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Flexible CMUT for Vibrating Mesh Nebulize

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***Abstract*—This work is a feasibility study aiming to demonstrate that CMUT technology could be used as an actuator source for vibrating mesh nebulizer. Ring shape PZT materials are commonly used in commercial products but they suffer from technological limitations (for example significant self-heating) that could be overcome by CMUT technology. This paper shows experimental results obtained from a first prototype realized with a linear array. A thin disk membrane was locally etched below few elements, on the rear face of the Si substrate. It is demonstrated that the excitation of the CMUT elements, at low frequencies (in the kHz frequency range), enables the thin membrane actuation, in air and in water. Significant displacement (≈1 µm) were observed for the first and the second resonance mode of the membrane**

Keywords*—: *capacitive micromachined ultrasonic transducers, drug delivery.

I. INTRODUCTION

Inhalation therapy, based on liquid atomization produced by a nebulizer, is a promising and non-invasive method for drug delivery in the treatment of pulmonary diseases. Vibrating mesh nebulizers [1] [2] based on piezoelectric actuation, is one of the most recent technologies. These devices are currently made with a metal-based circular membrane operated at the second harmonic mode (02) and moved by a PZT-ring actuator. Despite numerous advantages, there is still a need to enhance performances of these devices. Self-heating effects of piezoelectric materials, stability over time and reusable device considering the technology cost are limitations that justify the need to find other alternatives. To meet these requirements, the present work aims to fabricate vibrating mesh nebulizers based on monolithic membranes which actuation is realized by Capacitive Micromachined Ultrasonic Transducers [3] (CMUT).

Herein, we investigated the feasibility of using a single transducer made of CMUTs as an actuator (like the PZT-ring actuator) of the nebulizer membrane with enough efficiency to produce mechanical vibrations with amplitude of few hundred of nanometers.

First we describe the device fabrication steps and the device design. Next, we summarize a set of experimental results obtained with one prototype. The vibration of the nebulizer membrane was controlled and measured by doing laser interferometry measurements done in air and in water loading conditions.

II. DESIGN AND DEVICE FABRICATION

A. Design

Figure 1 gives a simple description of a CMUT-based vibrating mesh nebulizer. The main element is the membrane, shown in blue color, which shape and dimensions are chosen in agreement with the specified working frequency of the nebulizer. Typically, frequencies of few hundred of kHz are targeted, meaning that lateral dimensions of few millimeters with thickness of few dozen of micrometers are required to meet specifications. Silicon is one of the most popular materials used. Here, Silicon membrane is obtained from a bulk Si substrate that is locally etched on the backside in order to obtain a membrane that is clamped, on its periphery, to the bulk substrate. To actuate the circular Si membrane, standard systems use a PZT ring placed at the periphery of the membrane while here, it is replaced by an array of CMUT placed at the center of the membrane. CMUTs are fabricated directly on the substrate, which means that the CMUT + membrane assembly forms only one "monolithic" device. The free space on the membrane surface, where there is not any CMUT, is used to insert microscopic holes for drug atomization and aerosol production.

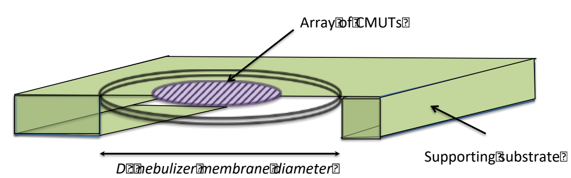

Fig. 1. 3D view of a CMUT-based vibrating mesh nebulizer.

The geometry of the CMUT array follows the mesh, i.e. circular, with dimensions smaller to leave place for holes. The CMUT are designed in order that their individual resonance frequency is in the MHz frequency but not at the operating frequency (typ. 100 kHz) of the mesh nebulizer. In other words, at the working frequency, CMUT vibrate like microphone, i.e. in a pure elastic regime. This choice simplifies the CMUT design and fabrication process since it's the same than for imaging arrays.

