SHORT-RANGE AND HIGH-RESOLUTION ULTRASOUND IMAGING USING AN 8 MHZ ALUMINUM NITRIDE PMUT ARRAY

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ABSTRACT

Ultrasound imaging uses costly bulk piezoelectric transducers and high voltage (200V+) electronics. Low-cost and low-voltage ultrasound transducers would enable many new applications in healthcare, biometrics, and personal health-monitoring. Here, we demonstrated short-range (~mm) and high-resolution (<100 µm) imaging based on piezoelectric micromachined ultrasonic transducers (PMUTs) and a 1.8 V interface ASIC. The PMUTs use piezoelectric Aluminum Nitride (AlN), which has the advantages of low-temperature (<400 °C) deposition and compatibility with CMOS fabrication but has a relatively low piezoelectric constant ($\varepsilon_{31}=-0.5$ C/m$^2$), making detection of ultrasound signals from tiny (50 µm) PMUTs a challenging task. To solve this problem, we developed an ASIC with a low-noise analog front-end pre-amplifier that is impedance matched to the PMUT. Furthermore, a novel beam-forming and scanning method was demonstrated to achieve a sub-100µm focus size and 70 µm scanning step. Pressure map measurement from phased PMUT array and pulse echo imaging results were demonstrated using 1-D and 2-D phantoms.

INTRODUCTION

Ultrasonic transducers have been used in many applications and famous for nondestructive testing (NDT) and medical imaging. Conventional ultrasonic transducers are largely based on bulk piezoelectric ceramic with poor acoustic coupling to air or liquids, and additional matching layer is required. In contrast, micromachined ultrasonic transducers (MUTs) have a compliant membrane structure with low acoustic impedance for good coupling to air and liquids. Compared with well-developed capacitive MUTs (CMUTs), PMUTs [1] do not require a high polarization voltage and small gap [2], and thereby reduce circuit and fabrication complexity.

Previous research on PMUT pulse-echo imaging was based on lead zirconium titanate (PZT) [3-4], a material with high piezoelectric coefficients and high relative permittivity, which make the receiving amplifier easier to design and remote electronics feasible. Relative to PZT, AlN is lead-free and is compatible with CMOS fabrication, making it attractive for highly integrated, low-cost PMUT arrays. However, AlN has lower piezoelectric coefficients and low relative permittivity, which result in PMUTs with lower pressure sensitivity in transmitting and lower charge output in receiving. Therefore AlN PMUTs make ultrasound pulse-echo detection more challenging and require a low-noise and impedance-matched local pre-amplifier.

In addition, high fill-factor PMUT arrays are needed to minimize grating lobes and increase acoustic efficiency per unit area. However, reported PMUTs have large dimensions and pitch and therefore low fill-factor; this results from fabrication using through-wafer etching [5]. Front-side etching using a sacrificial layer and etch holes has been used to make a high fill-factor PMUT array, demonstrated in MEMS-2014 [6], but required a complicated multi-layer fabrication process and an additional layer to seal the etch holes after the release etch. PMUTs based on cavity SOI wafers have the advantages of a simple fabrication process and a high fill-factor, with device characterization first demonstrated in Hilton-Head-2014 [7], and integrated circuit details and tissue-phantom imaging demonstration to appear [8]. Here, we show for the first time short-range and high-resolution imaging using fluid-immersed AlN PMUTs.

DESIGN

A focused, narrow acoustic beam is essential for high resolution, pulse-echo ultrasound imaging. When using a single ultrasound transducer, two methods can be used to obtain a narrow acoustic beam: higher working frequency and larger PMUT dimensions [9]. Calculated acoustic beam patterns at a distance 1.5 mm from a single 50 µm diameter PMUT with various working frequencies are shown in Figure 1. The results show that ~400 MHz working frequency is required to achieve sub-100 µm beam-width. Achieving such a high frequency requires a PMUT working in thickness mode rather than flexural mode, resulting in poor acoustic impedance matching to fluid and tissue. In addition, higher working frequency will result in much greater acoustic attenuation in these media.

