Abstract—This work demonstrates short-range and high-resolution ultrasound imaging using 8 MHz aluminum nitride (AlN) piezoelectric micromachined ultrasonic transducer (PMUT) arrays, which are compatible with complementary metal-oxide semiconductor circuitry and wafer-level mass manufacture. Because AlN has a low dielectric constant, the PMUTs have low capacitance and a custom 1.8 V interface application-specified integrated circuit with on-chip charge-pump (1.8 to 32 V) is capable of providing sufficient output current to drive the PMUT array. Transmit beam-forming is used to produce a 90 µm focused acoustic beam-width. A pressure map measured with a needle hydrophone agrees with finite element method-simulations. Finally, 1-D and 2-D pulse-echo imaging was conducted using metal targets.

Index Terms—Piezoelectric micromachined ultrasonic transducer (PMUT), piezoelectric, micromachined, ultrasonic, ultrasound, cavity silicon-on-insulator (SOI), phased array, beam forming.

I. INTRODUCTION

ULTRASOUND transducers have been used in many applications, such as nondestructive testing (NDT), object recognition, and medical imaging. Compared with conventional ultrasonic transducers, micromachined ultrasonic transducers (MUTs) with a compliant membrane structure [1], [2] have been reported as a promising solution for pulse-echo ultrasonic imaging [3], [4] due to their good acoustic impedance matching [5], [6], broad bandwidth [7], [8], low-cost array fabrication and ease of integration with supporting electronics [9], [10]. Capacitive MUTs (CMUTs) [2] have been developed for decades and demonstrated for 2-D array and 3-D pulse-echo imaging [11]–[13]. Compared with CMUTs, piezoelectric MUTs (PMUTs) [14] do not require a high polarization voltage or small gap [5] to achieve the required transducer sensitivity. Previous research on pulse-echo imaging used PMUTs based on lead zirconium titanate (PZT) [7], [15], a material with high piezoelectric coefficients and high relative permittivity [16], translating into higher sense capacitance and consequent reduced sensitivity to interface parasitics. Relative to PZT, Aluminum Nitride (AlN) is lead-free, can be deposited at low-temperatures (<400 °C), and is compatible with complementary metal-oxide semiconductor (CMOS) fabrication [17], [18], which makes it attractive for highly integrated, low-cost PMUT arrays. However, AlN has lower piezoelectric coefficients and low relative permittivity, which results in PMUTs with lower transmit pressure output and reduced receiver charge sensitivity. Therefore AlN PMUTs make ultrasound pulse-echo detection more challenging and require a low-noise and impedance-matched local pre-amplifier. However, an advantage of AlN’s low relative permittivity (∼100× smaller than PZT) is that ∼100× less current is needed for the transmit amplifier, which enables a low-voltage 1.8V interface ASIC with an on-chip 32V charge-pump to drive an array of AlN PMUTs [19]. Such low-voltage ultrasound imaging sensors will enable many new applications [20] in healthcare and biometrics, which require surface or short-range imaging.

For high-resolution and short-range ultrasonic pulse-echo imaging, a high fill-factor MUT array is required to have a narrow acoustic beam without near-field effects in the working range (see detailed discussion in Section II). Furthermore, a small pitch and high fill-factor are desirable to minimize grating lobes and increase the acoustic efficiency per unit area [10], [21]. However, previously-reported PMUTs have large dimensions and pitch and therefore low fill-factor; this results from fabrication using through-wafer etching [15], [22], [23]. PMUTs based on cavity silicon-on-insulator (SOI) wafers have the advantage of a simple fabrication process which enables small PMUT size and a high fill-factor of the PMUT array. Device fabrication and characterization of these cavity SOI PMUTs was first demonstrated in [16], and long-range pulse-echo imaging for human tissue thickness measurement was demonstrated in [19]. In this work, we demonstrate short-range (mm) and high-resolution (∼100 µm) pulse-echo ultrasonic imaging using cavity
A. PMUT Working Principle

As a transmitter, the electric field between the top and bottom electrodes creates a transverse stress in the piezoelectric layer due to the converse piezoelectric effect [5]. The generated stress causes a bending moment which forces the membrane to deflect out of plane, launching an acoustic pressure wave into the surrounding medium. As a receiver, an incident pressure wave deflecting the plate creates transverse stress which results in charge on the electrodes due to the direct piezoelectric effect.

B. AlN vs. PZT

Most of the previous work on PMUTs has focused on PZT [7], [8] and AlN [5], [26] due to the availability and maturity of film deposition processes for these materials. Material properties, including piezoelectric coefficient, $e_{31f}$, and the relative permittivity, $\varepsilon_{33}$, of AlN and PZT are listed in Table 1. PZT has a $\sim 10\times$ higher $e_{31f}$ and a $\sim 100\times$ higher $\varepsilon_{33}$ than AlN. Using the equivalent circuit model [5] of a PMUT with the assumption that the energy loss is dominated by acoustic damping, the transduction power efficiency, $k_2^2$, is proportional to the ratio:

$$k_2^2 \propto \frac{e_{31f}^2}{\varepsilon_{33}}$$

(1)

While PZT has higher piezoelectric constants than AlN, the lower dielectric constant of AlN allows for a comparable $k_2^2$ to be achieved. Furthermore, transmitter sensitivity (Pa/V), $S_T$, and receiver sensitivity (V/Pa), $S_R$, can be expressed as:

$$S_T \propto e_{31f}$$

(2)

$$S_R \propto \frac{e_{31f}}{\varepsilon_{33}}$$

(3)

These equations reveal that AlN has the potential for $\sim 10\times$ higher receiver sensitivity while PZT has the potential for $\sim 10\times$ higher transmitter sensitivity.

