DOI 10.5162/Ultrasonic2025/A6-a3

New manufacturing technique based on microsystems technology for flexible polymer ultrasonic arrays

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Abstract: This work presents a top-down manufacturing technology for the fabrication of flexible ultrasonic arrays made of polymer PMUTs. The top-down fabrication allows all contacting from the backside of the PMUTs and thus the aperture area stays free from any electrical contacts. The PMUTs of the fabricated array and test structures have center frequencies between 100 kHz and 450 kHz and an average 6 dB bandwidth of 8 %. The maximum amplitude in air for any membrane was 100 nm with a sinusoidal excitation of 10 Vpp. The bending radius of the array was 10 mm.

Keywords: flexible array, top-down fabrication, polymer PMUT

Introduction

The international state of the art in the fabrication of ultrasonic transducers is currently still dominated by the application of the piezoelectric ceramic PZT. Increasing demands on the environmental compatibility of the applied materials, energy efficiency, design options for the array, low manufacturing costs and increased demand have led to the development of PMUTs (piezoelectric micromachined ultrasonic transducers) and CMUTs (capacitive micromachined ultrasonic transducers). Both types of transducers are fabricated using microsystems technology. The state of the art in CMUTs corresponds to the developments in Prof. Khuri-Yakub's working group at Stanford University in California. Many publications on this topic can be found at https://profiles.stanford.edu/butrus-khuri-yakub. Prof. Khuri-Yakub is considered as the inventor of CMUTs and his work over the last 30 years describes the development of CMUTs. While this research group develops CMUTs with silicon technology, Gerardo et al [1] built an array of polymer CMUTs. Other works on polymer CMUTs are mainly focused on flexibility or transparency [2];[3];[4]. Although PMUTs can generate a higher sound pressure, have a higher sensitivity and do not require an additional bias voltage, the development of micromachined ultrasonic transducers was focused on CMUTs for a long time. The development of PMUTs was in the background because a high bandwidth is easier to achieve with CMUTs and this feature is necessary for a clear ultrasound imaging. This disadvantage was overcome with the work of Hajati et al [5] and Dausch et al [6]. Using innovative membrane designs, they succeeded in increasing the bandwidth to up to 170% . These two working groups are building PMUT arrays with silicon technology. The research groups of Paul Heremans and Jan Genoe at the Catholic University of Leuven and at imec in Leuven are working in the field of PMUTs made of polymer. However, they mostly produce PMUTs according to the conventional down-top principle. So far only one of their publications reports on the fabrication of PMUTs using the top-down method [7]. However, the fabrication route described there does not appear to benefit from the advantages of the top-down approach, as the PMUTs are contacted in the aperture area. The present work describes the manufacturing of flexible polymer PMUTs using the top-down approach. The PMUTs are contacted from their rear side and the aperture area remains free of electrical contacts.

Simulation

The micromachined manufacturing of PMUTs requires several masks for photolithographic structuring. To determine the necessary manufacturing steps and the dimensions of the masks required for this, the shapes of the PMUTs were simulated at the beginning.The simulations of the oscillation behavior of a single PMUT were performed using the finite element method with Ansys software. The following material parameters were used for the simulations with Ansys: polymer photoresist dry film ADEX™ from DJ MicroLaminates, Inc. (E = 4 GPa, density = 1.5 g/cm^3, Poisson number = 0.22), zinc oxide (ZnO) (E = 120 GPa, density = 5.68 g/cm^3, Poisson number = 0.34), polyimide (E = 2.6 GPa, density = 1.29 g/cm^3, Poisson number = 3.5). The finite element model for the simulation with ANSYS was a two-dimensional, rotationally symmetrical model, so that the entire three-dimensional geometry was taken into account. Figure 1 shows the results of the simulation in comparison with the measured center frequencies from Table 1. For disc-shaped ZnO and electrodes on the membranes a good agreement between the measurements and the simulation can be seen. For the ring-shaped ZnO and electrodes on the membranes, there was a deviation at lower frequencies. But at higher frequencies the geometry of PMUTs with ring-shaped ZnO and electrodes can be simulated with sufficient accuracy.

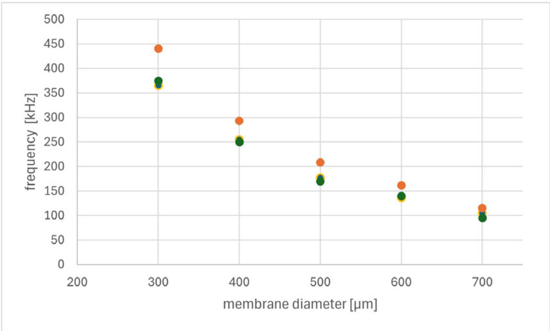

Fig. 1: green dots for measurement results of disc-shaped ZnO and eletrodes and orange dots for mesurement results of ring-shaped ZnO and electrodes, yellow dots for simulation results of disc-shaped ZnO and eletrodes.

