MEMS ultrasonic sensor array with thick film PZT transducers

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***Abstract*—Thick-film piezoelectric transducers have been produced and tested for implementation into a MEMS ultrasonic sensor array. The arrays are intended to be used for beam forming in sensing applications for fluidics in channels at millimeter or micrometer scale (e.g. flow rate measurement, detection of beads, bubbles). Stripe and matrix aligned elements have been fabricated for one-dimensional and two-dimensional beam steering, respectively. In this contribution we further concentrate on an improved Q-factor and PZT layer homogeneity as a major requirement for the transducer elements.**

Keywords—thick film, PZT, ultrasonic array, microfluidics, MEMS

I. INTRODUCTION

Currently, ultrasonic technology for microfludics that is based on the thickness mode is mainly used for fluid manipulating applications, e.g. particle sorting, mixing, cell disruption and deagglomeration [1][2][3]. To establishing ultrasonic in-situ analyzing methods for microfluidics (concentration and flow rate measurement, particle size distribution, sound attenuation measurement) new sensor devices have to become available. Many efforts have already been spent on micromachined ultrasonic transducers for in-air use such as ultrasonic imaging or object detection [4][5].

Ultrasonic transducer arrays employing capacitive actuators are available and have been intensively studied in the past [6]. For liquid analytes piezoelectric actuation provides better performance due to higher energy density. It is impossible to use traditional PZT ceramics to fabricate high frequency ultrasonic transducers, because such high frequencies require the thickness of the PZT ceramic plates to be as thin as 50 µm, which is difficult to machine due to its brittleness and poor mechanical strength [7]. Piezocomposite technology that has been mainly used for medical imaging can be impedance-matched to the analyte and driven with high excitation voltages. However, combination of piezocomposite and MEMS technology requires a separate mechanical processing. To our knowledge integration onto a MEMS substrate has not yet been developed.

Combination of PZT thick-film [8] and silicon technology provides both piezoelectric actuation with a piezoceramic layer and micro machining of coupling membranes.

Fluid chamber and channel were developed with the help of anodic bonding. For special applications a package is produced with MID (molded interconnect device) technology. The MID technology permits the production of not-planar chip assembly substrates. In order to contact the ultrasonic array electrically and mechanically flip-chip technology was used. This allows an integration of driver and amplifier electronics very close to the PZT elements and does not require an electrical impedance matching for a coaxial cable connection.

II. DESIGN AND FABRICATION

A. Sensor design

Fig. 1 shows the design of a 4x4 transducer matrix on top of a silicon membrane. With this sensor design the PZT transducers are operating as resonators in thickness mode – not as actuators to excite the eigenfrequencies of the silicon membrane. Therefore, it was mandatory to design the sensor

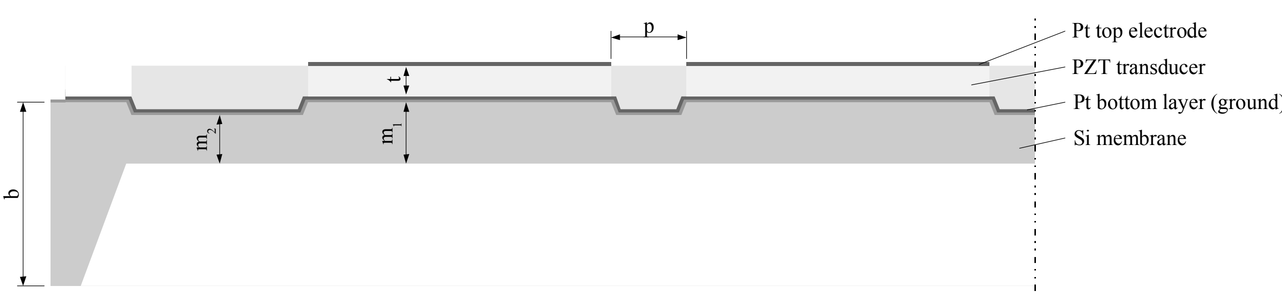

Figure 1. Schematic section thru a 4x4 transducer array on a silicon membrane (not to scale)

