Chemnitz University of Technology

Chair Measurement and Sensor Technology

H. Daßler, W. Manthey, L. Thieme

Broadband ultrasonic MEMs for liquids

Transducer principle and technology

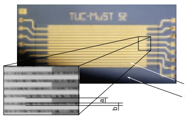

Figure 1: The structured silicon chip, zoom of etched trenches between electrodes

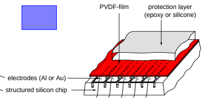

Figure 2: Structure of the complete transducer array based on the silicon chip

The developed micromachined ultrasonic transducer arrays are able to pan a sound beam electronically in an arbitrary direction in fluids (fig. 7). The operating principle is known as 'phased array' but the very broadband PVDF film is driven by short time shifted pulses. The ultrasonic transducer array (fig. 1) is based on a structured silicon substrate metallized with a metal electrode structure and a top mounted PVDF film. A silicone or epoxy layer protects the transducer array. One element of the array is formed by a single electrode (width $a = 20$ to 100 µm) on top of the silicon chip and the opposite gold electrode of the PVDF film. The transducer element works as a thickness vibrator by applying a voltage between these electrodes.

Characterisation of ultrasonic transducers

Acoustic far field measurement techniques are mainly used to determine the typical properties of an ultrasonic transducer. But it is impossible to investigate the generation of ultrasonic sound (deformation of the piezoelectric film resp. protection layer) and inner transducer effects (crosstalk etc.).

Figure 3: Measurement arrangement for transducer characterisation using a laser vibrometer and a positioning unit

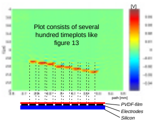

Figure 4: Three-dimensional representation of deformation along a line scan with corresponding transducer structure

To observe the transducer surface deformations laseroptical investigations were necessary. The used laser vibrometer is able to measure low deformations (< 2 nm) at high frequencies (50 kHz - 20 MHz). Up to 1000 time signals of deformation per line scan are logged in distances of 0.5 to 25 µm by means of a PC-controlled position unit (fig. 3). The measured timeplots are interpreted in a three-dimensional plot (similar to ambiguity plots), representing the scanning path (x-axis), measurement time (y-axis) and the deformation level (colour scale). All deformation levels are in Volt (scaling factor 50 nm/V). The corresponding transducer electrodes are shown in fig. 4. For demonstration purposes a progressive superposition in silicone using time shifted driven elements is shown in fig. 5. The laser beam can be focused on the PVDF film (fig. 5) or on the protection layer surface (fig. 6).

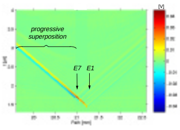

Figure 5: Demonstration of sound superposition forced for silicon rubber (laser focused to the PVDF-film)

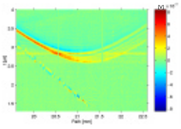

Figure 6: The same conditions like in figure 5, except the laser was focused to the surface of the protection layer

The measurement results are disturbed by echo waves which are caused by the reflection (nearly 99 %) of the acoustic waves at the crossing between the protection layer and the air. That's why the transducer is located in a water tank (fig. 3) to prevent these reflections.

Crosstalk within the transducer

Fig. 7 shows the directional characteristics of a time shifted driven transducer array for sound propagations of 30°, 40° and 50° without protection layer. Due to a small element width of a=40 µm there is no reduction in amplitude, because of the nearly circular directional characteristic of a single element. But there is an undesired sound peak in the normal direction of 0° (fig. 7). Crosstalk effects inside the transducer enlarge the active area to the PVDF film width which covers the whole silicon chip. Fig. 8 shows the measured deformation of the PVDF film of 8 elements driven at the same time (middle). There are 4 grounded elements to the left and to the right of the driven region which are not deformed. However, very small deflections (~0.15 nm) appear outside this grounded area. Thus the vibrating surface is much larger then the lowest wave length of the sound signal which leads to a very sharp peak in normal direction (fig. 7).

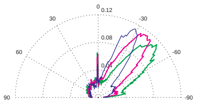

Figure 7: Directional characteristics in water of a time shifted driven transducer array

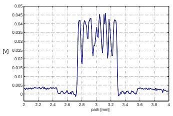

Figure 8: Electrical crosstalk outside the electrode region (laser measurement)

Transducer optimization

The PVDF film covers the complete silicon chip width for a better fixing. Test preparations were done with small PVDF films (like fig. 10) to remove the crosstalk. Those prepared transducer arrays achieve the wanted acoustic behaviour without crosstalk (fig. 9) but the fixing of the PVDF film gets worse.

