PMUT Array Design for mid-air Haptic feedback

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Abstract

Generating tactile sensation in mid-air has been widely demonstrated using an array of bulk piezoelectric transducers [1],[2]. Recently, micromachined devices have shown to be a valid alternative for this application [3], providing advantages in terms of form factor, resolution, ease of integration with supporting electronics and robustness. This paper describes the design of PMUT for short range mid-air haptic application. Circular PMUT and donut-shaped PMUT are investigated, and simulations are compared to measurements. Finally, a 1 by 1 cm silicon chip, containing 400um Aluminum Nitride PMUTs, is designed and characterized for delivering enough pressure to generate mid-air haptic feedback.

1. Introduction

Haptic feedback is now a common modality that is used to add information in multiple types of applications such as in the gaming and virtual reality industries [1,2], but also in the medical field, where, for example, haptic feedback has already been implemented in surgical training systems and tele-operated robotic surgery [4].

So far, most existing haptic feedback devices use a contact-based method to transfer force to the user. Vibrating smart phones and watches are now able to generate distinct vibration patterns correlated to a specific cue [5]. A straightforward drawback of these systems is the need for physical contact during operation, hereby limiting usability and introducing hygiene issues. Therefore, during the last decade, multiple modalities were explored to enable mid-air haptic feedback using air vortices, air jets and ultrasound [6].

Ultrasonic-based mid-air haptic feedback uses acoustic transducers to emit pressure waves in a way that it can be sensed by the human body. Arrays of bulk piezoelectric transducers [1,2] are currently commercialized to generate this sensation. Recently, micromachined devices have shown to be a valid alternative for this application, providing advantages in terms of form factor, resolution, ease of integration with supporting electronics and robustness [3].

Studies show that a human finger can sense a pressure wave at a frequency in the order of hundreds of Hz, provided the pressure is higher than 1 kPa (minimum sensing threshold) [7]. A high frequency carrier modulated with that low frequency is used to propagate and focus the acoustic stimulus at larger distances on a specific focus point. The current technology uses 40kHz or 100kHz transducers. Higher ultrasound carrier frequencies result in an increased achievable resolution for the targeted volumetric shapes. However, with higher frequencies also comes an increased attenuation of the ultrasound pressure in air. Therefore, in this work we focus on enabling haptic feedback with a transducer working around 300-600 kHz allowing to increase the resolution (wavelength being at 0.5-1mm) without reducing too much the pressure output at 1cm distance. This is a 3 to 6 times higher carrier frequency than the previously employed 40 kHz and 100 kHz (wavelength 3-8mm), hereby promising an increased shape resolution and therewith a more interesting user experience.

This research focusses on the design, fabrication and testing of micromachined devices, aimed at delivering short range mid-air haptic feedback. The sections below first describe the design of single PMUT with circular and donut shape to investigate the effect of the shape on the resonance frequency. Then the array configuration will be studied. Finally, characterization of the fabricated devices will be presented.

2. Device Process Description

The devices under investigation are unimorph AlN PMUT similar to what those developed for imaging [8]. In this particular case, the piezoelectric layer is deposited on a cavity silicon-on-insulator wafer. From bottom to top, the membranes consist of 5 um of silicon, covered by 200 nm of silicon dioxide, on top of which a 1 um thick AlN layer is layered between two electrodes and protected by 200 nm SiO_2. Figure 1 shows the cross-section of a single device. The cavity size is limited to 420 um by the process design rules and the spacing between cavities is minimum 40 um.

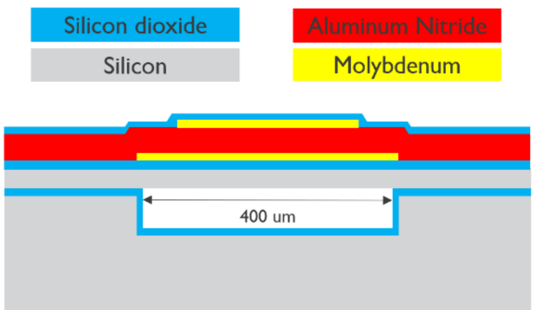

Figure 1: Simplified cross-section of the PMUT stack.

