BROADBAND ULTRASONIC MEMS FOR LIQUIDS

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Abstract: Micromachined ultrasonic transducer arrays were developed to pan a sound beam electronically in an arbitrary direction. These PVDF-based transducer arrays are suitable for applications in liquids. The characterisation of these tranducers is done by acoustical and laseroptical measurements. The single transducer element dimensions varies from 20 to 100 μm for the generated high frequencies up to 20 MHz. The knowledge of the transducer behaviour based on acoustical and laseroptical characterisation of the transducer arrays results in a improved transducer layout. A modified micromechanical realisation is presented. The advantages of these transducer arrays for the well known transit-time fluid flow measurement are described and the applicability for the beam deflection method in liquids is discussed.

Keywords: ultrasonic array, micro technology, fluid flow measurement

1 TRANSDUCER PRINCIPLE AND REALIZATION

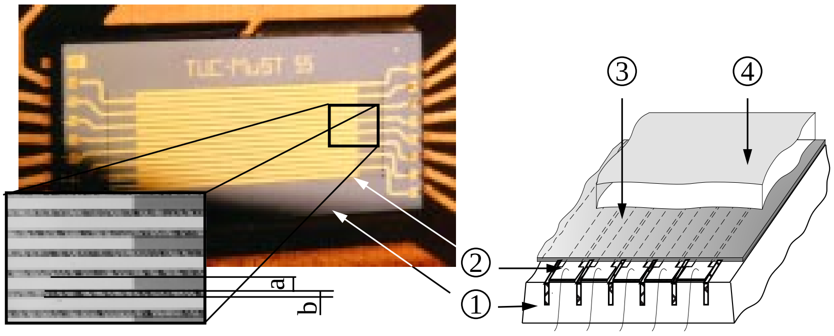

Figure 1: Structure of the transducer array

The presented MEMS (micro-electro-mechanical-system) is an ultrasonic transducer array, which can work as transmitter and receiver, too. It is realized in hybrid integration based on the piezopolymer Polyvinylidenfluorid (PVDF), other research is done to develop acoustical arrays in monolithic integration like [1]. The transducers described here (see Fig. 1) consist of a structured silicon substrate (1) metallized with the desired gold or aluminium electrode structure (2) and a top mounted PVDF film (3). The PVDF film is gold coated on the upper side only. A silicone rubber or epoxy layer (4) protects the whole transducer array. One transducer element of the array is formed by a single electrode on top of the silicon chip and the opposite electrode of the PVDF film. The PVDF film and consequently the transducer element works as a thickness vibrator by applying an electrical signal between these electrodes [2].

The operating principle is known from “Phased Arrays“, but the excitation is done by short high voltage pulses. As a result of broadband characteristics of PVDF, a time shifted pulse excitation of the elements and constructive sound wave interference an aimed sound beam (see Fig. 2) is generated. The generated sound beam can be panned in any desired direction from -60 to +60 degrees by electronically time shifting.

To achieve such a large panning range with sufficient sound pressure a single element should have a wide directional characteristics. Therefore, single transducer element dimensions from $a = 20...100$ μm (Fig. 1) are required for the generated exceptional high frequencies (up to 20 MHz). The element distances b varies in the same range. The radiation characteristics and the sound pressure level of the transducer array can be improved by increasing the number of transducer elements.

