Display Compatible pMUT Device for Mid Air Ultrasound Gesture Recognition

C.H. Huang, L. Demi, G.B. Torri, S. Mao, M. Billen, Y. Jeong, D. Cheyns, X. Rottenberg, and V. Rochus
Imec, Kapeldreef 75, 3001 Heverlee, Belgium
Chih.Hsien.Huang@imec.be

Abstract

In this paper, the design, modeling, and characterization of a display compatible pMUT platform dedicated for mid air ultrasound gesture recognition is presented. A FEM model has been built using COMSOL for evaluating the frequency response, static profile, acoustic pressure, and driving efficiency of our pMUT device across all vibration modes of circular plates. In parallel with it, a first mode analytical model has been developed including electrical, mechanical, and acoustic domains to provide fast estimation for future design. A laser Doppler vibrometer is used to measure the frequency response, displacement, velocity as well as mode shapes of pMUTs with different designs in the air. Besides, an optical profilometer and impedance meter are used to check the static profile and electrical impedance of devices of different sizes, respectively. Finally, a standard reference microphone is used to measure the acoustic pressure of a pMUT inside its frequency range (<125 kHz). The measured resonance frequency of the first mode across 121.5kHz to 1.16MHz with radius from 500um to 120um fits the prediction of FEM and analytical models. The measurements of the acoustic pressure on the transverse axis of a 500um pMUT also fit the values from the acoustic analytical model.

1. Introduction

Recently, piezoelectric micromachined ultrasound transducers (pMUTs) have shown their capability to be used for high density, cost effective, and reliable 2D ultrasound transducer array compared to traditional piezoelectric ultrasound transducer, which mainly works on thickness mode [1]. The working mechanism of pMUT is shown in Figure 1. The displacement of a piezoelectric material layer is activated by AC signals/acoustic waves, and the actuating/receiving signals are delivered/measured through electrodes on both sides. A structural layer is included to modulate the pMUT frequency response. Although the output pressure is not currently comparable with capacitive micromachined ultrasound transducer (cMUT), pMUT technology does not require a high DC bias voltage, and is thus a better candidate for acoustic transmitters/receivers for consumer electronic products. In this paper, we present a novel pMUT design, which is compatible with flat panel display fabrication process, along with its modelling and characterization. The final device is expected to be transparent, after replacing the electrodes with transparent materials. This will allow placing the pMUT array close to the display, ultimately improving the transmission efficiency and receiving sensitivity. This pMUT design is expected to find its ideal implementation for novel acoustic based applications for electronic devices with flat panel display like haptic feedback, gesture recognition, and finger print imaging [2]. One of the first applications of choice could be airborne gesture recognition. Thanks to its flexibility in terms of size and acoustic properties, this pMUT design could be in fact easily arranged in a system of three to four array structures with quasi-spherical radiation pattern, and applied to the recognition of simple gestures (e.g. push, pull, left, right, clockwise and anticlockwise rotation), which are however sufficient to control basic functions of a laptop, tablet or mobile phone. More complex arrangements in a matrix array sensor could also be considered to enable advanced gesture recognition thanks to a spatial resolution able to “imaging” the hand.

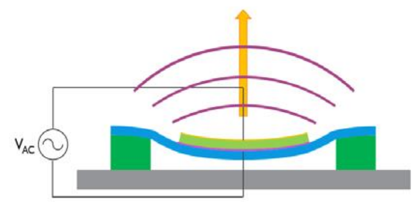

Figure 1: Schematic of pMUT device.

2. Design and modeling

The design parameters are indicated in Fig. 2. The ratio of top and bottom electrodes were about 67% to achieve the best driving efficiency based on our simulation and previous research [3]. For the first prototype, most of the materials were transparent except the metal electrodes. Micro-cavities are created using standard photo-lithography, to achieve suspended poly-imide membranes with a radius from 100 um to 1 mm. The actuation layer consists of Polyvinylidene fluoride (PVDF) sandwiched between two metal layers. The structural layer was built with 15um polyimide, and the actuation layer was made by 500nm Polyvinylidene fluoride (PVDF) and two metal electrodes (100nm).

