2.5 dB lower (Fig. 4). When the d.c. bias voltage was increased, we observed larger sound pressure levels with a slight increase in operation frequency, which indicates that the device was not operating in conventional operation mode anymore. At a d.c. bias voltage of 310 V we lost a bonding wire, and, thus, stopped the measurement.

The behavior that we observed for this CMUT with a horn can be explained as follows: The glue below the horn at the center of the plate creates some tensile stress, which increases the static deflection of the CMUT plate in contrast to our initial expectation that the d.c. operation point stays unchanged. This is a similar effect as caused by thermal stress, observed in CMUTs with silicon-nitride-based half-metallized plates [15]. Instead of operating in conventional mode, as we originally expected, the device operates in a permanent contact mode. Therefore, the horn cannot deploy its full enhancement in terms of sound pressure. The peak of sound pressure at a d.c. bias voltage of 290 V can be explained by the fact that the effective aperture size of the silicon plate (vibrating ring) below the horn increases, and, thus, less energy is coupled into the horn via both the contact point and the air between horn and plate. The slight increase in operation frequency for every increment of d.c. bias voltage is typical for a CMUT with its plate in contact with the bottom of the cavity (permanent contact mode or beyond pull-in).

To test this hypothesis we extended our FEM with the following feature to model the influence of the glue on the static d.c. operation point of the CMUT plate. It is essential to realize that the horn is glued onto the silicon plate after it is deflected by the ambient pressure and before it is connected to the d.c. voltage source. Similar as in the work described in [15] we use the element birth and death feature (ekill and ealive command, [13]). Killing an element means that its stiffness-matrix will be multiplied by a small multiplication factor, eliminating its influence for a particular static solution step. This extended FEM revealed that a small tensile stress inside the glue layer below the horn of only 5 MPa is sufficient to bring the plate into permanent contact operation mode. Further, we repeated the non-linear pre-stressed modal analysis and obtained good agreement to our measurement results (Fig. 4).

In addition, we also performed a pre-stressed harmonic analysis for a device with an assumed larger gap, i.e. for which a conventional operation mode can be expected after the horn is glued on. The calculated improvement for the expected sound pressure level is about 10 dB. At the moment we prepare another device with a significant larger pull-in voltage to validate this harmonic calculation as well.

V. Conclusion

Our finite element analysis and our first measurement results confirm that for single-cell air-coupled CMUTs, operating at frequencies below 150 kHz, it is a promising idea to simply glue a lightweight hollow conical-shaped structure (horn) on top of the plate. Further, our experiments demonstrate that the static operation point of the CMUT can be affected by the glue in the opposite direction as expected. Thus, instead of operating the modified CMUT in conventional mode, we only managed to validate our model for the non-intended permanent contact mode of a CMUT with a glued horn. Even for this non-intended suboptimal operation mode for a CMUT with horn, the obtained sound pressure levels have been increased by around 3 dB.

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