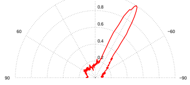

Figure 9: Directional characteristics in water of a transducer array like shown in Fig. 10

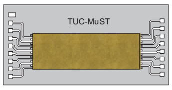

Figure 10: To avoid crosstalk the PVDF-film covers only the electrode region

An improved transducer design contains a grounded shield around and between the active electrodes.

Design realization: trenches with a width of only 4 µm were etched to separate electrodes from the surface of the wafer (fig. 11). After a metal deposition the wafer surface can be grounded to avoid electrical coupling effects. The electrodes are insulated because of no sufficient metallization on the bottom of the trenches. First measurements showed that the crosstalk between driven array elements is negligible (fig. 12).

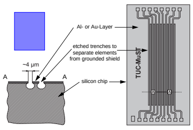

Figure 11: New sensor design to avoid crosstalk using a grounded chip surface

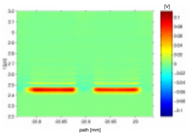

Figure 12: New sensor layout: crosstalk between driven array elements is negligible

Protection layer influence

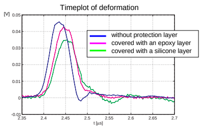

Figure 13: Influence of protection layer (epoxy, silicone) on the deformation of a pulse driven PVDF-film.

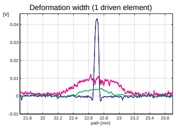

Figure 14: Changes of deformation shape for 1 driven element measured on the protection layer surface

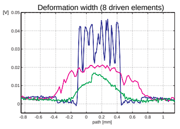

Figure 15: Changes of deformation shape for 8 driven elements measured on the protection layer surface

A protection layer is needed to protect the transducer array from mechanical damage and chemical corrosion. Because of the broadband excitation and the very broadband characteristics of PVDF based transducers a λ/4-adaption layer (as known from ceramic transducers) is not applicable. Due to the acoustic impedance of PVDF is close to the one of fluids (opposed to the one of ceramic transducers) an adaption layer is not necessary. However, the acoustic impedance of the protection layer can be chosen properly for a used fluid.

Because of the highly damped PVDF film there are only small changes in deformation of the PVDF film with and without a protection layer (fig. 13). In contrast fig. 14 and 15 show the difference between the deformation of the PVDF film itself (under the protection layer) and the deformation of the protection layer surface (layer thickness ~1 mm) for 1 and 8 driven elements. As expected the width of deformation enlarges and the deflection decreases with a protection layer. The enlarged vibrating surface influences the directional characteristics of a single element and therefore the maximum panning range of the array. To study the influence of protection layer thickness and different materials extended measurements are necessary. The complete measurement plots of a transducer array with an element width of a=40 µm are shown in fig. 16 (8 elements, no time shift) and fig. 17 (8 elements, time shifted).

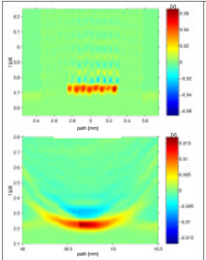

Figure 16: Deformation plot without (top) and with protection layer, 8 elements driven, no time shift (sound propagation 0°)

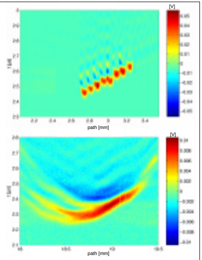

Figure 17: Deformation plot without (top) and with protection layer, 8 elements driven, time shift for sound propagation 30°

Simulation

The deformation data from laseroptical characterisation can be used as feedback and input to improve the transducer simulation. This is mainly realized using ANSYS® for coupled field and piezoelectric simulations as well as MATLAB® for point source synthesis. The small dimensions of the transducer elements in conjunction with the very high frequencies (up to 20 MHz) results in large models and long calculation times in ANSYS® simulations. Fig. 18 shows a simulation of the electrical coupling in a modelled transducer using piezoelectric elements. The use of ANSYS® simulation results as input for the point source synthesis for sound field calculations are advantageous. Fig. 19 shows the simulation of the silicone protection layer surface's deflection (thickness 1 mm) for a sound beam panning into 30°.

Both results show good conformity to the measurement results in fig. 8 and fig. 17.

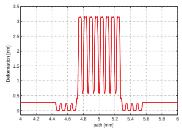

Figure 18: ANSYS® simulation of electrical crosstalk using piezoelectric elements (measurement result see Fig. 8)

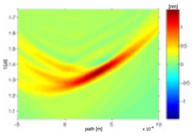

Figure 19: Simulation of protection layer deformation using point source synthesis (measurement result see Fig.17)