Fabrication

With the results of the simulations the shape and dimensions of test structures and a linear array with 32 elements and a center frequency of 300 kHz were determined. Each element of the array should have 2 x 70 PMUTs. The linear array was placed in the center of a wafer and the remaining area was filled with test structures of 2 x 2 PMUTs of different diameters and thus different frequencies. The diameters of the PMUTs of the test structures were 300 µm, 400 µm, 500 µm, 600 µm and 700 µm. The PMUTs were manufactured according to the fabrication steps described below:

1) Application of a 5 µm thick layer of polyimide (PI) with additives on a silicon wafer using spin coating. 2) Application of a second 5 µm thick layer of PI on the first PI layer. 3) Deposition of a 300 nm thick platinum ground electrode by sputtering. The pads for contacting the array with an electronic were placed after the first and last PMUTs of an array element. The vias for contacting the top electrode were positioned between the array elements at approx. 100 µm from the PMUT's edge of an array element. 4) Sputtering of the piezoelectric zinc oxide (ZnO) and its photolithographic structuring using a wet etching process. The dimensions of the ZnO layer were kept slightly smaller than those of the ground electrode. In this way, the ZnO could be applied exclusively to the ground electrode. 5) Deposition and structuring of the platinum top electrode with titanium as an adhesion aid on the structured ZnO using a lift-off process and sputtering. The ZnO and the top electrode were made disc-shaped and ring-shaped. Figure 2a schematically shows the status after fabrication step 5).

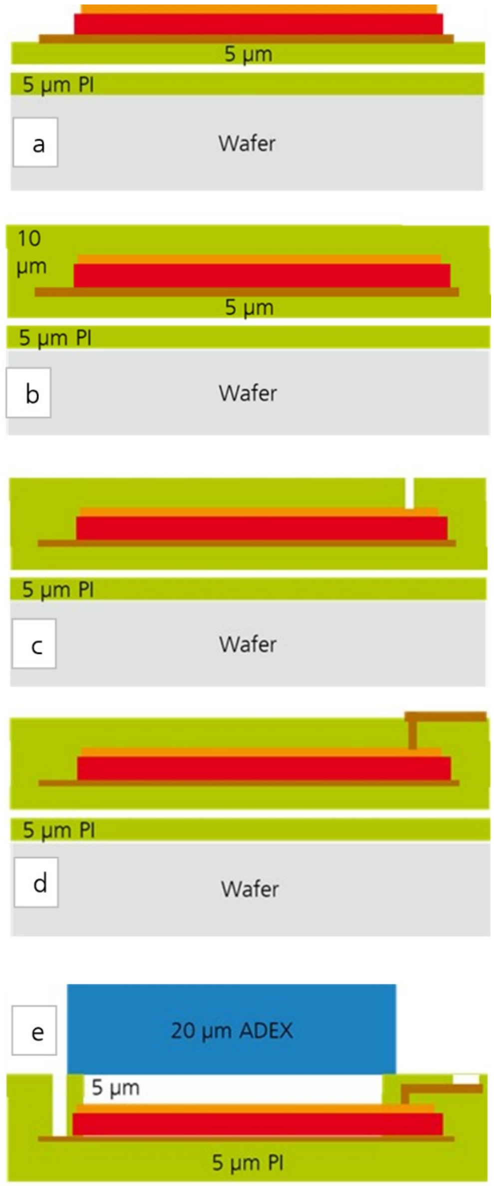

Fig. 2: schematical description of the steps involved in the new top-down PMUT manufacturing process.

6) Application of a 10 µm thick layer of PI using spin coating and structuring the via holes for contacting the top electrode using reactive ion etching. Figures 2b and c schematically show these fabrication steps. 7) The 70 via holes of one element were connected to each other. The contact was routed to the outside

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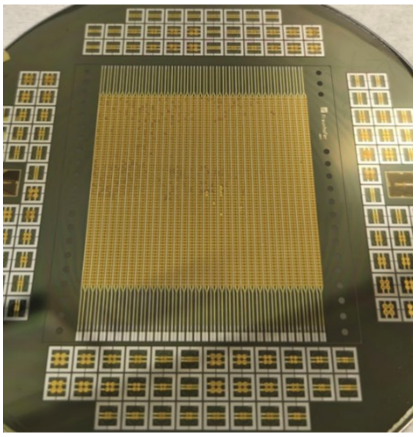

Fig. 3: photo of the 32-element linar array in the center and test structures araound on a wafer.

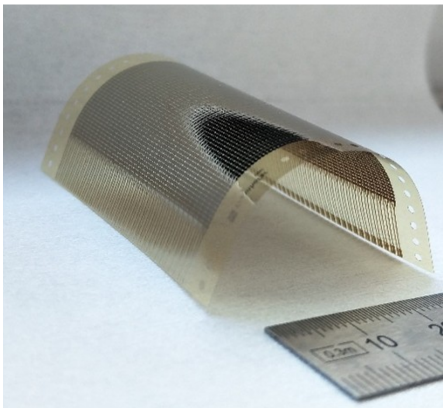

Fig. 4: photo the flexible array with a bending radius of 10 mm.

of the array. The deposition and structuring of the platinum was carried out using a lift-off process and sputtering. Figure 2d schematically shows the status after the step 7). 8) Application of a further 5 µm thick PI layer. 9) The cavity and the electrical contacts were structured using reactive ion etching. 10) Lamination and structuring of a 20 µm thick ADEX film on the cavity for stabilization. The ADEX was laminated onto the entire surface of the wafer and then structured lithographically. The array and the test structures are detached between the first and second 5 µm PI layer. Figure 2e shows the structure of the resulting PMUT cell.