B. CMUT fabrication

CMUTs were fabricated by using standard surface micromachining process. The process flow have been explained previously [3]. For the fabrication, 500 µm thick p-type silicon wafers were used. A 1.2 µm thick silicon dioxide layer was grown by thermal oxidation followed by the deposition of 450 nm thick polysilicon film using Low Pressure Chemical Vapor Deposition (LPCVD). The doping was achieved during phosphoryl chloride ($POCl_3$) annealing step. Therefore, this layer acts as the bottom electrode and hence the geometry of the membrane was also defined with it. Once defining the bottom electrode, phosphosilicate glass (PSG) was deposited to act as a sacrificial layer and patterned with bottom electrode to obtain the required shape and to reduce parasitic capacitances. Later, a 400 nm silicon nitride (SiN) film was deposited by LPCVD, then patterned and dry etched to open SiN layer to access the sacrificial layer.

To release the membrane, the sacrificial layer has been removed by chemical etching using hydrofluoric acid (HF). Then, 1.5 µm undoped silicon glass (USG) was deposited using Plasma Enhanced Chemical Vapor Deposition (PECVD) to seal the SiN membranes. After, a 450 nm thick aluminum layer was sputtered and patterned on the membranes, which acts as the top electrode.

C. Mesh fabrication

The substrate thinning is done by isotropic DRIE (Deep Reactive Ion Etching) process using an Alcatel 601E equipment. The process starts with the bonding of a mask (adhesive Kapton) on samples which is then, structured by laser etching (steps (a) and (b) in Figure 2).

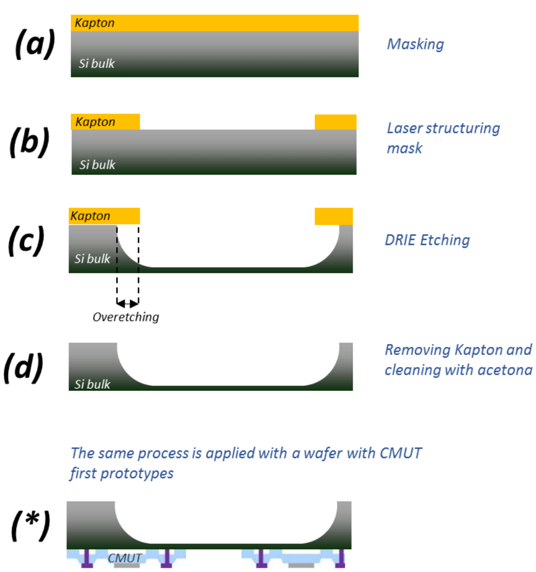

Fig. 2. : DRIE process flow.

DRIE etching is performed with a SF6 plasma (600sccm) at -10°C (step (c)). Preliminary results showed that more polished is the surface, longer is the etching. In this study, the substrate was chosen with a grinded finishing Z1=10 µm and Z2=5 µm. The final step (d) consists in removing and cleaning the substrate with acetone. In these conditions, the etching rate was approximately 9 µm/min and the overetching was around 300 µm (figure 3). Figure 4 shows the profile of a silicon sample etched using the conditions described above and during 50 min. On the edge (a) the thickness is between 495 µm (bulk) and 56 µm. In the center (b), the sample is 49 µm thick.

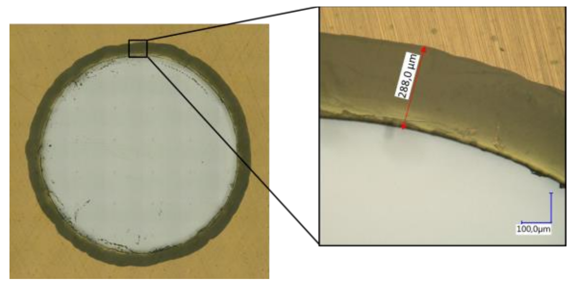

Fig. 3. : Overetching observed between the mask and the cavity.

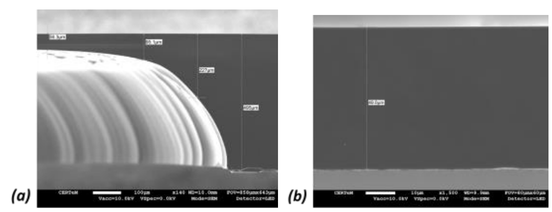

Fig. 4. SEM images of a sample etched during 50 min ; Edge (a) and Center (b) of the thinned part

To produce a membrane likewise nebulizer mesh, the process would be directly applied to CMUT chips (figure2 (*)).