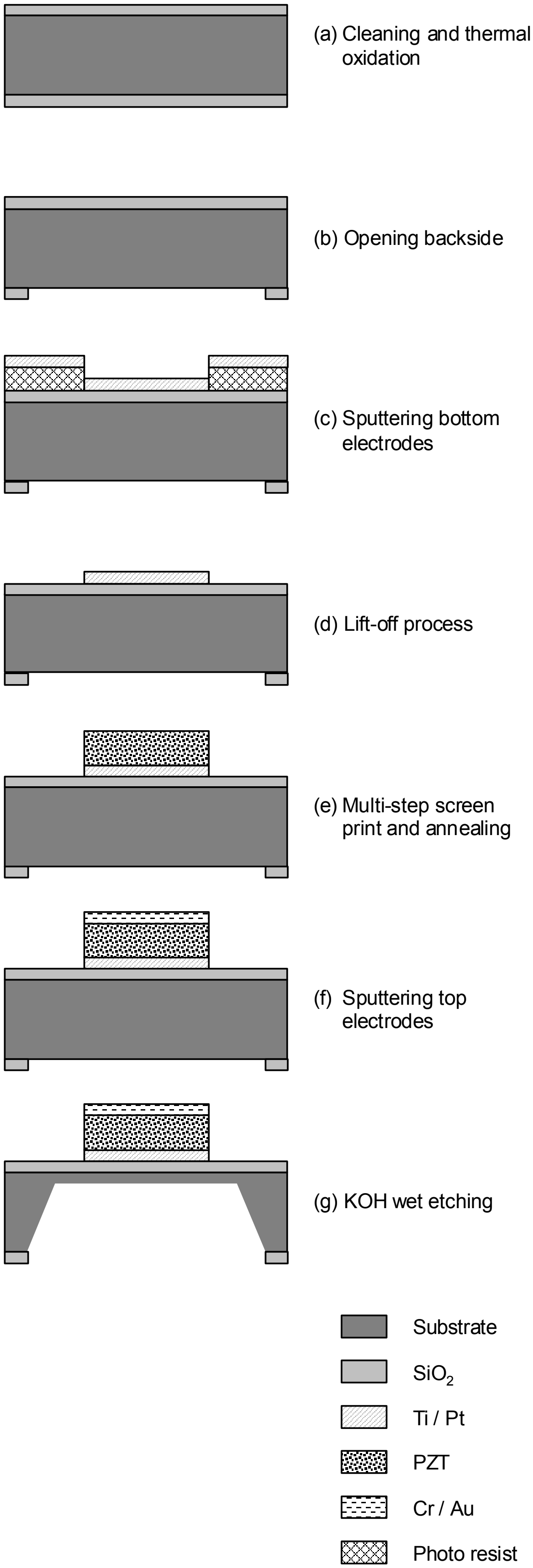

Figure 2. Schematic diagramm of the device fabrication process

and membrane geometry without having an overlap between PZT transducer and system resonance. Membrane shape and thickness have been optimized using ANSYS to analyze the system frequencies and to reduce the cross coupling between single elements while maintaining required stiffness for the fluid channel. First test samples were made with Ti / Pt bottom electrodes on the silicon test wafers and structured with a lift-off process. A multi-stage screen printing process allowed creating layers of PZT with variable thickness between 30 µm and 110 µm. The top electrodes have been formed by additional sputtering.

B. Device fabrication

The detailed fabrication process of the ultrasonic array is shown in Fig. 2. Before starting the fabrication process, the 4 inch silicon wafer was cleaned in acetone, isopropanol and Carot`s acid (H_2O_2 : H_2SO_4) and kept on a hotplate at 150°C for 20 minutes.

The first fabrication steps are: (a) thermal wet and dry oxidation on both sides until the thickness of silicon oxide layer reaches 500 nm and (b) backside etching of silicon oxide to open the etching window for the silicon diagram. Then the lift-off resist (TI35ES, Micro Chemicals) was deposited with spin coating, structured with UV light and developed. The bottom electrodes were deposited with sputter technology (c). For the connective layer titanium (100 nm) was sputtered at typical power level. The platinum layer (400 nm) was sputtered at a higher power level. The higher power led to a better adhesion of the platinum to the titanium layer. Then the sputtered layers were patterned with lift-off method (d) to form the bottom electrodes.

The PZT layers (e) were fabricated by screen printing. The printing paste was made by mixing 80% of PZT powder (APC Piezokeramica 856), with 20% of lead oxide (PbO) and adding a solution of 4% ethyl-cellulose as an organic binder and 96% terpineol as a solvent, the organic vehicle determines the flow properties of the paste and the bonding agent provides adhesion of the particles between each other and to the substrate [9][10][11]. A 325 mesh/inch steel screen was used. Multiple print/dry/fire cycles were performed on the piezo-layers to achieve different dry thicknesses. Peak firing temperatures of 950°C were adopted for the conductors and the PZT paste respectively. During the firing process the organic binder is burned, metallic particles are reduced or oxidized, and glass particles are sintered.

Chromium (30 nm) and gold (100 nm) thin films are deposited on the front side by sputtering and are patterned by lift-off method to form the top electrodes (f). For the first experiments a highly conductive bonding epoxy H20-E (Epoxy Technology) has been used to contact the top electrodes to the contact pads. Finally, (g) bulk silicon anisotropic wet etching with potassium hydroxide (KOH) is used to produce the thin membrane structure. The etching process was performed at a concentration of 30%-wt and a temperature of 80°C.

