Design, Modelling, and Characterization of Display Compatible pMUT Device

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Abstract

In this paper, the design, modeling, and characterization of a display compatible pMUT platform are presented. A FEM model is built using COMSOL Multiphysics for evaluating the frequency response, mechanical performance, 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 air. The measured resonance frequency of first mode range from 121.5kHz to 1.1MHz with radius from 500µm to 120µm and fits the prediction of FEM and analytical models. A standard reference microphone is used to measure the acoustic pressure of pMUT inside its frequency range (<125 kHz). The measured acoustic pressure on transverse axis of a 500µm radius pMUT also fits the values from analytical model on acoustic domain.

1. Introduction

Recently, piezoelectric micromachined ultrasound transducers (pMUT) have shown their capability to be a high density, cost effective, and reliable 2D ultrasound transducers array compare to traditional piezoelectric ultrasound transducers which mainly work on thickness mode [1]. The working mechanism of pMUT is shown in Figure 1, the displacement of piezoelectric material layer is activated by AC signals/acoustic waves, and the actuating/receiving signals are measured through electrodes on both sides. A structural layer is included to modulate its frequency response. Although the output pressure is not currently comparable to the capacitive micromachined ultrasound transducer (cMUT), pMUT does not require a high DC bias voltage, which makes it a better candidate for acoustic sources/receivers for consumer electronic products.. In this research, we are presenting a novel pMUT design which is compatible with flat panel display fabrication process along with the modelling and characterization. The entire device would be expected to be transparent after replacing electrodes with transparent materials. By placing the pMUT array close to the display, the efficiency of transmission and receiving of acoustic signals is expected to be significantly improved. It makes our pMUT a great candidate for the novel acoustic based applications in electronic devices with flat panel display like haptic feedback, gesture recognition, and fingerprint sensing [2].

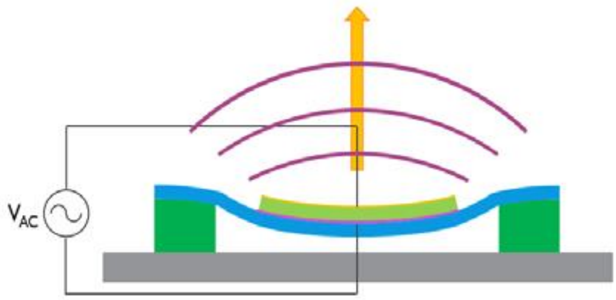

Figure 1: Schematic of pMUT device.

2. Design and modeling

The detailed design parameters are indicated in Figure 2. The ratio of top and bottom electrodes is about 67% to achieve best driving efficiency based on our simulation and previous research [3]. For the first prototype, most of the materials are transparent except the aluminum electrodes. A photo-patternable adhesive layer was put on top of a glass substrate to create 25µm depth cavities for each pMUT device with radius from 100µm to 1000µm [4]. The structural layer is built with 15µm or 35µm polyimide, and the actuation layer is made by 500nm Polyvinylidene fluoride (PVDF).

Geometry and design parameters (unit: µm)

Parameters	t_0	t_1	t_2	t_3	t_4	a'	a''
Values	25	15/35	0.1	0.5	0.1	100-1000	100-1000

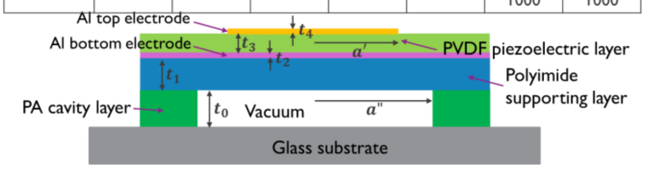

Figure 2: Cross section of pMUT design.