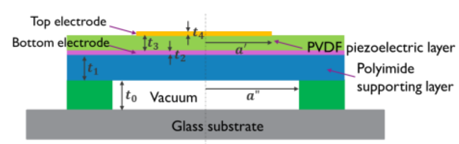

Figure 2: Cross section of the pMUT design. (Cross-sectional drawing is not to scale)

A FEM model was built with COMSOL with the same stack as the design of the pMUT using axial symmetric geometry (Figure 3). The mechanical properties of the materials were measured by nano-indenter. An acoustic propagation region was also created to simulate the ultrasound wave generated/received by the device in a given medium. A perfect matching layer was added to absorb acoustic pressure at the edges of the numerical domain. To minimize the computational burden of modeling the effect of all the different design parameters with respect to the generated acoustic pressure, and achieved resonance frequency under predefined driving voltages and dimension constrains, we developed an analytical model implemented in MATLAB and based on previous research [4-7], see Figure 4. The model consists of three domains: electric, mechanical, and acoustic. In the electric domain, the shunt capacitance C0 was calculated based on the piezoelectric properties of the PVDF, dimensions of the top and bottom electrodes, and thickness of piezoelectric layer. In the mechanical domain, the velocity of the circular plate was evaluated based on the mechanical properties of the entire stack and the electromechanical coupling factor of PVDF. In the acoustic domain, the acoustic field of a pMUT cell was computed by Rayleigh integral and based on the radiation impedance of the clamped circular plate mode[7].

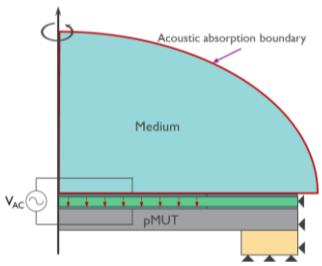

Figure 3: Illustration of the COMSOL model

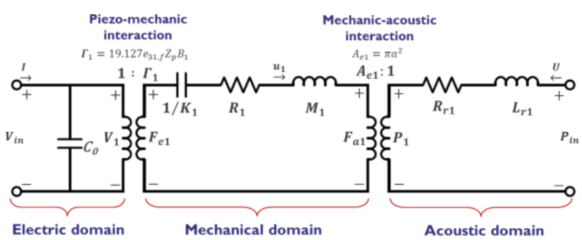

Figure 4: Analytical model of the pMUT device

3. Characterization

Figure 5 shows pictures of the fabricated pMUT devices with different dimensions, metal coverages, and arranged in an array. A laser Doppler vibrometer (Polytec MSA 500) was used to measure the dynamic profile when the device is actuated. To conduct the measurement, a 6-inch wafer with thousands of pMUT devices was placed on a probe station. Two probes were contacted with the top and bottom electrodes, respectively, and used to apply the driving signal. The laser was focused on the center of each pMUT, and the driving signal amplitude was 9V peak to peak. A sinusoidal voltage sweeping from 10kHz to 1.5MHz was used. The membrane velocity measured as a function of frequency was recorded to identify the frequency response. Moreover, driving the device at its resonance frequency using a monochromatic sinusoidal excitation, and scanning the laser focal spot on the entire membrane, the three-dimensional mode shape could also be assessed. The frequency response of the electrical impedance of each device was also checked by a high precision LCR meter (E4980A, Keysight) with driving frequencies sweeping around its resonance frequency, which was found by laser vibrometer. Besides, an optical profile meter (Wyko NT3300, Veeco) with a custom probe station was used to measure the static profile when the devices were in air and without actuation. To characterize the frequency spectrum a reference microphone (Brüel & Kjær 4160) with a 2mm tip diameter was used to measure the acoustic pressure of the pMUTs inside its frequency range (<125 kHz). The wafer was placed on a custom probe station where the aligning microscopy was on the side. In this case, the microphone could be placed perpendicularly on top of the pMUT device being measured, and moved three dimensionally. In this research, the microphone was moved along the axial distance of a 500um radius pMUT from a depth of 0 mm to almost 44 mm.