After these fabrication processes, piezoelectric activity was induced in the layers by applying a poling field of about 4 $MV \cdot m^{-1}$ for 30 min at 150°C and maintaining it during cooling back to room temperature [12].

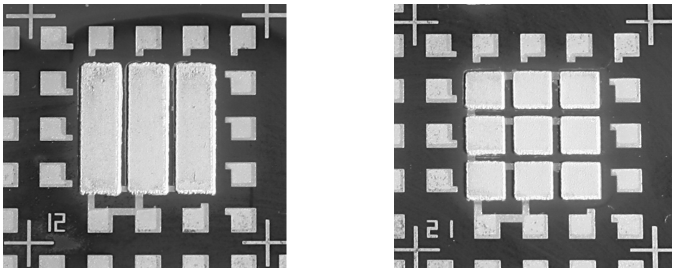

Figure 3. Fabricated ultrasonic test devices in (a) stripe and (b) matrix configuration

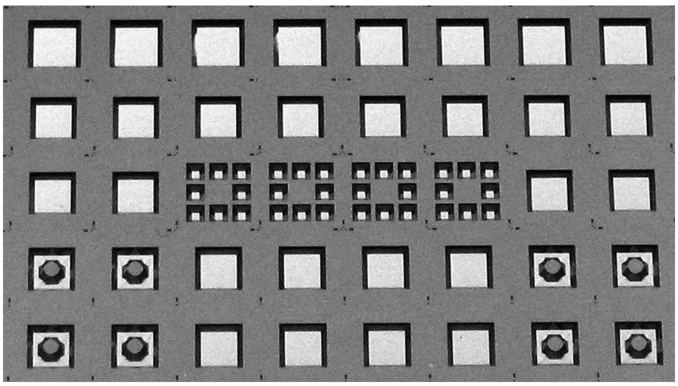

Figure 3. Backside containing membranes of different thickness

III. Experimental

For the screen printing process a multiplicity of forms and adjustment were tested to the scraper. In Fig. 3 different fabricated ultrasonic transducer forms (squares, stripes) are presented.

With the help of a white light profilometer (Fries Research & Technology) the height profile as well as the roughness of individual elements was examined. It could be stated that the height distribution remained in its tolerances over the entire wafer. However, the roughness increased with the elements becoming smaller. There were larger problems with decreasing of the pitch. With screen prints a pitch of 500 µm was reproducibly possible. In order to employ smaller pitches a laser machined stencil proceeded very well. Additionally, experiments have been performed to test the usability of photo resist as stencil that is spin coated on the wafer, filled with PZT paste and removed during the baking process.

For researching the influence of the membrane stiffness, a test bench of membranes was developed. Fig. 3 shows single membranes, membrane arrays and membranes with MESA structures.

A. Impedance spectrum analysis

An Agilent 4295A network / impedance spectrum analyzer was used to acquire the impedance spectra of resonator test elements. The system has been calibrated with a three-term calibration at the test tips. The measurements were performed to analyze the resonant frequency at different PZT layer thickness as well the matching between elements on the same wafer. Furthermore the quality factor of the fabricated PZT elements has been characterized.

Fig. 4 shows exemplarily the impedance plot for a single element (solid line). It has been processed with a six-stroke screen print. This results in a final layer thickness of 110 µm offering a series resonant frequency of f_s=4.9 MHz. The fabricated resonator offers a remarkably increased quality factor compared to a commercially available PZ35 piezo-ceramic (Ferroperm). Measurements between resonators on same wafers resulted in a tolerance for the series resonant frequency of less than 5%. This close tolerance is required for beam steering applications.

B. Modal analysis

For studying the vibration modes during excitation and decay phase a high resolution vibrometer SH-140 from Thomson has been used. The test structure has been mounted into a fixture and traversed using a piezo driven 3D-table to allow an area scan. The displacement equivalent output signal from the vibrometer was then sampled with a very high-speed 420 MSPS / 12 Bit DAC system from Acqiris to maintain an appropriate resolution in measurement of displacement and time. Excitation voltage of the single sine burst was 40 V peak-to-peak with a frequency of 5 MHz.