Results

Figure 3 shows a photo of the wafer with the finished linear array and test structures and figure 4 demonstrates the flexibility of the array with a bending radius of 10 mm.

The bandwidth and the oscillation behavior of the

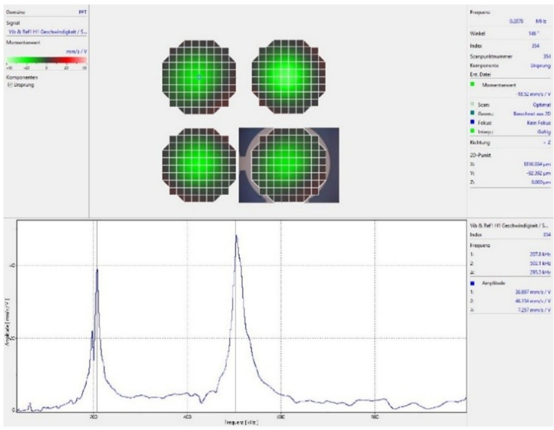

Fig. 5: averaged spectrum of a 500 µm test structure, fundamental oscillation 208 kHz, first harmonic 503 kHz.

Tab. 1: frequencies of the fundamental oscillation of the test structures.

Diameter µm	disc-shaped structure kHz	ring-shaped structure kHz
300	365	440
400	255	293
500	177	208
600	136	161
700	105	115

test structures and the array were determined using the UHF-120 vibrometer from Polytec GmbH. Circuit boards for contacting and holding the foil-like structures were designed and commissioned externally. The center frequency and the 6dB bandwidth were determined with a pulse-shaped electrical excitation and a Fast Fourier Transformation. Figure 5 shows an example of the frequency spectrum of a 2 x 2 test structure with 500 µm diameter membranes. The fundamental oscillation is at 208 kHz and the first harmonic at 503 kHz. Table 1 shows the frequencies of the fundamental oscillation of the test structures as a function of the membrane diameter. In all cases, the max. 6 dB bandwidth was approx. 8 %.

For the examination of the oscillation behavior, the membranes were excited with a sine burst with 50 cycles and 10 Vpp. The surface of the membranes was scanned with approx. 100 measuring points. Figure 6 shows an example of the oscillation behavior of a 500 µm membrane with a ring-shaped ZnO layer and electrodes. The amplitudes of the fundamental oscillation at 10 Vpp were 100 nm for all membranes

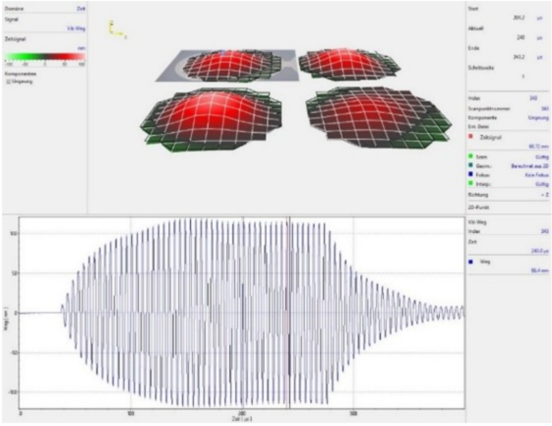

Fig. 6: oscillation of a 500 µm membrane excited with a sine burst of 10 Vpp and 50 cycles.

regardless of the shape of the ZnO and the electrodes.

Summary

The top-down manufacturing technology presented here enables the fabrication of flexible arrays made of polymer PMUTs. The advantage of top-down fabrication is the contacting from the backside of the array and therefore the free array aperture. The PMUTs have center frequencies between 100 kHz and 450 kHz according to the selected dimensions. The measured average 6 dB bandwidth of 8 % is too small for ultrasound imaging and further work must be invested to increase bandwidth. In this context alternative membrane geometries could be tested. The developed simulation tool calculates the geometries of PMUTs with disc-shaped ZnO and electrodes with good accuracy. Higher frequencies over 1 MHz for medical imaging can be easily achieved with smaller membrane diameters. The maximum amplitude in air for each membrane was 100 nm with a sinusoidal excitation of 10 Vpp. The bending radius of the flexible array was 10 mm. Further investigations into beam forming are planned once the driving electronics have been finalized. With the piezoelectric polymer PVDF or thin translucent ZnO and electrodes made of transparent indium tin oxide, transparent PMUTs could also be produced in the future.

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