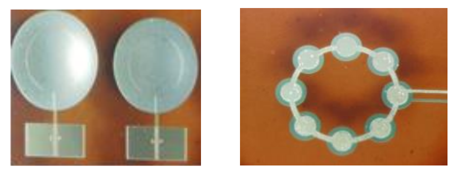

Figure 5: Pictures of single pMUTs with dummy metals on the entire device (left) and pMUT annular array without dummy metals (right).

4. Results

The frequency responses of pMUTs with 400um in diameter and fabricated by 15um technology is shown in Figure 6. The averaged -3dB bandwidth was 11.5kHz, which corresponds to a Q factor of 42. The simulated frequency spectrum as obtained with the COMSOL model is also shown. The dynamic mode shape of a 560um device with a 15um thickness polyimide, and actuated at its resonance frequency, is shown in Figure 7. The mode shapes for pMUTs from 240um to 800um in diameter are also shown in Figure 8, as well as the mode shape from mechanical domain of the analytical model (The model of a circular membrane was also included for comparison). From Figure 6 and 8, it can be observed how the simulation results fit the measured frequency responses and dynamic profiles.

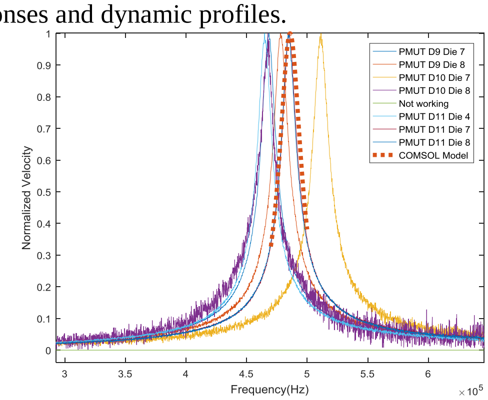

Figure 6: Measurement and simulation results (from COMSOL model) for pMUTS with 15um polyimide with 400um diameter.

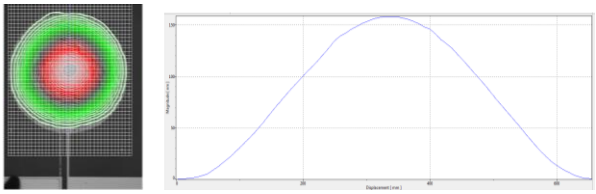

Figure 7: 2D profile lines (Left) and mode shape (Right) on one of the cross section of a pMUT with 560um in diameter.

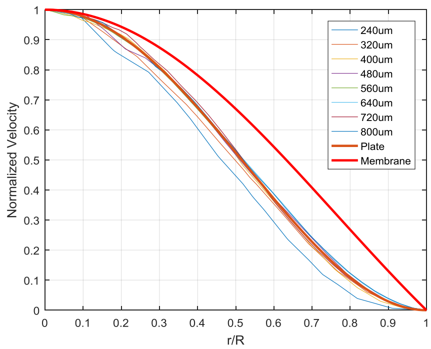

Figure 8: Dynamic mode shapes from measurement and analytical models (Both plate model and membrane model were plotted)

Figure 9 shows the measured resonance frequencies for different pMUTs radius, as obtained with a 15um thickness polyimide as structural layer. The simulation results obtained with the FEM and analytical model were also compared. The resonance frequencies of the smaller devices were closer to results from both models. A possible explanation is that in both models a fully clamped edge is expected. Moreover, the young's modulus of polyimide was low, resulting in non-ideal clamping conditions, as shown in Figure 7. Besides, the static profile measured with the optical profilometer showed that the membranes were no longer flat when the diameter increased above 600um, see example in Figure 10. The collapsing may explain the obtained results. To better fit the actual situation, an investigation of collapsing depth was made by FEM model by considering the pressure difference between air and vacuum, see Figure 11. The simulation results matched the measurements until the depth went over 35um, which is the designed depth of the cavity. By applying the collapsing condition into dynamic simulation using the COMSOL model, the simulation predicted the resonance frequencies with a higher accuracy, as shown in Fig. 12.