![Figure 1: Calculated beam patterns at 1.5 mm away from a single PMUT. A 100 µm -6dB beam-width occurs at 400 MHz.](image-url)
Here, rather than using a single high-frequency transducer, we use an 8 MHz phased array to achieve narrow acoustic beam-width. Optical images of the 72×9 PMUT array are shown in Figure 2. The array, composed of 50 µm diameter PMUTs with 70 µm pitch, was fabricated using cavity SOI wafers [7]. The 9 PMUTs in each column are connected together. Phased-array beam-forming is conducted using groups of transducers that are fewer than the whole 72-column array. Figure 3 shows calculated acoustic beam patterns for a 15-column group with various beam-forming pitches. The array’s acoustic beam-width at 1.5 mm away from the array narrows with increasing PMUT pitch (70 µm, 140 µm, 210 µm) because the aperture of the array is increased. Conversely, a small pixel is required for high resolution ultrasonic imaging, and achieving high fill-factor requires minimizing the PMUT pitch. To satisfy both of these objectives, a novel beam-forming and scanning method was developed, as shown in Figure 4. High fill-factor is achieved through a small 70 µm PMUT pitch, and a narrow beam-width is achieved by using a beam-forming pitch that is an integer multiple of the PMUT pitch, thereby achieving a larger aperture from a small group of PMUTs. The focused beam can be scanned by sequentially switching between groups with a small step size that is defined by the PMUT pitch. As illustrated in Figure 4, the phase delays within a group are symmetric; this allows an N-channel amplifier to drive a group containing 2N-1 columns of PMUTs. In experiments, amplifiers with \(N = 7\) and \(N = 8\) channels were used, corresponding to 13-column and 15-column PMUT groups.

**EXPERIMENT RESULTS**

Ultrasound experiments were conducted with the array immersed in a fluid (Fluorinert FC-70, 3M) that has similar acoustic impedance with that of human tissue (\(Z \approx 1.5\) MRayls) and high electrical resistance to eliminate the need to insulate the wire-bonds and pads. A needle hydrophone with 40 µm effective diameter (Precision Acoustics) was used to measure the acoustic pressure.
from a 15-column group of PMUTs driven with 2-cycles of 8-MHz 18 V pp pulses. Shown in Figure 5, the measurement results demonstrate that beam-forming increases the pressure amplitude to 80 kPa peak-to-peak, ~2.5× the pressure produced from the same PMUT group without beam-forming (all PMUTs driven with the same phase delay). Furthermore, beam-forming results in a short acoustic pulse, <0.5 µs, corresponding to ~200 µm axial pulse-echo imaging resolution.

The acoustic pressure patterns of a 15-column group with 70 µm and 140 µm beam-forming pitch were measured using the needle hydrophone, as shown in Figure 6. The beam-forming phase increments were selected to focus the beam 1.5 mm away from the array. In agreement with simulation results shown in Figure 3, larger beam-forming pitch, 140 µm, results in reduced peak pressure from 80 kPa to 70 kPa, but narrower beam-width, from 200 µm to 90 µm diameter. Using 140 µm beam-forming pitch, the 2-D acoustic pressure field measured in the x-z plane (x is the lateral dimension and z

Figure 6: 8 MHz transmit pressure measured using a hydrophone laterally scanned at a distance 1.5 mm from the array surface.

Figure 7: 8 MHz transmit pressure measured using a hydrophone; 2-D acoustic pressure pattern in x-z plane (PMUT array in x-y plane).

Figure 8: System diagram of pulse-echo imaging using AlN cavity SOI PMUT array and 1.8V 180 nm CMOS ASIC interface [8]. Pulse-echo imaging was conducted using a custom 1.8V 7-channel interface ASIC [8]. Figure 8 shows the system diagram. Because the capacitance of the 9 AlN PMUTs in each column is low (~pF, including bond pads), a low-power on-chip 32V charge pump is capable of providing sufficient output current to drive a 15-
ultrasound images. Because the ASIC is close to the PMUT array, rather than remotely connected through cables, parasitic capacitance is reduced, resulting in higher signal-to-noise ratio. Additionally, the fact that AlN has low dielectric constant means that lower input currents are needed to drive the array, and a 1.8V to 32V on-chip charge-pump provided sufficient power for this purpose.

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REFERENCES

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