3. PMUT Design

3.1 Single PMUT design

In order to obtain a low frequency PMUT, the cavity radius of the circular PMUT should be increased to the maximum size allowed by processing. In this case, the maximum dimension is 420 um which results in a resonance frequency of 625 kHz, based on simulations. Figure 2 shows the resonance frequency computed using the following analytical formula [8]

$$f = \frac{\lambda_{ij}^2}{2\pi a^2}\sqrt{\frac{Eh^2}{12\rho(1-\nu^2)}}$$

where λ_{ij}^2 is around 10.22 for a clamped circular membrane, a is the PMUT radius, E the equivalent Young modulus considering the different layers of the stack, h the total thickness of the stack, ρ the equivalent mass density of the stack, and ν the Poisson ratio, which is taken to be 0.28.

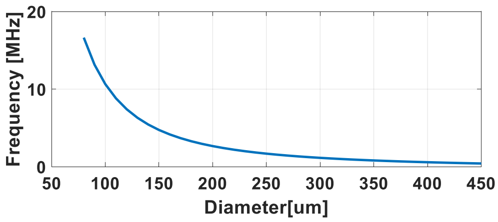

Figure 2: Expected frequency for circular PMUT in the current stack.

For a donut-shaped PMUT, the equation stays the same, but a is now the total external radius of the cavity and λ_{ij}^2 becomes a function of the ratio between the external radius a and the inner radius b (radius of the central pillar) as described in table 1.

a/b	0.1	0.3	0.5	0.7
Mode1	27.3	45.2	89.2	248

Table 1. λ_{ij}^2 for different ratio between the outer radius a, and the inner radius b.

The frequency expected of the donut PMUT decreases by a factor 2 compared to circular PMUT for the same cavity dimension. For the largest membrane dimension (420 um), the frequency reaches about 365 kHz.

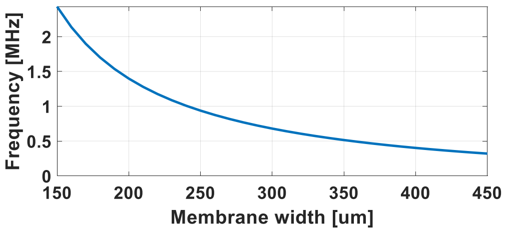

Figure 3: Expected frequency for donut PMUT keeping the central pillar to 200 um diameter and varying the membrane width.

As seen in Fig. 4, the diameter of the central pillar does not impact the resonance frequency of the donut PMUT significantly. This has been confirmed by FEM simulation as shown in Fig. 5.

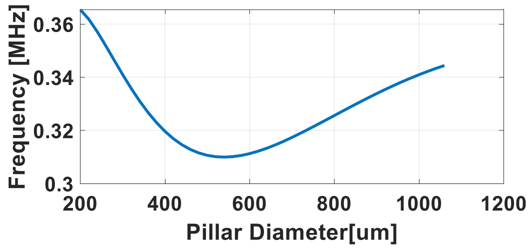

Figure 4: Expected frequency for a 420 um membrane donut PMUT varying the central pillar width.

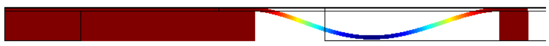

Figure 5: FEM model of a 420 um membrane donut PMUT with a 300 um diameter pillar reaching a resonance frequency of 340 kHz.

3.2 Design of PMUT Array

For a proper design of an array of PMUT, the pitch between PMUT should be smaller than the acoustic wavelength in the medium, in order to avoid side lobe formation. For 400 um diameter circular PMUT, the frequency being around 685 kHz, the wavelength is about 500 um. For the donut PMUT, a typical PMUT for 340 kHz has a size of 1140 um (420 um membrane and 300 um diameter pillar) and the wavelength in air is around 1010 um. The circular PMUT design is suitable to be placed in an array while the donut PMUT are – in theory - slightly too large.

In order to compare the different designs, acoustic simulations are performed for different configurations using *k-wave* [10]. For circular PMUT, a comparison is done between the 380 um, 400 um and 420 um diameter ones which have a resonance frequency of 760, 685 and 625 kHz respectively, as seen in figure 6. Taking a quality factor of 100, the simulated velocity model is around 250 mm.s^{-1}.V^{-1} for all the sizes.