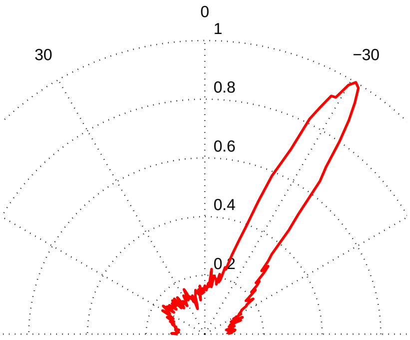

Figure 2: Sound beam panned into the direction of 30^{o}

2 TRANSDUCER ARRAY CHARACTERIZATION

2.1 Acoustical characterization

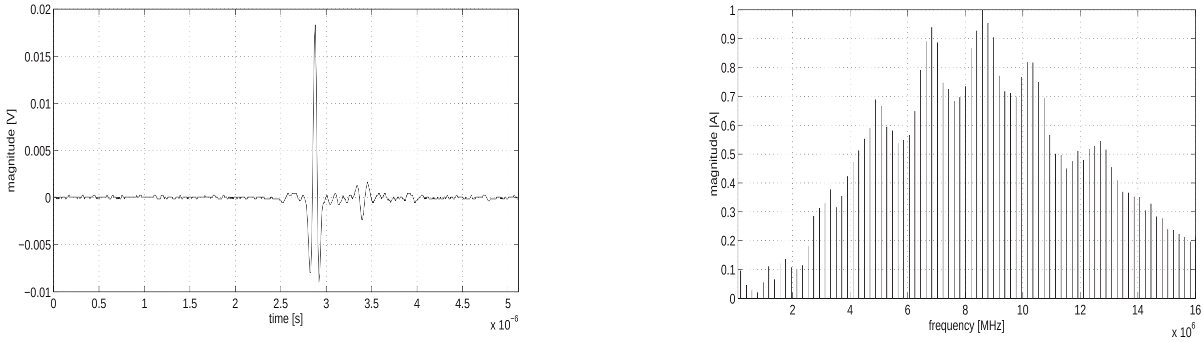

Figure 3: A pulse response of a transducer element (left) and FFT of the pulse response (right)

Acoustical far field measurement techniques using a hydrophon were mainly used to specify typical ultrasonic transducers properties [3]: directional characteristics (Fig. 2), electrical excitation pulse response (Fig. 3 left), frequency characteristics with a relative bandwidth up to 0.8 (Fig. 3 right) and sound pressure level. A typical value for a single transducer array element of these transducer arrays is >160 dB (related to $p_0 = 20\,\mu$Pa, measuring distance: 10 cm).

The main disadvantage of acoustical measurements is the impossibility to investigate the generation of ultrasonic sound (deformation of the piezoelectric film resp. protection layer) and inner transducer effects (coupling between elements, influence of a single element, material properties influence). For example the cause of the undesired sound peak in the normal direction of 0^{o} (Fig. 4) could not be detected by acoustical measurements.

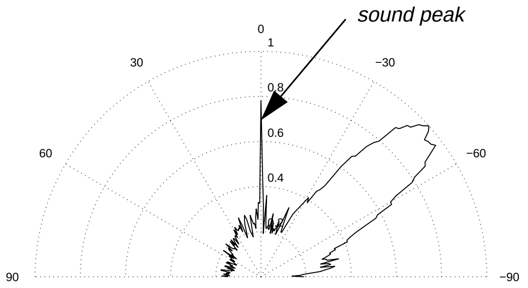

Figure 4: Directional characteristic incl. peak

2.2 Laseroptical characterization

It was necessary to observe the transducer surface deformations to overcome this. Hence, laseroptical investigations were forced, detailed described in [4]. A laser vibrometer combined with a PC-controlled position unit was used to log deformation signals of a *line scan* in distances of a few micrometer. The measured signals show elongations less than 2 nm and a broadband characteristic from 3 to 15 MHz.

Fig. 5 shows a ambiguity plot (time vs. scan path, greylevel represents magnitude) of a time shifted driven array with 8 elements, the laser was focused to the PVDF film covering the whole chip. The plot is column normalized to detect smallest vibrations on the transducer surface. Fig. 5 represents a transducer with 8 driven electrodes and 4 ground connected outer electrodes on each side. The time shifted excitation in the active area, but no vibrations in the grounded area can be seen. Because of technological reasons the PVDF film covers the complete silicon chip. Therefore, the line scan was enlarged to the whole PVDF film

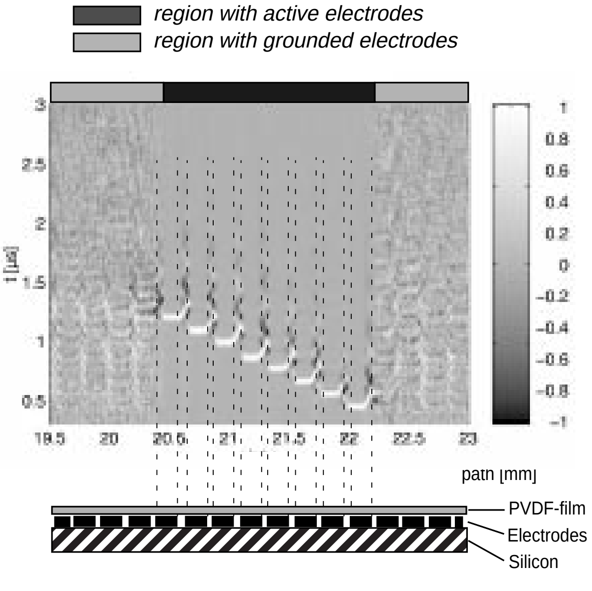

Figure 5: Ambiguity plot of deformation signals - column normalized plot!