Figure 13 shows the frequency spectrums of a 600um (diameter) device, as measured with the laser Doppler vibrometer and LCR meter. The relative permittivity of the PVDF layer was about 5.5, as obtained by curve fitting using the relationship between the parallel capacitances of the pMUTs with the different dimensions and driving frequencies, see Figure 13. The value was closed to preliminary studies of PVDF films. The relative permittivity could be used to quickly evaluate the electrical impedance for different sizes of pMUTs. For the design and layout of different pMUT arrays, the impedance should be considered to optimize the driving efficiency.

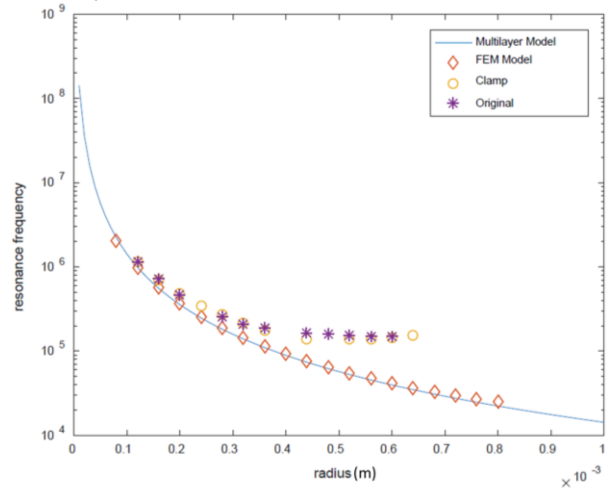

Figure 9: Measurements and simulations of resonance frequencies for pMUTs with different radius. (Solid line: Analytical model. Diamond: COMSOL model. Circle: Measurements from device with dummy metals. Star: Measurements from device without dummy metals)

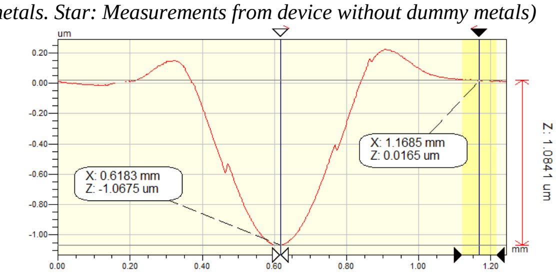

Figure 10: Measurement of optical profile meter of a 480um diameter pMUT device in the air.

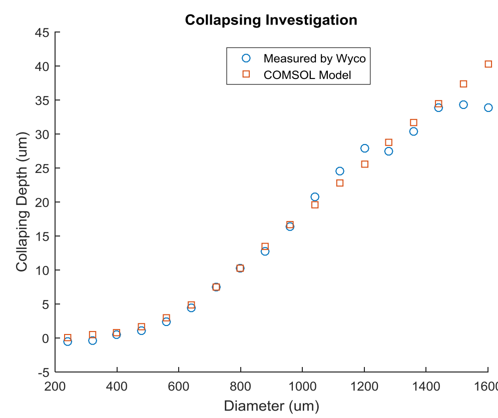

Figure 11: Measurements and simulations of collapsing depth (Circle: Measurements of Wyco, Square: Simulations from COMSOL Model)

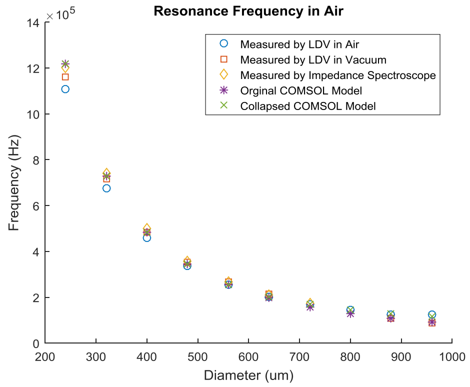

Figure 12: Measurements and simulations of resonance frequencies for pMUTs with different diameters in air and vacuum. (Circle and Square: Measurements of LDV in air/vacuum, Diamond: Measurements of impedance meter. Star and Cross: Simulation results from COMSOL model without/with considering collapsing issue