A FEM model is built with COMSOL with the same stack as the design of the pMUT using axial symmetric geometry (Figure 3). The mechanical properties of materials are either measured by nanoindenter or from previous study [4]. An acoustic propagation region is also created to simulate the ultrasound wave generated or received by the device in a certain medium. To closely model the real situation of the acoustic propagating wave, a perfect matching layer is added to absorb acoustic pressure and exclude interference of reflection. To fast evaluate design parameters for achieving specific acoustic pressure and resonance frequency under predefined driving voltages or dimension constrains, an analytical model is also developed using MATLAB based on previous research [5-8] (Figure 4). The model is composed of an electric domain, a mechanical domain, and an acoustic domain. In the electric domain, shunt resistance C_0 is calculated based on piezoelectric properties of PVDF, dimensions of top and bottom electrodes, and thickness of piezoelectric layer. In the mechanical model, the membrane velocity is evaluated based on the mechanical properties of entire stack and the electromechanical coupling factor of PVDF. In the acoustic domain, the spatial acoustic field of a pMUT cell is computed by Rayleigh integral based on the radiation impedance of a clamped circular plate mode [8].

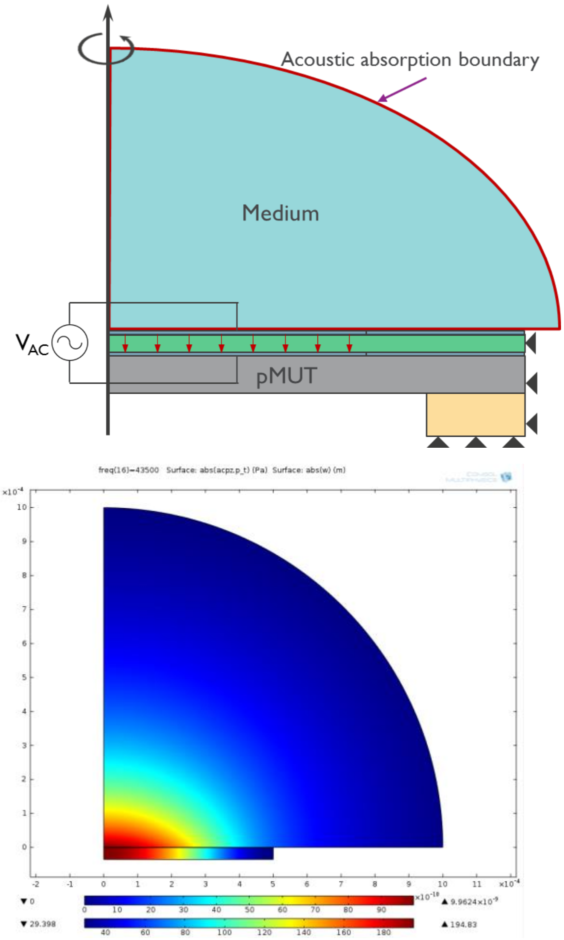

Figure 3: Illustration of the COMSOL model (Top) and simulation result represented with 2D graph (Bottom).

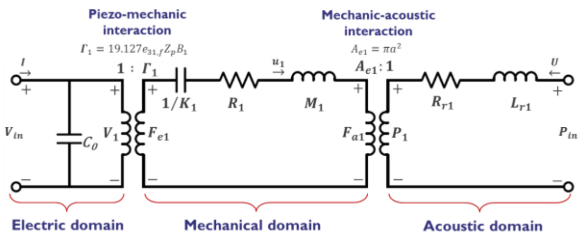

Figure 4: Analytical equivalent model of pMUT device.

3. Characterization

Figure 5 shows the fabricated pMUT devices with different dimensions, array numbers, configuration and metal coverages. The characterization of the pMUT includes measurement of dynamic motion of the membrane and the acoustic pressure in air. First, a laser Doppler vibrometer (Polytec MSA 500) is used to measure the velocity when the device is actuated. To conduct the measurements, the top and bottom electrodes are connected to the driving voltage and the laser is focused on the center of each pMUT. The driving signal is a 10V peak to peak sinusoidal voltage swept from 10kHz to 1.5MHz. The velocity for different driving frequency is recorded to detect the resonance frequencies. Then, by driving the device with its resonance frequency and scanning the laser focal spot across entire device, the three-dimensional mode shape is also measured.

