HIGH FREQUENCY AND HIGH FILL FACTOR PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCERS BASED ON CAVITY SOI WAFERS

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ABSTRACT

This paper presents a high frequency and high fill factor piezoelectric micromachined ultrasonic transducer (PMUT) array, which is fabricated with a simple and CMOS compatible process based on commercially available cavity SOI wafers. This 2-mask process eliminates the need for through-wafer etching and enables $10\times$ higher fill factor and thereby higher acoustic performance. PMUTs based on both lead zirconium titanate (PZT) and aluminum nitride (AlN) piezoelectric layers are designed, fabricated and characterized. For the same $50\text{ }\mu\text{m}$ diameter, PZT PMUTs show large dynamic displacement sensitivity of 316 nm/V at 11 MHz in air, which is $\sim 20\times$ higher than that of AlN PMUTs. Electrical impedance measurements of PZT PMUTs show high electromechanical coupling $k_t^2 = 12.5\%$, and $50\text{ }\Omega$ electrical impedance that is well-matched to circuits. The resonant frequency and static displacement of PMUTs with different diameters are measured and agree well with FEM results. The acoustic pressure generated by an unfocused 9×9 array of $40\text{ }\mu\text{m}$ diameter PZT PMUTs was measured with a needle hydrophone, showing a pressure sensitivity of 2 kPa/V .

INTRODUCTION

Ultrasonic transducers have been used in many applications, such as nondestructive testing (NDT), ranging and velocity sensing, industrial automation, object recognition, collision avoidance, and particularly medical imaging [1-2]. Conventional ultrasonic transducers are largely based on bulk piezoelectric ceramic that has poor acoustic coupling to air or water, and is also expensive to machine into two-dimensional (2D) transducer arrays needed for 3D imaging [3]. In contrast, micromachined ultrasonic transducers (MUTs) have a compliant membrane structure with low acoustic impedance for good coupling to air and liquids. Furthermore, MUTs have several other advantages over conventional ultrasonic transducers, including small element size, low power consumption, improved bandwidth, low cost, easy fabrication of large arrays with compact designs, and easy integration with supporting electronics [4-5].

MUTs can be divided into two types based on the actuation mechanism: capacitive MUT (CMUT) and piezoelectric MUT (PMUT). To achieve the same sensitivity as that of a PMUT, a CMUT needs either a very small gap, increasing fabrication complexity and cost, or a high DC bias [6]. Previous PMUTs were fabricated by a through-wafer etching approach to produce $400\text{ }\mu\text{m}$ diameter PMUT operating in air [7-8]. However, MHz-range PMUTs are an order of magnitude smaller, and through-wafer etching results in a low fill-factor, small element count, and therefore poor acoustic efficiency [9]. Front side etching can also be used to make a high fill factor array, but it results in a more complicated fabrication process and requires an additional layer to seal the etching holes, which reduces fluid-immersed PMUT performance [6]. Here, we present a PMUT array with a simple process based on cavity SOI wafers. This 2-mask process eliminates the need for through-wafer etching [9] and enables $10\times$ higher fill factor, which is important for minimizing grating lobes of the acoustic beam and obtaining a high array gain and coupling ratio.

DESIGN

A 3D schematic diagram of a PMUT array based on cavity SOI wafers and the cross section of a single PMUT are shown in Figure 1. In the 72×9 array, the top electrodes of the 9 PMUTs in each column are connected together to minimize the number of electrical connections to the die. Each PMUT functions as both a transmitter and receiver. As a transmitter, the electric field between the top electrode (TE) and the bottom electrode (BE) creates a transverse stress in the piezoelectric layer due to the inverse piezoelectric effect. The generated stress causes a bending moment which forces the membrane to deflect out of plane, launching an acoustic pressure wave into the environment. As a receiver, an incident pressure wave deflecting the plate creates transverse stress which results in a charge between the electrodes due to direct piezoelectric effect.

The PMUTs demonstrated here are fabricated using cavity SOI wafers with a $2.5\text{ }\mu\text{m}$ device Si layer over $2\text{ }\mu\text{m}$ deep vacuum-sealed cavities of various diameters. Devices were fabricated using both lead zirconium titanate (PZT) and aluminum nitride (AlN) piezoelectric layers to allow the performance of these two types of PMUTs to be compared. Both analytical methods and finite element method (FEM) simulations were used to determine the best piezo/silicon layer stack to optimize receiving performance. The optimal designs for PZT and AlN PMUTs are $1.1\text{ }\mu\text{m}$ PZT/ $2.5\text{ }\mu\text{m}$ Si and $0.8\text{ }\mu\text{m}$ AlN/ $2.5\text{ }\mu\text{m}$ Si, respectively. These layers are sufficiently thin that they allow the PMUT diameter to be smaller than half the acoustic wavelength ($\lambda/2$), which minimizes grating lobes and enables efficient beam forming. In addition, the top electrode area is optimized at half the membrane area to maximize electromechanical coupling.

Figure 1: (a) 3D schematic diagram of a PMUT array based on cavity SOI wafers; (b) cross section of a single PMUT.

