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Design and Fabrication of Aluminum Nitride Piezoelectric Micromachined Ultrasonic Transducers for Air Flow Measurements

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***Abstract* — Beam-drift based flow measurement technique requires frequency matched ultrasound transmitters and receivers for determining the flow rate. Aluminum nitride (AlN) piezoelectric micromachined ultrasonic transducers (PMUTs) suitable for such an application have been designed and fabricated. The bottom electrode is designed in such way that it reduces the stray capacitances, without degrading the piezoelectric properties of the AlN layer deposited on it. Frequency matching within a PMUT array and PMUTs fabricated across a wafer are challenging due to residual stress and membrane radius variations. A fabrication process to reduce the residual stress by optimizing the AlN layer deposition parameters, and membrane radius variations by optimizing Deep Reactive Ion Etching (DRIE) process, is developed in this work. The relative frequency variation (Δf*100/f) of the fabricated 7-element transmitter array is 0.5 %, and the variation between two receiver elements is 0.8%. Even though there is frequency variation across the wafer, PMUT transmitters and receivers within a reticle have matching frequencies and they can be utilized as transmitter-receiver pairs for flow measurement applications.**

Keywords—PMUT, Aluminum Nitride, Frequency variation, DRIE optimization.

I. Introduction

Beam-drift based ultrasound airflow measurement is used in air-conditioning, petrochemical, food and medical applications for determining the volume and mass flow rate [1]. The measurement is based on an ultrasound beam bending in the flow field. This method utilizes one ultrasound transmitter and two ultrasound receivers, to measure the airflow. The arrangement of the transmitter and receivers is shown in Figure 1. The transmitter generates ultrasound waves, which, after passing through the flowing gas, reach the receiver side. The flow rate can be measured from the phase difference between the two receiver outputs. When the gas is stationary ($v = 0$), the phase difference is zero. As the gas flows ($v > 0$), the measured phase difference deviates from zero and is approximately a linear function of the flow rate [1].

The advantage of this method is that the measured flow rate is an integral of the flow rate in the direction of the segment formed by the sensors and not just one streamline measured [2]. The sensors are located on the walls of the pipe and the measurement does not cause any disturbances or pressure drift in the flow. The size of the device can be scaled according to the wavelength and maximum flow rate to be measured, enabling the receiver pair integration to the same chip.

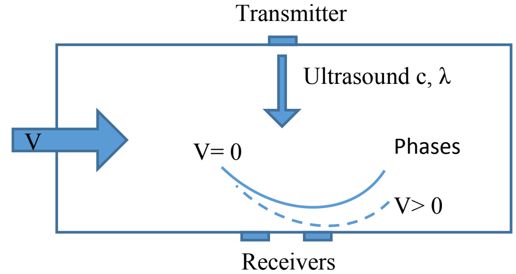

Figure 1. Beam-drift based ultrasound flow measurement.

The conventional beam-drift flow meters utilize piezoceramic ultrasound transducers and receivers. Even though, they offer good transmitting characteristics and high reliability, the large diameter of the ceramic transducers limits the minimum possible distances between two receivers. Furthermore, the temperature effects are also higher and the receiving sensitivity of ceramic transducers is limited because of higher input capacitance. Micromachined Ultrasonic Transducers (MUT) can overcome these disadvantages of ceramic-based transducers. As operating frequency range is less than 2 MHz, piezoelectric MUT (PMUT) transducers offer better performance than the capacitive MUTs (CMUTs) because of geometric flexibility and lower operating voltage [3].

This work describes the design, fabrication and characterization of PMUTs for beams-drift based ultrasound airflow measurement. To achieve good sensitivity, the transmitter and two receivers should have well-matching characteristics. Aluminum Nitride (AlN) is chosen as piezoelectric material. Compared to Lead zirconate titanate (PZT), AlN offers better receiving sensitivity, temperature stability and CMOS compatibility [4]. Piezoelectric coefficients of Scandium doped AlN (ScAlN) is better than AlN, however frequency matching is more challenging as the fabrication processes are still under development compared to the AlN.