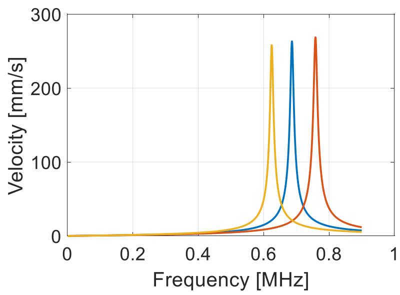

Figure 6: Frequency response of circular PMUT of 380 um (red), 400 um (blue) and 420 um (yellow) diameter.

Using this data, the acoustic propagation is computed in k-wave for a 32x32 PMUT array focusing at 1 cm. For the three cases the pressure profile is very similar and looks like the one of the 400 um PMUT array as shown in Fig. 7.

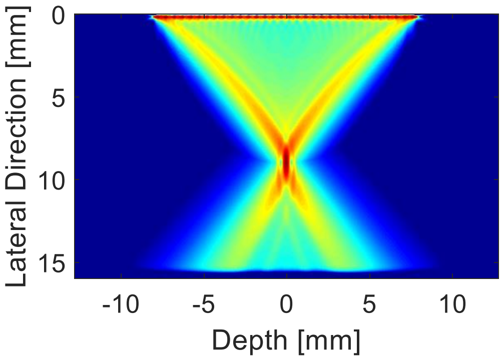

Figure 7: Pressure profile for 400 um diameter PMUT at 685 kHz with a pitch of 500 um focusing at 1 cm.

The pressure along the propagation axis is plotted in Fig. 8. Even if the frequency is quite different, it results to very similar pressure output of around 70 Pa/V at the focusing point.

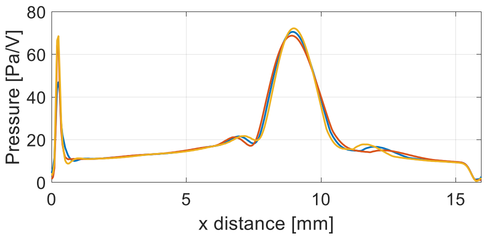

Figure 8: Pressure amplitude for 380 um (yellow) 400 um (blue) and 420 um (red) PMUT array focusing at 1 cm.

For the donut PMUT, the resonance for the 400 um wide donut is around 400 kHz. The pressure profile shown in figure 9 is wider than that of the circular PMUT.

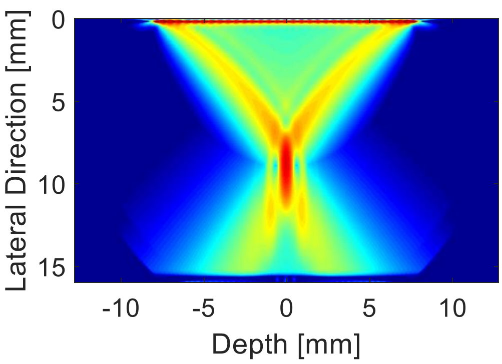

Figure 9: Pressure profile for 400 um membrane donut PMUT at 400 kHz.

The comparison between the donut-shaped PMUT and the circular PMUT for similar array size is shown in figure 10. The focus region is indeed wider for the donut PMUT; however, the amplitude is lower. 55 Pa/V instead of 70 Pa/V for the same array size.

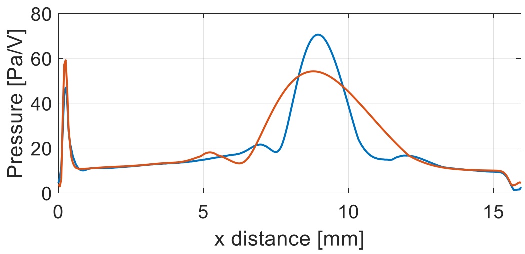

Figure 10: Pressure amplitude along the propagation axis for 400 um membrane donut PMUT at 400 kHz in red and the 400 um diameter circular PMUT at 685 kHz in blue.

Finally, we know that across the PMUT array, not all PMUT have exactly the same resonance frequency. While in liquid, this non-uniformity is less noticeable, due to the larger element bandwidth. For mid-air haptics, however, due to the very high quality factor, the PMUT are not often resonating at the same resonance frequency. When applying an AC voltage at a single frequency to the array, this will result in some PMUT exhibiting a lower oscillation amplitude than others. To mimic this nonuniformity, the acoustic simulation is performed adding a random component in the PMUT amplitude. The results are shown in figures 11 and 12. The pressure amplitude at the focus point is expected to be decreased by factor 3.