width. A vibration in the sub-nm range outside the electrode region could be observed. As there is no time shift between this vibration and the electrical excitation this effect must be forced by an electrical coupling through the silicon. This coupling enlarges the active transducer surface and leads to the sound peak in Fig. 4.

Additional to coupling effects laser measurements can be used to determine protection layer influence to the directional characteristics, piezo film damping, surface vibration mode, speed of sound and the sound wave superposition of time shifted driven transducer elements. Furthermore, the laser can be focused to the protection layer surface, too. The resulting deformation data can be used as feedback to improve the transducer simulation.

3 VARIANT TRANSDUCER LAYOUT AND MICROMECHANICAL REALIZATION

One of the laseroptical measurement results is a new layout for the silicon chip to avoid coupling effects. First considerations lead to transducer preparations with shield electrodes around the electrode region and grounded electrodes between the active electrodes. A simple way to achieve this is derived from SCREAM technology (single crystal reactive ion etching and metallization), described in [5]. This-technology is widely used at the “Center of microtechnologies“ in Chemnitz to realize moving parts for micromechanical devices. The idea is to separate electrodes (Fig. 6) from a grounded metal shield - covering the whole silicon chip - by etching trenches around the electrodes.

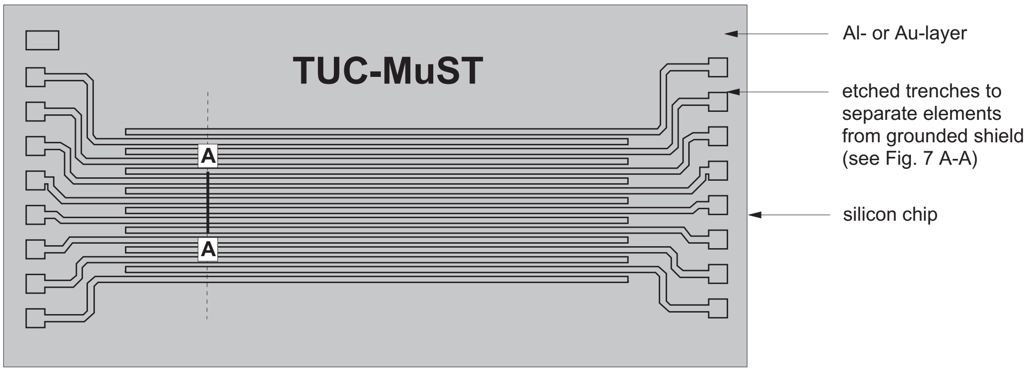

Figure 6: Improved sensor electrodes layout based on etched trenches around the electrodes separating the electrodes from the shield (realized with a single mask process).

This will be done with a single mask process as follows: The silicon wafer is prepared with a deposited SiO_2 layer, which is structured by photolithography. This mask is copied to the silicon wafer by anisotropic depth etching (fig. 7 left), using *reactive ion etching* (RIE). A very isotropic *chemical vapor deposition* (CVD) covers the structure with SiO_2. The bottom of the trench will be etched back to the silicon using an anisotropic RIE. The unprotected silicon on the bottom will be isotropic etched to form a cave. The tear-off edges of the cave are barriers (to prevent short circuits) for the final metallisation. The trench witdh will be only 4 µm to maximize the shielding effect and to ensure sufficient surface for PVDF film mounting.

A simpler variant will be tested without the depth etching (Fig. 7 right), but only with isotropic etching to form the caves. This would reduce parasitic capacitances..