II. PMUT Design and Simulation

The structure of the PMUT is shown in Figure 2. It consist of a circular membrane supported by a silicon structure. The membrane composed of an AlN passive layer, Titanium/Molybdenum (Ti/Mo) as bottom electrode, AlN as piezoelectric layer and Aluminum-Silicon (AlSi) as a top electrode. The passive layer is a structural layer, and the thickness of this layer should be equal or greater than the piezoelectric layer thickness to keeps the stress of the neutral plane outside the piezo layer. A thicker passive layer could move the neutral plane further way from the piezoelectric layer, however, it increases the membrane thickness which in turn reduces the receive sensitivity. The bottom electrode is patterned at the interconnect regions to reduce unwanted offset capacitance, resulting in improved receiver sensitivity. The top electrode covers about 70% of the membrane area.

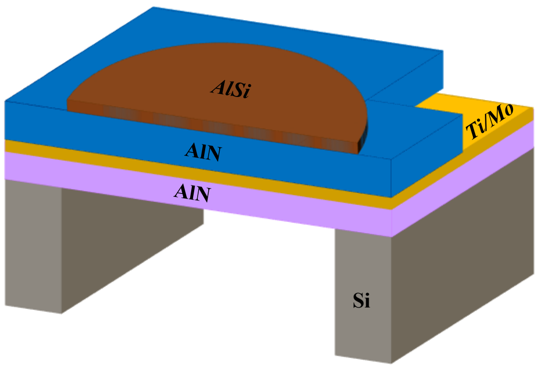

Figure 2. Cross-sectional view of a PMUT.

The performance of the proposed PMUT structure is studied using COMSOL Multiphysics. Details of device layer thicknesses, membrane radius and the top electrode radius to provide maximum transmit-receive sensitivities at 400 kHz are given in Table 1. The simulated output power from the PMUT excited with 1Vpp at different frequencies is shown in Figure 3. In order to utilize the PMUTs for the beam-drift flow measurements, the operating frequency of the transmitter and receiver should be within the bandwidth, which is 3.1 kHz from simulation results. The major factors that contribute to the frequency variation of PMUT within an array and across the wafers are membrane stress variations and residual stress variation. The effect of the residual stress and membrane radius on resonance frequency of the PMUT is studied and plotted in Figure 3. In order to limit the frequency variation within the bandwidth range, the radius variation need to be lower than 1-μm and stress variation should be less than 10 MPa. It is very challenging to have wafer level stress variation of a thin membrane (2.8 um) below 10 MPa. However, PMUTs in same wafer location have similar stress and have similar resonance frequencies. Therefore, the transmitter and receivers in same reticle have closer resonance frequency and can be used as pairs.

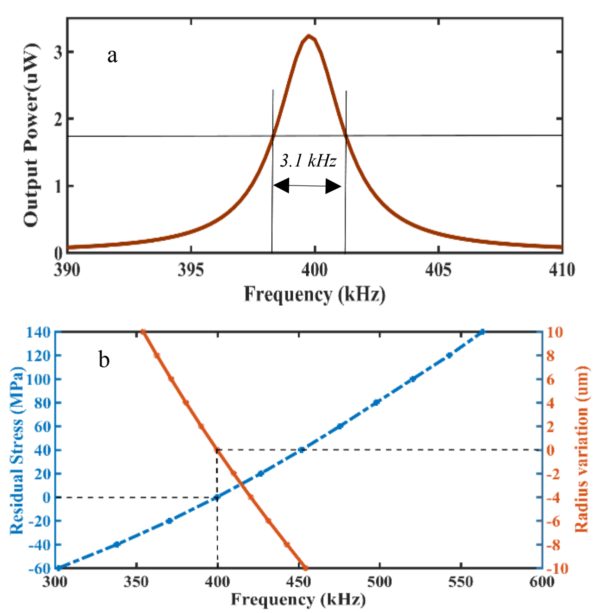

Figure 3. Simulation results (a) Acoustic output power, (b) Change in resonance frequency with residual stress and membrane radius variation.

Table 1. Device layer thickness, membrane radius and the top electrode radius to provide maximum transmit-receive sensitivity.