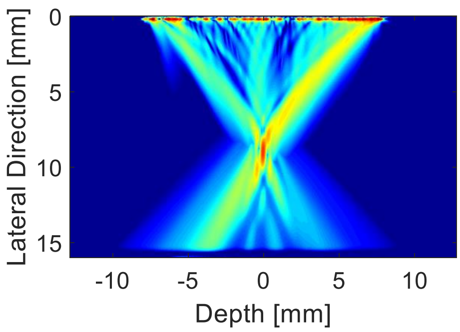

Figure 11: Pressure profile for 400 um circular PMUT at 685 kHz with a random component added to the amplitude.

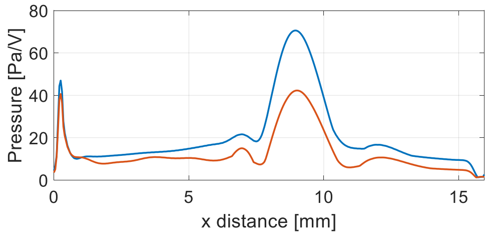

Figure 12: Pressure along the propagation axis for 400 um circular PMUT at 685 kHz with a random component added to the amplitude in red and in the ideal case in blue.

Finally, for the final layout design, we have selected the circular PMUT design as it is a more mature design, showed a higher pressure output and is less prone to side lobe effects. The pitch between PMUT has been selected to be 450 um, which is lower than the wavelength in air (500 um). The total active area is 9x9 mm^2, occupied by 20x20 PMUT. Figure 12 below shows a sketch of part of the array.

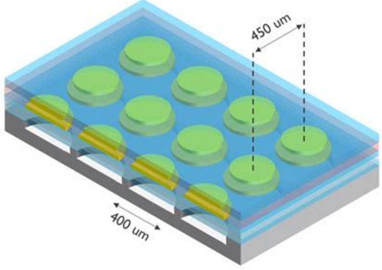

Figure 13: Sketch of the final array design.

4. Measurements of single PMUTs

Laser Doppler vibrometer measurements are performed to extract the resonance frequencies of circular and donut PMUT for different membrane sizes. The results are plotted in figures 14 and 15 respectively. The model is updated to fit the frequency measurements on the circular PMUT by reducing the equivalent Young modulus by 30%. This fitting includes the uncertainties that we have on the exact material properties and the stress in the layers. Using the same fitting, we can see that the donuts model is also fitting to the measurements.

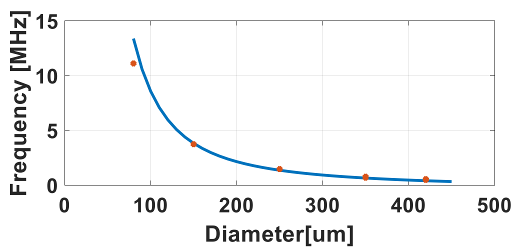

Figure 14: Measured resonance frequency (dots) of the circular PMUT for diameters from 75 um to 420 um.

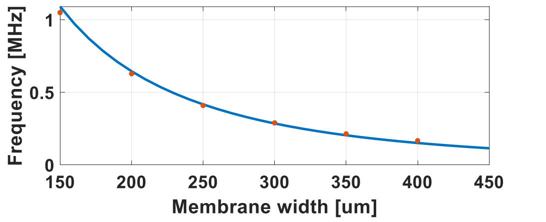

Figure 15: Measured resonance frequency (dots) of the donut PMUT for membrane size varying from 150 um to 400 um.

On Fig. 16, we can see the velocity measured on the circular and the donut PMUT. The velocity of the circular ones is higher than the one of the donuts PMUT and is reaching 500 mm.s^{-1}.V^{-1} which is the double that what was expected. This difference can be explained by the quality factor which was estimated at 100 while it is actually reaching 150-200.

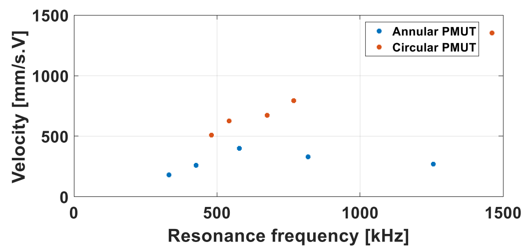

Figure 16: Velocity measurement for circular and donuts PMUT.