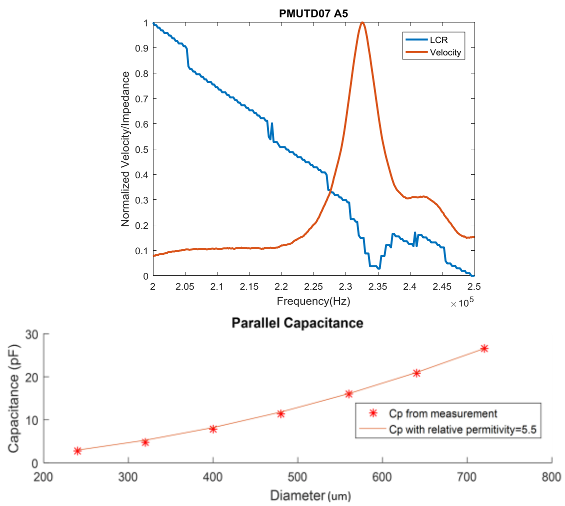

Figure 13: Frequency responses of impedance and velocity of a device with 600um in diameter (Top). Measured values of parallel capacitances for different sizes of pMUTs and simulated curve with relative permittivity is 5.5 (Bottom).

The measurement and simulation results of the acoustic pressure are shown in Figure 14. The acoustic model accurately predicted the acoustic pressure based on the peak velocity of the membrane. Although, measurement of higher frequency pMUT devices are currently not available. This result has proved the capability of using the acoustic model proposed in this study to develop higher frequency devices.

5. Conclusions

The design, modeling, and characterization of a display compatible pMUT platform for gesture recognition application is presented in this article. The stack consisted in a cavity layer, polyimide, PVDF, and metal layers. A FEM model and an analytical model were developed by COMOSL and MATLAB respectively. Measurements including the frequency response (in the mechanical domain) and the pressure field (in the acoustic domain) were presented. Results show that for devices smaller than 500um in radius, each model is capable to predict accurately the resonance frequency. However, for larger devices, the natural frequency is affected by the collapsing of the membrane. The reason is that the structural layer was fabricated in vacuum where the pressure difference has more significant impact for the devices with larger diameters. Based on the frequency response characterization, the potential of using this pMUT platform for novel acoustic applications has been shown. Future work will focus on the design, implementation, and testing of pMUT array sensors based on the presented design and targeting gesture recognition applications.

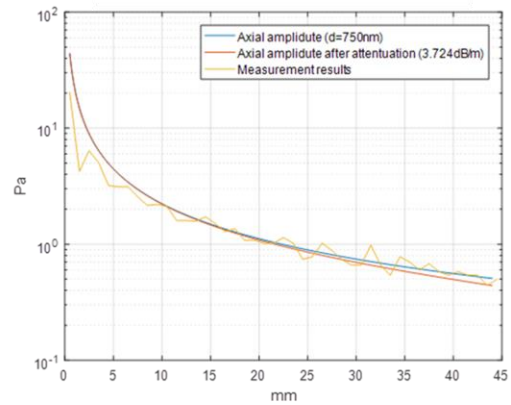

Figure 14: Measurements of acoustic pressure along the axial distance as obtained from of a 500um (radius) pMUT.

References

1. M. S. NessAiver, S. Moriel, et al. " Piezoelectric micromachined ultrasound transducer (pMUT) arrays for integrated sensing, actuation and imaging." Sensors, 2015, 15, 8020-8041.
2. Y. Jeong, et al. "pMUT device compatible with large-area display technology." 16th International Symposium on Electrets, 2017.
3. C.H.J. Fox, et al. " Analysis of the deflection of a circular plate with an annular piezoelectric actuator" Sensors and Actuators A, 2007, 133, 180–194.
4. M. Deshpande, et al. “An analytical model and working equations for static deflections of a circular multi-layered diaphragm-type piezoelectric actuator.” Sensors and Actuators A, 2007, 136, 673–689.
5. M. Herza, et al. “Design of ideal circular bending actuators for high performance micropumps.” Sensors and Actuators A, 2010, 163, 231–239.
6. S.M. Heinrich, et al. ”Fundamental Theory of Resonant MEMS Devices.” Wiley Online Library, 20153.
7. K. Smyth et al., “Experiment and simulation validated analytical equivalent circuit model for piezoelectric micromachined ultrasonic transducers,” IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2015, 62(4), pp. 744–766.