Parameter	Thickness (μm)
Passive layer thickness	1.2
Bottom electrode thickness	0.17
Piezo layer thickness	1
Top electrode thickness	0.50
Membrane radius	157
Top electrode radius	110

PMUT transmitter arrays are shown in Fig 6a and b. Figure 6a is a 19-element PMUT array with an inter-element distance of $\lambda/2$. Figure 6b is a 7-element array with an element distance of λ. The receiver array shown in Figure 6c consists of 8-linearly arranged elements and the distance between the elements is 1 mm.

III. PMUT FABRICATION

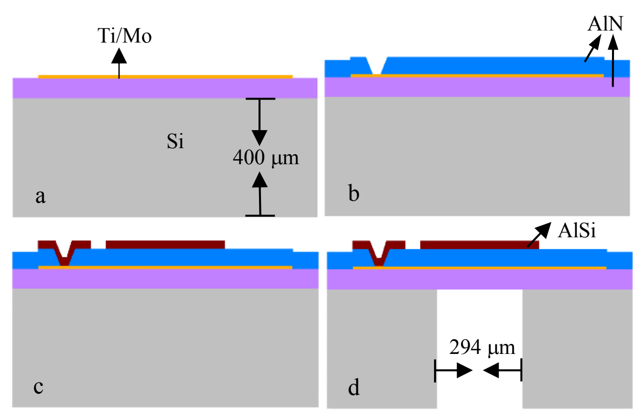

Figure 4. PMUT fabrication process flow: a) Sputter deposition of AlN Passive layer and Ti/Mo bottom electrode; pattering of the Ti/Mo bottom electrode, b) Piezo layer sputter deposition and contacts to the bottom electrode are opened in the piezo layer, c) AlSi top electrode deposition an patterning, d) Backside lithography and DRIE etch to release the membrane.

The PMUT is fabricated on a Silicon (Si) wafer using VTT's general piezo-MEMS platform processes developed over the last decade. Fabrication process flow is shown in Figure 4. The process begins with a sputter deposition of an AlN passive layer on a double-sided polished (DSP) Si wafer, followed by the deposition and patterning of the bottom electrode. Next, an AlN piezo active layer is deposited and contacts to the bottom electrode are opened in the piezo layer using a wet etch process. AlSi is then deposited as the top electrode and patterned. Finally, the PMUT membrane is released by patterning at the wafer backside and etching through the silicon using a deep reactive ion etch (DRIE) process, and stopping at the AlN passive layer.

The crystalline structure AlN piezo layer deposited on patterned Ti/Mo bottom electrode is studied using X-ray diffraction (XRD) techniques. Figure 5, shows the wafer-level rocking curve map of 1µm AlN (002 peak) deposited on patterned bottom electrodes. The full-width- half-maximum (FWHM) of the peak is ~1.5°, indicating that the AlN thin film has a good crystallinity even on patterned electrodes. Figure 6 shows optical micrographs of a fabricated 19-element, 7-element and a 8-element array on a 9 mm die/chip.

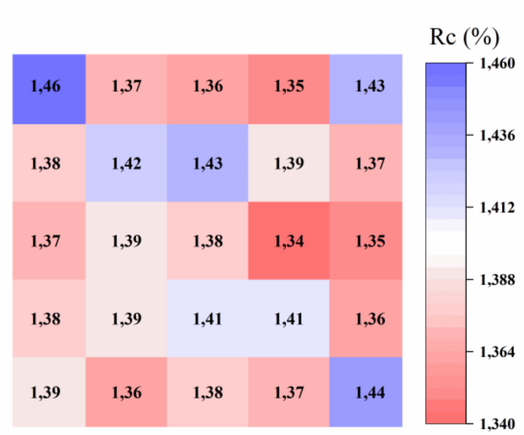

Figure 5. XRD measurement of AlN deposited on patterned Ti/Mo bottom electrode and rocking curve measurement of AlN (002) peak at several locations.