Figure 2: Fabrication process flow of PMUT array.

FABRICATION

PMUT arrays were fabricated via a simple 2-mask process. A cross-section of the fabrication process flow is shown in Figure 2. The process is based on custom-fabricated cavity SOI wafers (IceMos Technology, Belfast, Ireland), as shown in step (a). The cavity SOI wafers are prepared by wafer bonding in vacuum, resulting in a vacuum-sealed cavity beneath the PMUT and eliminating the possibility of squeeze-film damping beneath the PMUT membrane. The bottom electrode metal and piezoelectric layer are then deposited via sputtering. In AlN PMUTs, sputtering is conducted at $<400^\circ\text{C}$ and begins with a 25 nm AlN seed layer, followed by a 100 nm Mo layer and the 800 nm AlN layer. The PZT sputtering process is conducted at 600°C and a 20 nm conductive oxide layer SrRuO_3 (SRO) is sputtered between the PZT layer and the 100 nm Pt bottom electrode to improve the lifetime by reducing oxygen defects accumulating at the Pt/PZT interface when the polarization is switched. After sputtering, the first mask is used to define vias to the bottom electrode through wet etching, step (b), with $\text{HNO}_3/\text{BHF}/\text{H}_2\text{O}$ in a volumetric ratio of 4.5/4.55/90.95 at room temperature used to etch PZT [10], and TMAH-based developer (MF-319) at 60°C used to etch AlN. In the final step, step (c), the second mask is used to define the top electrode through lift-off of 150 nm of Al deposited by sputtering. Devices were fabricated with diameters range from $25\ \mu\text{m}$ to $50\ \mu\text{m}$, corresponding to theoretical fundamental mode frequency range from 13 MHz to 55 MHz. The minimum pitch used was $45\ \mu\text{m}$, which is composed of $25\ \mu\text{m}$ PMUT diameter and $20\ \mu\text{m}$ space between adjacent PMUTs. Figure 3 shows a top view optical image

Figure 3: Optical image of 72×9 PMUT array.

Figure 4: SEM cross section images of a $50\ \mu\text{m}$ AlN PMUT showing the vacuum cavity beneath the device layer Si.

of a 72×9 PMUT array with $70\ \mu\text{m}$ pitch and $50\ \mu\text{m}$ PMUT diameter, which has a fill-factor 40%. Scanning electron microscope (SEM) images of the cross section of a single PMUT are shown in Figure 4.

CHARACTERIZATION

Frequency responses of displacement sensitivities for PZT and AlN PMUTs measured via laser doppler vibrometry (LDV) in air are shown in Figure 5. The PZT PMUT shows a large dynamic displacement sensitivity $316\ \text{nm/V}$, $\sim 20\times$ higher than that of AlN PMUTs for the same $50\ \mu\text{m}$ diameter. Because the quality factor (Q) is limited by anchor loss, measurements conducted in air and in vacuum show the same Q . While Q diminishes with diameter, as expected, no significant difference was observed between the Q of AlN and PZT devices, confirming that material dissipation losses are negligible in comparison to the anchor loss.

FEM and measured results of the center frequencies in air for both PZT and AlN PMUTs with various diameters are shown in Figure 6 (a). The measurement results agree well with FEM results, indicating the FEM model can be used to efficiently guide PMUT design. The theoretical frequency of the PMUT's fundamental

Figure 5: Frequency response of displacement sensitivity in air: PZT PMUTs ($1.1\ \mu\text{m}$ PZT/ $2.5\ \mu\text{m}$ Si) vs. AlN PMUTs ($0.8\ \mu\text{m}$ AlN/ $2.5\ \mu\text{m}$ Si).

Figure 6: Measured and FEM (a) resonant frequency and (b) static displacement of PZT and AlN PMUTs in air versus radius.

vibration mode in air can be obtained from:

$$f_n = \sqrt{(3.2/a)^4 \frac{D}{\rho}} / 2\pi \quad (1)$$

where a is the radius, ρ is area mass density and D is the flexural rigidity of the plate. D can be obtained by integrating from the bottom surface of the Si device layer to the top electrode:

$$D = \int_{Bottom}^{Top} \frac{E(z)z^2}{1-\nu(z)} dz \quad (2)$$

where $E(z)$ is Young's Modulus and $\nu(z)$ is Poisson's ratio of the material at a distance z from the neutral axis. Referring to (1), because PZT has a smaller Young's modulus ($E_{PZT} = 76$ GPa, $E_{AlN} = 330$ GPa) and larger density ($\rho_{PZT} = 7.7$ g/cm³, $\rho_{AlN} = 3.2$ g/cm³) than that of AlN, PZT PMUTs show a ~40% lower resonant frequency than that of AlN PMUTs of the same diameter.