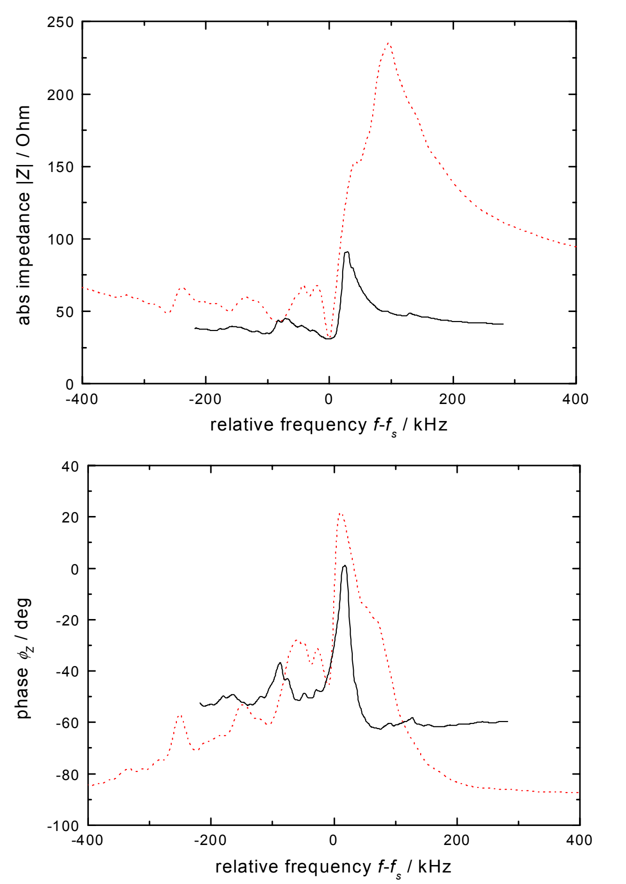

Figure 4. (a) impedance spectrum and (b) phase spectrum of the fabricated transducer (solid line, f_s=4.9 MHz) in comparison to a commercially available PZ35 piezoceramic (dotted line, f_s=2.45 MHz)

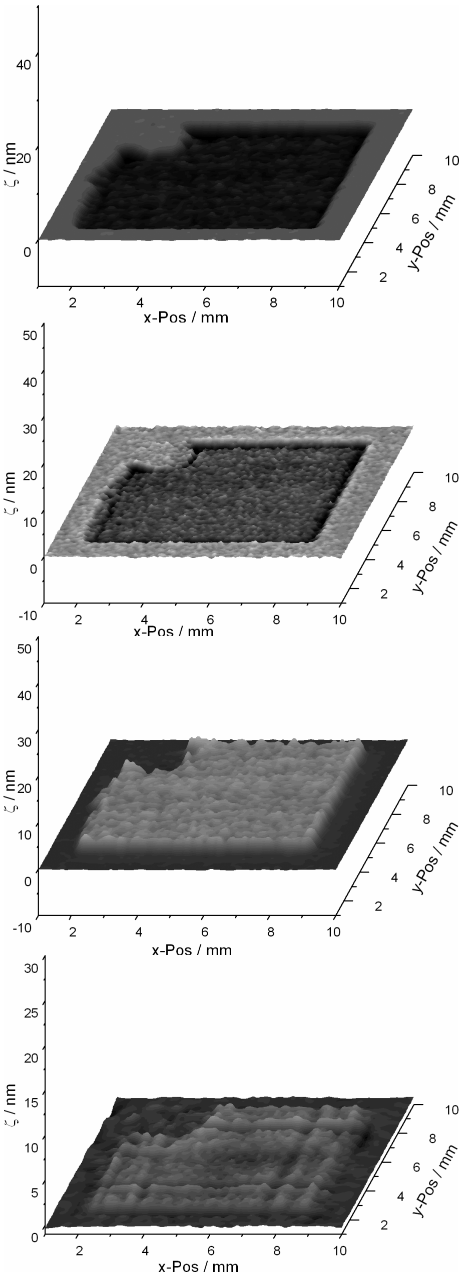

Figure 5. Vibrometer scans of resonator test structure (a) 245 ns, (b) 280 ns, (c) 360 ns, (d) 1200ns after excitation with a sine burst

Fig. 5 shows the vibrometer measurement results. The first area scan (a) during the negative part of the excitation burst shows a consistent displacement ς across the element's surface. This confirms the good homogeneity of the deposited PZT layer. At the zero crossing (b) the displacement is still well consistent. At the positive half wave (c) the edges already reveal the generation of the first radial wave. After four periods within the decay phase (d) the dominating radial wave with a wavelength of $\lambda\approx0.9$ mm can be observed very well. However, the area scans do not reveal a dominating bending wave that would degrade the emission behavior for the use in beam forming and beam steering applications.

IV. Conclusion

PZT thick-film ultrasonic test arrays have been fabricated using a combined MEMS and multi-stage screen printing process. Impedance and vibrometer measurements show the resonator elements offering a high quality factor and a good homogeneity in the deposited PZT layers. Various shape types and pitch dimensions have been patterned with the multi-stage screen printing process to test alignment and layer homogeneity capabilities of this method.

Subsequent objectives will include a vibrometer setup for characterizing shear modes occurring in the resonator elements and an inter-element cross-coupling analysis between adjacent resonators.

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