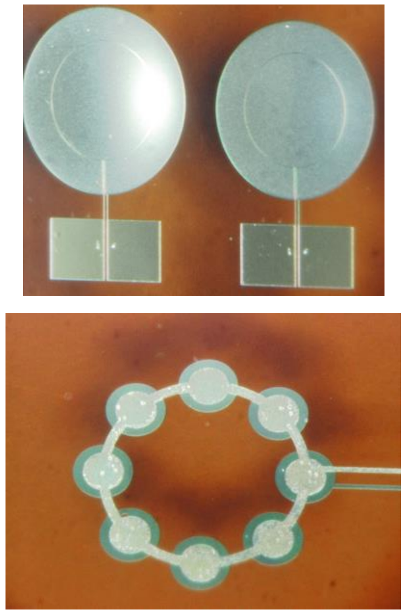

Figure 5: Pictures of the fabricated pMUTs. Top: Single pMUTs with dummy metals on the entire device. Bottom: pMUT annular array without dummy metals.

To quantify the frequency spectrum of an ultrasound transducer, a sensor with flat response across a large frequency bandwidth is usually used (ex: hydrophone). However, there are not too many options in the air compare to immersion applications. In this research, a standard reference microphone (Brüel & Kjær 4138) with 2mm diameter on the tip is used to measure the acoustic pressure of pMUTs inside its frequency range (<125 kHz). The wafer is put on a custom probe station where the aligning microscopy is on the side. In this case, microphone could be put perpendicularly on top of the pMUT device being measured and moved in XYZ dimensions. In this research, the microphone is moved along axial distance of a 500µm radius device from almost 0mm to 44mm.

4. Results

The frequency responses of pMUTs with 400µm in radius fabricated by 15µm and 35µm thicknesses are respectively shown in Figure 6. The resonance frequency of the first mode of 35µm technology is significantly higher than the 15µm technology due to thicker structural layer. Besides of first mode, other higher modes are also observed with strong amplitude which implies the possibility to apply the same device in multiple applications with different required resonance frequencies. The mode shape of a 280µm device with 15µm thickness polyimide actuated on its first resonance frequency is shown in Figure 7.

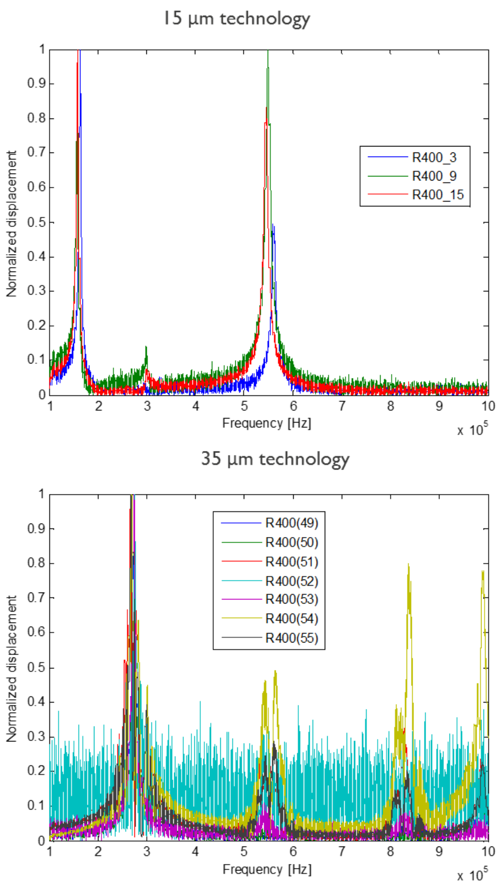

Figure 6: Measurement results for PMUTS with 15µm and 35µm polyimide with 400µm radius. The driving frequencies are swept from 100kHz to 1MHz with peak to peak voltage of 10V.

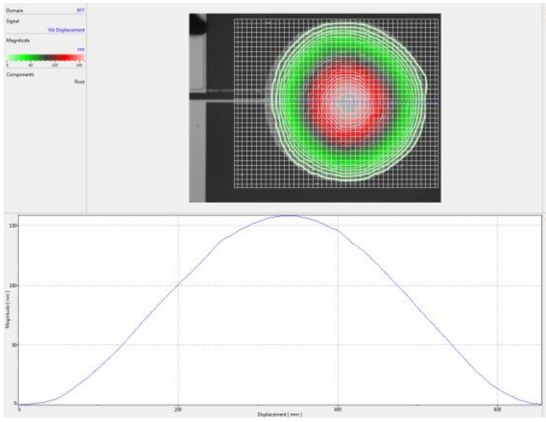

Figure 7: 2D profile lines (Top) and mode shape (Bottom) on one of the cross section of a pMUT with 280µm in radius.