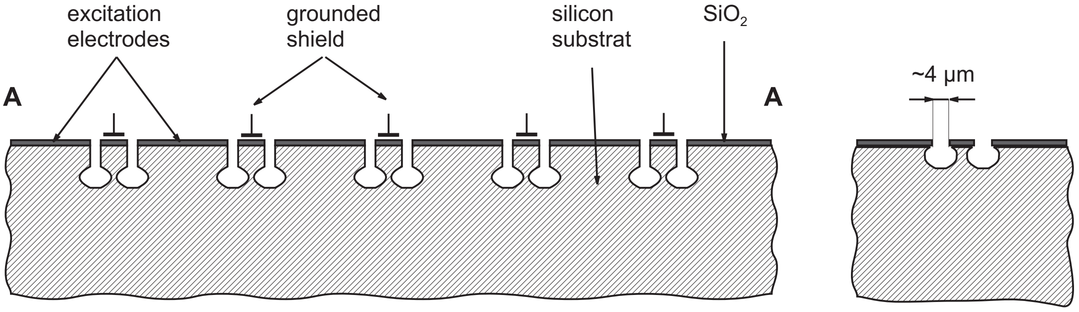

Figure 7: The proposed micromechanical realization derived from SCREAM technology with (left) and without depth dry etching (right)

4 APPLICATIONS FOR FLUID FLOW MEASUREMENT

4.1 Advantages of described transducers for “transit time difference“ method

Since the transducer array is able to pan the sound beam in arbitrary directions the described transducer array is very suitable for fluid flow measurement. Because of a justified pipe-mounting (Fig. 8 right) of the transducer array interfering vortices and the deposit of impurities or gases in ’normal-mount’ cavities (Fig. 8 left) disappear. Due to usage of short, steep ultrasonic pulses (Fig. 3 left) the precision can be improved and the death time can be shorten.

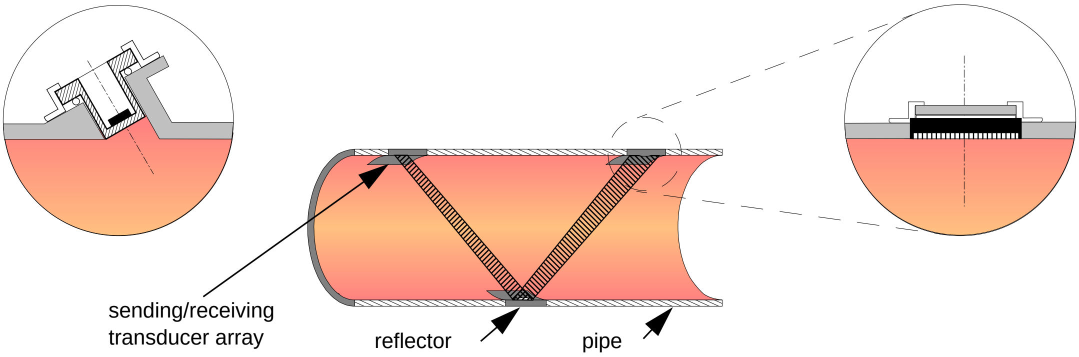

Figure 8: Pipe mounting for fluid flow measurement using conventional transducers (left) vs. micromechanical transducer arrays

4.2 The “beam deflection method“ for liquids

The principle to use the deflection of a sound beam to measure the fluid velocity is described in [6]. The disadvantages of this method are the low resolution, especially the small deflection for low fluid flow. So this principle is not popular. At present it is used only for gases [7], like in natural gas pipelines with large pipe diameters and very high fluid flow [8]. The less electronic requirements are advantageous, because there is no need to determine the signal transit time with a resolution of few picoseconds like in “transit time difference“ method.

The classical implemention works as follows (Fig. 9 left): A sender is driven in continous wave mode by a generator. The fluid influenced sound wave is received by two sensors. The two transducers receive the same amount of ultrasonic energy, if there is no fluid flow. A fluid flow generates a beam deflection proportional to the average fluid flow velocity. The receiver outlets are connected to a differential amplifier to determine the drift (Fig. 9 left).