Figure 6 (b) shows FEM simulation and measured results of static displacement in air for both PZT and AlN PMUTs with various diameters. The displacement sensitivity (nm/V) scales approximately as f_n^{-2} . The static displacement per unit volt is an important metric to characterize PMUTs, and can predict the pressure per volt when the PMUT is immersed in fluid, because the large damping in the fluid results in low Q (≈ 1). The PMUT static displacement sensitivity, d_s , can be expressed as:

$$d_s \propto \frac{e_{31}Z_n}{D} \quad (3)$$

where e_{31} is the piezoelectric coefficient, and Z_n is the distance from the middle of the piezoelectric layer to the neutral axis. For the same diameter, 50 μm, the PZT PMUT shows a ~28× higher static displacement than that of the AlN PMUT, which indicates a higher transmitting efficiency and pressure sensitivity when immersed in

fluid. Referring to (3), the difference in d_s is due to the lower rigidity D , the greater distance from the piezo layer to the neutral axis Z_n , and the 16× higher piezoelectric coefficient ($e_{31} = -8$ pC/m² for PZT vs. -0.5 pC/m² for AlN) of the PZT PMUT.

Impedance measurements of single PZT and AlN PMUTs with 50 μm diameter are shown in Figure 7 (a) and (b), respectively. The resonant frequencies extracted from the impedance measurement agree well with the values extracted from LDV measurements. The electromechanical coupling coefficient, k_t^2 , can be extracted from these impedance measurements using:

$$k_t^2 = \frac{f_a^2 - f_r^2}{f_a^2} = \frac{C_{MEMS}}{C_0 + C_{MEMS}} \quad (4)$$

where f_a and f_r are the anti-resonant frequency and resonant frequency, respectively, and C_{MEMS} and C_0 are the motional capacitance and the electrical capacitance, respectively. From impedance measurements, the dielectric constants of the PZT and AlN films are extracted to be $\epsilon_{33,PZT} = 528$ and $\epsilon_{33,AlN} = 9$, respectively. After calibration to remove the parasitic capacitance C_p (74 pF) caused by pad and interconnect, the PZT PMUT shows $k_t^2 = 12.5\%$ ($C_{MEMS} = 0.6$ pF and $C_0 = 4.17$ pF). In addition, the PZT PMUT has 50 Ω impedance, which is matched to the impedance of conventional remote readout electronics and coaxial cables. However, PZT's high dielectric constant results in large parasitic C_p . C_p can be reduced by removing PZT from beneath the interconnect and bond pads, by adding an additional dielectric layer, or both.

Figure 8 shows acoustic pressure measurements conducted on a 9×9 array of 40 μm PZT PMUTs using a needle hydrophone with 40 μm probe (Precision Acoustics) in fluid. Fluorinert-70 is used for

Figure 7: Impedance measurement of a single 50 μm PMUT with (a) PZT and (b) AlN piezoelectric layers.

Figure 8: Acoustic pressure output from a 9×9 PMUT array: a) time domain b) FFT of received pulse.

the fluid immersed measurement, because it has acoustic impedance similar to that of human tissue and high electrical resistivity which eliminates the need for epoxy protection of the bondwires. Four cycles of 25 V_{pp} short-duration (0.4 μs) pulses were used to drive the PMUT array. PMUTs are driven individual phase control, resulting in an unfocused acoustic beam. The 1.5 μs time delay between the driving signal and the received pressure signal, shown in Figure 8 (a), is consistent with the 1.25 mm distance between the needle hydrophone and the PMUT array. In addition, the measurements show a high pressure response, 2 kPa/V, from the unfocused array. As shown in Figure 8 (b), the fast Fourier transform (FFT) of the received pressure signal shows a 3.4 MHz bandwidth at 10.4 MHz center frequency, sufficient for medical imaging. The measured pressure is in good agreement with the measured displacement, and can be further increased using beam forming to focus the acoustic beam.

CONCLUSION

This paper presents high frequency (10 - 55 MHz), fine pitch (45 - 70 μm) PMUT arrays, which are fabricated with a simple 2-mask process based on commercially available cavity SOI wafers. This process eliminates the need for through-wafer etching and enables 10× higher fill factor and thereby higher acoustic performance. PMUTs based on both PZT and AlN piezoelectric layers are designed with 1.1 μm PZT/ 2.5 μm Si and 0.8 μm AlN/ 2.5 μm Si layer stacks. Measurement results for PZT PMUTs with 50 μm diameter show a large dynamic displacement sensitivity of 316 nm/V at 11 MHz, a high electromechanical coupling coefficient $k_t^2 = 12.5\%$, and 50 Ω electrical impedance that is well-matched to circuits. 50 μm diameter PZT PMUTs have 2.75 nm/V static displacement sensitivity, ~28× higher than that of AlN PMUTs of the same diameter, because PZT has a larger piezoelectric

coefficient e_{31} , smaller Young's modulus E and higher density ρ than that of AlN. Acoustic pressure generated by an unfocused 9×9 array of 40 μm diameter PZT PMUTs was measured with a needle hydrophone. The measurement results show pressure sensitivity of 2 kPa/V at 1.25 mm away from the array, and a 3.4 MHz bandwidth at 10.4 MHz center frequency, sufficient for medical imaging.

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