Figure 8 indicates the measured resonance frequencies of different radius of pMUTs with 15µm thickness polyimide as structural layer. Some devices are covered by dummy metals to investigate the influence of uniformity of the membrane. The simulation results of FEM model and analytical model are also compared. The resonance frequencies of smaller devices are closer to the results from both models. The first reason is that in both models a fully clamped edge is expected. However, the young's modulus of polyimide is low which makes for an imperfect clamping condition as indicated in Figure 6. Besides that, the static profile measured by Wyko NT3300 optical profilometer (with custom probe station) shows that the membranes are no longer flat when the dimension increased (Figure 9). The collapsing of the membrane could also affect the results of measurements. However, from a design perspective, the difference between simulation and measurement is negligible when the radius of devices is smaller than 500µm.

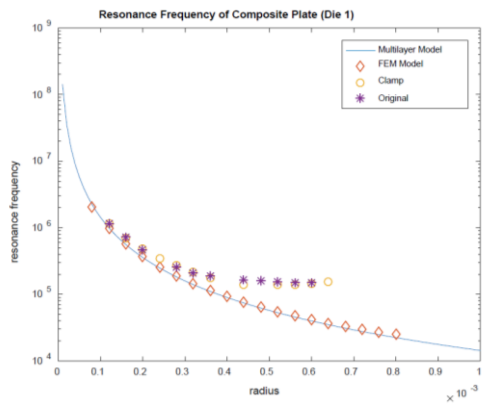

Figure 8: Measurements and simulations of resonance frequencies for pMUTs with different radius. (Solid line: Analytical model. Diamond: COMSOL model. Circle: Measurements from device with dummy metals. Star: Measurements from device without dummy metals)

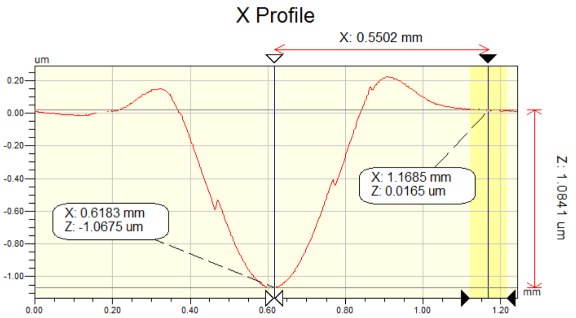

Figure 9: Cross section profile of a 480µm pMUT device in the air

The measurement and simulation results of acoustic pressure is demonstrated in Figure 10. The acoustic model accurately predicts 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 acoustic model proposed in this study on developing higher frequency devices.

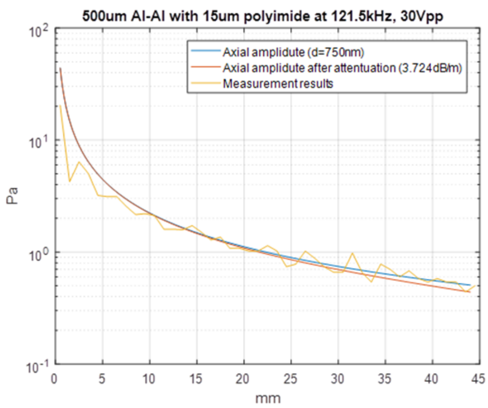

Figure 10: Measurements of acoustic pressure on axial distance of a 500µm pMUT.

5. Conclusions

The design, modeling, and characterization of a display compatible pMUT platform is proposed in this article. The stack consists of photo-adhesive, polyimide, PVDF, and aluminum layers. A FEM model and an analytical model are developed by COMSOL and MATLAB. The measurements including frequency response in mechanical domain and pressure field in acoustic domain indicates that for devices smaller than 500µm in radius, each model is capable to predict well 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 in devices with larger diameters. Based on the characterization of the frequency response, the potential of using this pMUT platform for novel acoustic applications has been proved. The next step is to increase the resonance frequency and conduct the characterization in liquid environment where most of the ultrasound imaging applications are taking place. Additionally, the transparency of our pMUT devices makes it a good 2D receiver array for photoacoustic tomography where optical signals and acoustic signals could be delivered and received in the same direction.

References

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