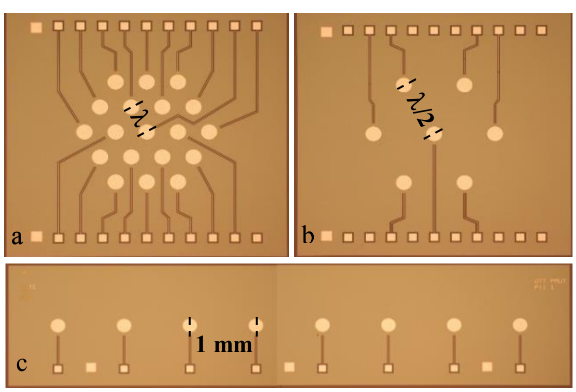

Figure 6. Optical image of a fabricated (a)19-element, (b)7-element and (c)8-element air-coupled PMUTs on a 9 mm chip.

A. PMUT Frequency Matching Challenges

As discussed in section II, factors that contribute to the frequency variation in these devices is the stress variation across the wafer of the sputter deposited films and the geometric variation in the released membranes diameter created by the backside DRIE etch process. It is desirable to have the frequency variation is within 3 kHz for flow measurement applications. A fabrication process is being developed and ongoing to reduce the residual stress and membrane radius variation during PMUT fabrication. PMUT's radius variations are controlled by optimizing Deep Reactive Ion Etching (DRIE) process, whereas the residual stress variation is reduced by optimizing the AlN, Ti/Mo, piezo layer and top electrode layer deposition parameters.

Cross-section scanning electron micrographs of DRIE etch released structures prior to etch optimization using commonly used etch recipes showed a 15 µm membrane diameter variation from center to edge of the wafer. In order to correct this, we developed and optimized DRIE etch process. Here, an AlN layer was sputter deposited on top side of the DSP Si wafers, followed by patterning the marks for backside alignment of DRIE etch holes as well as for measuring the cross-sectional (CD) diameter of the membrane. Next, the wafers are backside aligned, etched, and stopped at the AlN. The membrane diameter across the wafer was then measured using a CD measurement tool after several rounds of optimization of etch process parameters such as chamber pressure, platen power and gas flows, etc. The recipe leads to a uniform etch profile, which translates to less frequency variation across the die and the wafer. 80% of the device in a wafer showed DRIE etch dimensional variation of 2-3 µm. Figure 7, shows a cross-sectional membrane diameter map on a wafer after DRIE etch.

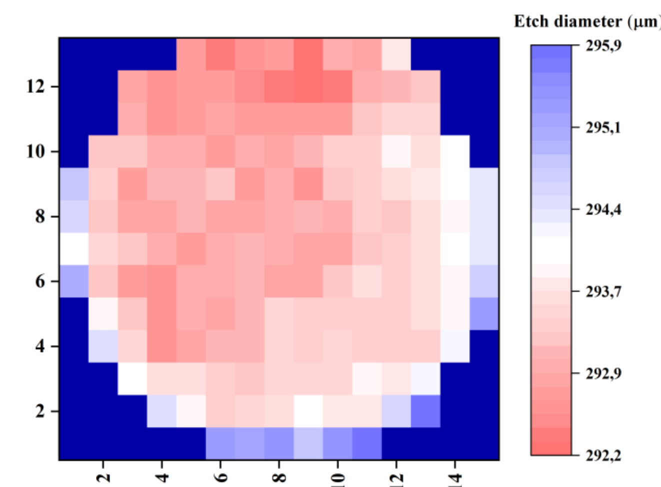

Figure 7. DRIE etch released membrane dimensional variation across a wafer.

IV. PMUT Measurements

The performances of the fabricated PMUTs are evaluated using electrical characterization. Impedance characteristics of the fabricated PMUTs are similar to the COMSOL simulated values. The patterning of the bottom electrode reduced the pad and interconnection capacitance by 40%. The phase characteristics of PMUT transmitters and receiver arrays are shown in Figure 8. The relative frequency variation ($\Delta f \times 100/f$) across 7-element array is 0.5 %. The 19-element array showed a relative variation of 1.5 %. The $\Delta f \times 100/f$ of the receiver array is 1.25%. However, for beam drift measurement, only two elements (first and last) will be used. The relative frequency variation between the two elements is 0.8 %. The transmitter and receiver elements showed good frequency matching. Relative variation of average frequencies of 7-element transmitter and receiver array is 0.4%. The average frequency of 19-element array is 1.5 % higher than the average receiver frequency. The higher frequency variation within the 19-element array and its higher average frequency than other elements might be due to the DRIE loading.