III. EXPERIMENTAL RESULTS

A. Fabricated device

Prototypes were obtained from a CMUT-based linear array, as previously reported [4] by Boulmé & al. The array was made of 24 elements, with a pitch of 850 µm and an elevation of 8 mm. Each element was made with square CMUTs of 32x32 µm^2 surface. A membrane of 50 µm thick and 4 mm of diameter was etched at the rear of CMUT array. Figure 5 shows a representative photograph of a prototype: (a) the front face of the device where the linear array is visible, (b) the rear face where a disk was etched and (c) the prototype glued on a PCB. To enable experiments in water, and to protect CMUT, a thin parylene layer of 1.5 µm thick was sputtered on the device.

All elements of the array were wedged, meaning that a part of them (5 elements) was directly on the etching zone and the others were outside the etching zone, as shown in Figure 5.

B. Electrical characterization

To assess device performances and functionality, electrical impedance of each array element was measured, at the beginning and at the end of the process. The initial frequency resonance was 8 MHz, and the final was 10 MHz; the slight increase was due to the parylene layer stiffness. The collapse voltage changed from 60 V to 80 V, as shown in figure 6. Interestingly, despite the DRIE etching step, the device integrity was preserved.

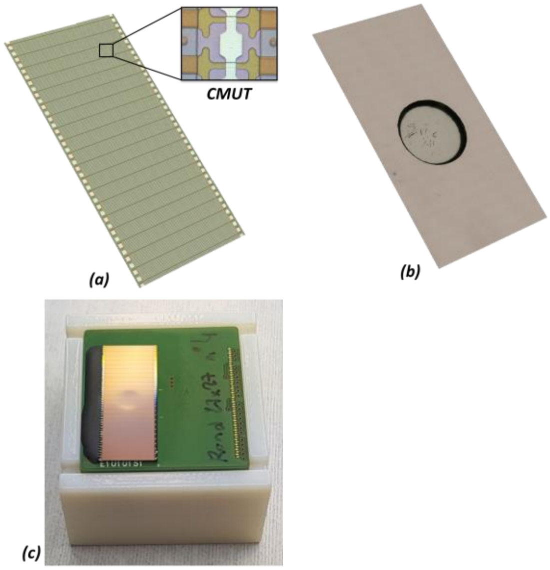

Fig. 5. (a) Front of the CMUT-based linear array; (b) Back side etched locally by DRIE; (c) Chip wedged on PCB.

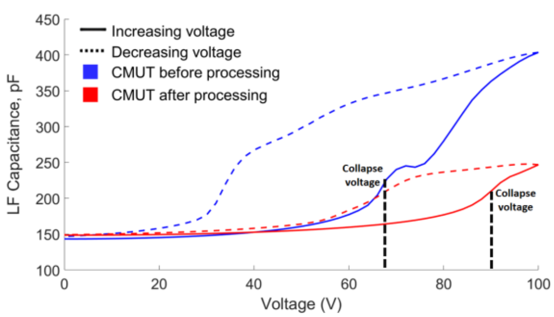

Fig. 6. Low frequency capacitance according to the biasing voltage of one element array measured at 100 kHz.

C. Vibrometry measurements

To perform actuation tests, the CMUT elements were biased at 80 % of the collapse voltage, thus 64 Volt and a CW voltage signal were applied as excitation source. The vibration of the membrane was measured with Vibrometer Polytec MS-500 (30 kHz-20MHz) to scan easily (with stitching mode) a large area of moving surface. Excitation frequency was automatically swept in order to detect resonance modes of the membrane in air. Next, several excitation configurations were tested to evaluate the impact of elements placed outside the etching zone. Vibration amplitudes were successively compared in the following configurations: 1- only the five elements on the membrane were excited, 2- excitation of only the elements outside the membrane and 3- all elements of the array were excited. The best amplitude was obtained with only the five elements connected. This configuration was selected for further investigations and presented herein. Figure 7 shows the mesh displacement cartography for the two first resonances observed at 54 kHz and 198 kHz.