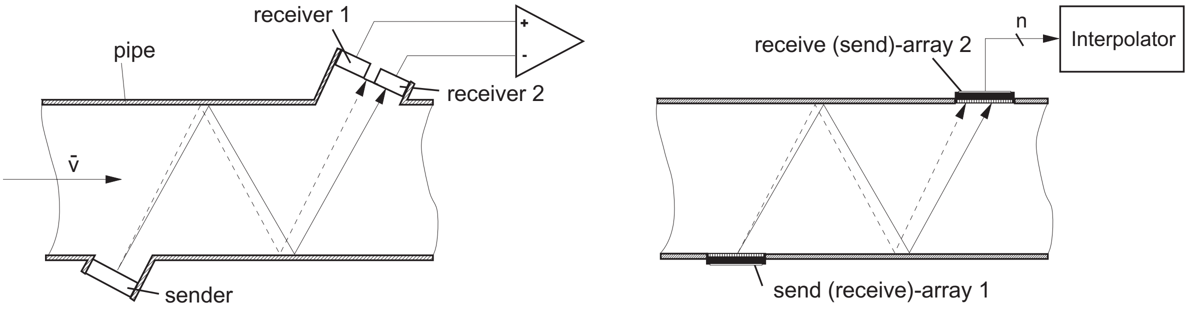

Figure 9: Beam deflection method: classical realization and a new implementation with MEMs for liquids.

Because of higher sound velocity in liquids the beam deflection is less, than is gases. Therefore, the micromechanical transducer array comes into operation. The new variant will not use 2 receivers and a differential amplifier but a special more element edition of the presented transducer array. The small element dimensions down to 20 µm and the amount of elements allow a much higher resolution, further improvable by signal processing interpolation (Fig. 9 right). An additional signal transit time acquisition and toggling the sending and receiving array enable the sound velocity elimination.

5 CONCLUSIONS AND OUTLOOK

A realized micromechanical ultrasonic tranducer array was presented. Acoustical and laseroptical measurements characterize the arrays and lead to a novel tranducer layout with improved sensor behaviour.

The ultrasonic tranducer arrays will be completed with sending and receiving electronics integrated into ASICs to form a complete fluid flow sensor device as *multi-chip-module* (MCM). The collaborative research center (“SFB 379“) in Chemnitz had developed ASICs containing the complete sender controller, high voltage sending amplifiers and receiver amplifiers. Additional signal processing functions will be integrated like time shifting and addition of the received ultrasonic pulses of every transducer element. This causes in a better signal-to-noise ratio without decreasing the measurement dynamic.

The new sensor layout shall demonstrate the advantages for a “transit time difference“ method realization and allow to use the „beam deflection“ method for liquids.

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REFERENCES

[1] Eccardt, P.C.; Niederer, K.; Fischer, B.; *Micromachined Transducers for Ultrasound Applications*; Proceedings of Ultrasonics Symposium, Toronto, vol.2, pp.1609-18 (1997)

[2] L. Thieme, W. Manthey, T. Neundorf; *Micromechanical ultrasonic sensor array with piezopolymer as active sensor material*; Micro Materials - Micro Mat 97; Berlin; 16.-18.4.1997

[3] L. Thieme, W. Manthey, H. Daßler*; Micromachined ultrasonic transducer array for applications in liquids*; MICRO SYSTEM Technologies 98; Potsdam; 1.-3.12.1998; VDE-Verlag Offenbach; ISBN 3-8007-2421-9

[4] H. Daßler, W. Manthey, L. Thieme; *Characterisation and optimization of micromachined ultrasonic transducer arrays using laseroptical investigations*; SENSOR 99; Nürnberg

[5] Shaw, K. A.; Zhang, Z. L.; MacDonald, N. C.; *SCREAM I: a single mask, single-crystal silicon, reactive ion etching process for microelectromechanical structures;* Sensors and Actuators A, 40 (1994), pp. 63-70

[6] Knapp, C.; *Geschwindigkeits- und Mengenmessung stroemender Fluessigkeiten mittels Ultraschalls*; Diss. ETH Zuerich (1958)

[7] VDI/VDE Richtlinie 2642, *Ultrasonic Flow-rate Measurement of Fluids in Pipes under Capacity Flow Conditions*; December 1996; Available from Beuth Verlag, 10772 Berlin, Germany

[8] Bonfig, K.W. (Hrsg.); *Sensoren und Mikroelektronik*; expert-verlag (1993); ISBN: 3-8169-1017-3

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