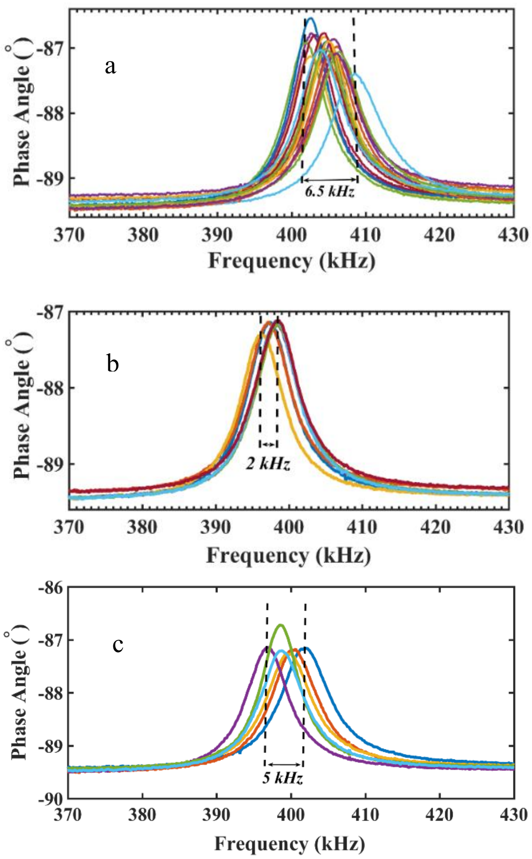

Figure 8: Frequency response of (a)19-element, (b)7-element and (c)8-element array.

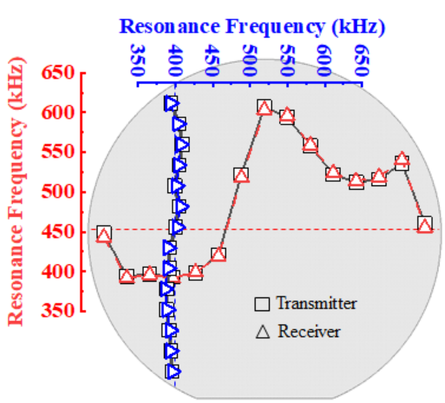

Figure 9: Horizontal and vertical frequency variation of transmitter and receiver PMUTs across the wafer.

The wafer level horizontal and vertical resonance frequencies of 9-element transmitter and receiver array is shown in Figure 9. The vertical wafer level variation is within the acceptable range and it is much smaller compared to horizontal variation. The horizontal variation could be due to the membrane stress variation across the wafer. From the measurement and simulation results, horizontal stress will be between -20 MPa and 150 MPa. The frequency variation is similar for transmitter and receiver. Hence, the transmitter and receiver in same reticle can be used as pair in flow measurement application.

V. CONCLUSION

AlN based air-coupled PMUTs suitable for flow measurement applications are designed. The layer thickness and membrane dimensions are optimized and the PMUT devices showed good receiver-transmitter performance. Simulation study of the PMUT structure showed that in order to fabricate frequency matched PMUTs, the wafer level radius variation should be less than 1 μm and membrane stress variation should be less than 10 MPa. The PMUT arrays are fabricated using simple and a low cost fabrication processes. By optimizing the DRIE parameters, wafer level radius variation is reduced to 1.85 μm. Fabricated PMUTs are electrically characterized. The patterning of the bottom electrode reduced the parasitic capacitance by 40%, without degrading the quality of piezoelectric layer. The measured relative frequency variation (**Δ** f*100/f) of 7-element transmitter array, 19-element transmitter array and 2-elements in the receiver array are 0.5%, 1.5% and 0.8%, respectively. There exists a large frequency variation across the wafer, which could be due to residual stress variation. However, the transmitters and receiver in a reticle showed matching frequency responses and they could be used as pairs for beam drift based flow measurement applications.

ACKNOWLEDGMENT

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