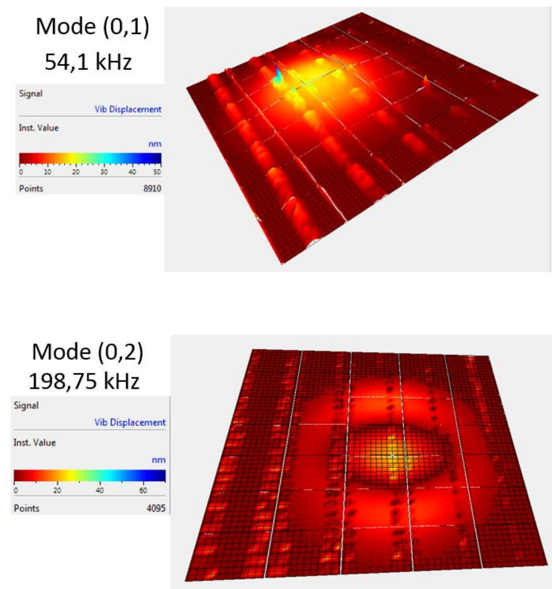

Fig. 7. 2D scan of the mesh (in air) vibration measured at the two first resonances, modes (0.1) and (0.2).

These values are in agreement with the theoretical resonance frequencies, i.e 52 kHz and 204 kHz (in clamped mode) respectively. Despite the membrane overetching, the apparent membrane diameter remains the area where the thickness is 50 µm and clamped boundary conditions seem valid hypothesis. The vibration amplitude of the membrane in the center was measured using a CW excitation signal of 80 Volt peak-to-peak. To obtain such condition, we used a RF amplifier (from Amplifier Research company) at the output of the CW generator. Large displacements were observed, up to 500 nm peak-to-peak for mode (0,1).

The same assays were undertaken by placing the mesh in water. Water (layer of 5 mm thick) was added on the front face of the CMUT array likewise a drug solution to atomize. Displacements were scanned automatically, and resonance modes were detected for water loading conditions. Many modes were observed and mostly the two first (0.1) and (0.2). The water loading caused a drop of the resonance frequencies to 19.5 kHz and 100 kHz respectively. Commercial products mainly use the (0.2) mode since it's the most efficient for drug atomization. Thus, our findings are encouraging as they show that CMUT enable mesh actuation at the (0.2) resonance mode, in particular in submerged conditions.

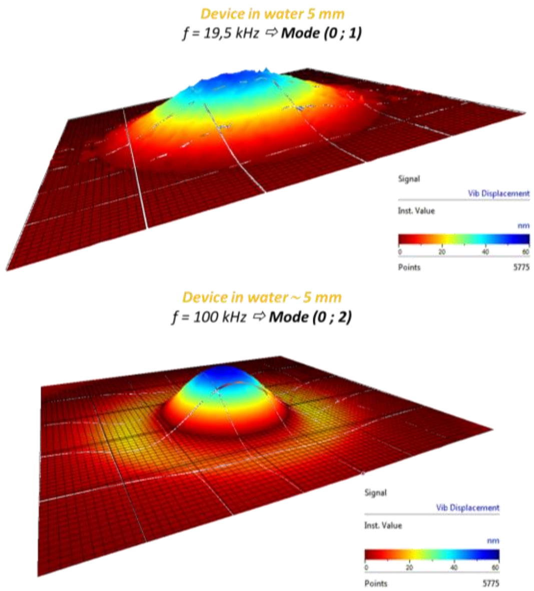

Fig. 8. 2D scan of the mesh (in water) vibration measured at the two first resonances, modes (0.1) and (0.2).

Furthermore, the measured resonance frequencies matched with the standard working frequencies of commercial products. Displacement amplitudes for the high excitation voltage (80 Vpp) were measured, showing values of 600 nm-pp and 150 nm-pp for the lower and higher resonance frequencies respectively.

IV. CONCLUSION

Our preliminary results show that CMUT may be used as actuator to move the membrane of a mesh nebulizer. Both the first and the second modes were excited efficiently in the air and in immersed conditions, with amplitudes close to 1 µm. The next step will be the design and fabricate prototypes with CMUT disk array covering partly the membrane. To perforate the membrane with microscopic holes (2-4 µm), we consider using laser etching that enables to fabricate holes after the membrane realization and avoids adapting the CMUT process.

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