5. Measurement of PMUT array

To investigate the overall array performance, the array was wirebonded on a PCB such that all PMUT are actuated simultaneously with one driving signal. The assembly of the chip on the PCB is shown in figure 17.

Figure 17: Picture of the PMUT chip, wirebonded to a PCB.

The frequency of multiple PMUT is measured across the array. As observed in figure 18, the resonance frequency is quite variable and the model of a nonuniform array makes sense.

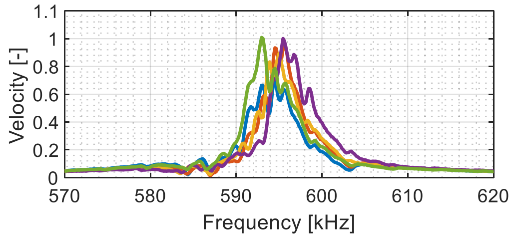

Figure 18: Measured velocities of 5 PMUT in the 20 x 20 array, when actuating the full array with a frequency sweep.

Figure 19 shows the pressure at different distances for a plane wave excitation at 20 V, which leads to roughly 20 Pa/V between 20 and 40 mm axial distance. More details of the characterization can be found in [11].

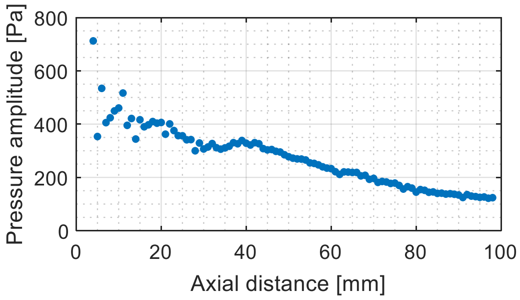

Figure 19: Output pressure above the center of a 1 cm² silicon PMUT chip varying with distance from the chip surface, for 20 V amplitude driving at the resonance frequency of 596 kHz.

The k-wave acoustic model is subsequently updated based on the velocity and the frequency measured previously. The results for a plane wave excitation are plotted in figure 20 and a pressure of 20 Pa/V is also indeed computed.

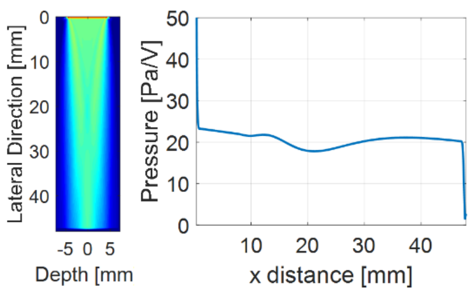

Figure 20: k-wave simulation of a plane wave

6. Haptic sensation

As an addition to the pressure measurements, a small user experiment was set up. While actuating the array with a 596 kHz sinusoidal signal of 20 V amplitude and amplitude modulation with 200 Hz, 10 lab-users were asked if they could feel a haptic sensation on their fingertips. The 200 Hz modulation was selected in accordance with previous work, establishing this as being within the optimal range for mechanoreceptor stimulation [1]. All 10 volunteers claimed to feel a haptic sensation when hovering their fingertips above the silicon chip. This observation, combined with the pressure data above, confirms that a 1 cm² PMUT array reaches the necessary pressures for haptic feedback, but an in-depth user experience study should be set up to draw further conclusions on the user experience [11].

Figure 21: Picture of the haptic sensation set-up.

7. Conclusions

It has been demonstrated in [11] that a 1 cm² Aluminum Nitride based PMUT array is able to reach the required pressures for mid-air haptic feedback at a 6 times higher resonant frequency compared to previous work. The higher ultrasound carrier frequency allows higher resolution patterns and although attenuation in air is increased at elevated frequencies, the array reaches 100 Pascal at a 100 mm distance. This is in the same range as the well-established 40 kHz bulk transducer achieving 20 Pascals at 300 mm.

In this work, we clarified the procedure that is used to design the PMUT array. Analytical model for circular and donut PMUT has been presented and fitted to the measurement data. This tool will allow us to model the next generation of mid-air haptic feedback transducers. Adapting the model to an AlN layer doped with Scandium - which is already available for our standard PMUT - will allow to design a new array promising even higher output pressures for the next generation chip

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