C. Acoustic Beam Pattern of a Single Transducer

A focused, narrow acoustic beam is essential for high resolution, pulse-echo ultrasound imaging. The far-field acoustic directivity, $D_{dir}(\theta)$, of a movable piston is given by [28]:

$$D_{dir}(\theta) = 2J_1(k a \sin \theta)/(ka \sin \theta)$$

(4)

where $\theta$ is the angle of incidence, $a$ is the piston radius, $k = 2\pi/\lambda$ is the wavenumber, and $J_1$ is the Bessel function of the first kind. Then the normalized pressure, $D(r)$, at radial distance $r$ from the center of a PMUT for a specific axial distance $z_0$ can be calculated using the following equation:

$$D(r) = D_{dir}(\arctan(r/z_0)) \left(\frac{z_0}{\sqrt{r^2 + z_0^2}}\right)$$

(5)

Based on the equations above, one method to obtain a narrow acoustic beam is by increasing the working frequency when using a single ultrasound transducer. Calculated acoustic beam patterns at a 1.5 mm distance from a single 50 μm diameter PMUT with various working frequencies are shown in Figure 2 (a). Since the beam pattern is axisymmetric, only half of each pattern is shown. The calculations were performed using $c = 750$ m/s, which is the speed of sound in the insulating fluid used in our experiments, Fluorinert FC-70 (3M Inc.). The results demonstrate that $\sim 400$ MHz working frequency is required to achieve sub-100 μm beamwidth. However, achieving such a high frequency requires a PMUT working in thickness mode rather than in flexural mode, resulting in poor acoustic impedance matching to fluid and tissue. Additionally, higher working frequency results in greater acoustic attenuation in such media.

Another method to obtain a narrow beam is to enlarge the transducer’s diameter. Figure 2 (b) shows calculated beam patterns for an 8 MHz transducer with various diameters from 0.2 mm to 2 mm. The results demonstrate that a 2 mm transducer is needed to achieve sub-100 μm focus at 8 MHz. However, large transducers suffer from undesired near-field patterns, posing a problem for short-range imaging.

The on-axis pressure, $P(z)$, generated by a moving piston is [29]:

$$P(z) = 2\rho_0 c_0 u_0 \left| \sin \left[ \frac{1}{2} k z \left( \sqrt{1 + (a/z)^2} - 1 \right) \right] \right|$$

(6)
where $c_0$ is the speed of sound in the media, $u_0$ is the vibration velocity amplitude, and $\rho_0$ is the density of the media.

A plot of the on-axis pressure, Figure 3, demonstrates a strong interference effect that creates fluctuating near-field pressure. The range over which these fluctuations occur can be reduced by decreasing the piston diameter. When the diameter is equal to or smaller than the wavelength ($\lambda = 87.5 \, \mu m$ for $c_0 = 750 \, m/s$ at $f = 8 \, MHz$), the pressure decreases monotonically without near-field fluctuations. For this reason, small-diameter transducers are desirable for short-range imaging.

D. PMUT Array

To solve the problems noted above, rather than using a single high-frequency transducer, we use an 8 MHz phased array to achieve narrow acoustic beam-width [24]. Optical images of the 72×9 AlN PMUT array [25] are shown in Figure 4. The PMUTs use 0.8 $\mu m$ thick piezoelectric Aluminum Nitride (AlN). PMUT arrays were fabricated via a simple process [25] based on custom cavity SOI wafers with a 2.5 $\mu m$ thick Si device layer. 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 array is composed of 50 $\mu m$ diameter PMUTs with 70 $\mu m$ pitch, and the 9 PMUTs in each column are electrically connected together.

E. Beam-Forming and Scanning

In transmit beam-forming, the acoustic beam is focused by varying the time-delay of the transmit waveform applied to the columns of the PMUT array. The diameter of the focused spot depends on the aperture, which is equal to the number of columns multiplied by the pitch between columns,
Fig. 6. Beamforming using sub-array groups. The beam-forming pitch is shown as twice the PMUT pitch but may be any integer multiple. The focused spot of the beam is translated by switching from the 1st group of odd-numbered PMUTs (blue) to the 2nd group of even numbered PMUTs (red). The minimum scan step is defined by the PMUT pitch.

Fig. 7. Acoustic pressure measurement setup using a needle hydrophone.

III. RESULTS AND DISCUSSION

A. Hydrophone Measurements

Ultrasound experiments were conducted with the PMUT array immersed in an insulating fluid (Fluorinert FC-70, 3M Inc.) with similar acoustic impedance to that of human tissue \(Z \approx 1.5\) MRayls and high electrical resistance to eliminate the need to insulate the array. Figure 7 is a diagram of the setup for pressure measurements in fluid. The PMUT array was wire bonded on a printed circuit board (PCB) and a glass tube is affixed on the PCB to form a small reservoir for the fluid. Then a needle hydrophone, with 40 μm effective diameter (Precision Acoustics), was immersed in the fluid to measure the acoustic pressure.

Figure 8 shows the measured acoustic pressure from a 15-column group of PMUTs, which are connected in columns as shown in Figure 4. The PMUTs are driven with 2-cycles of 8-MHz 18 Vpp pulses using an ultrasound transmitting evaluation kit (TX-SDK-V1, Texas Instruments, Dallas, Texas) with a time delay resolution of \(\sim 0.78\) ns. The selected phase delay of each column is calculated based on the acoustic propagation path length from each PMUT to the desired focal point. Figure 8 (a) and (b) show measurement results for a 15-element PMUT array with 70 μm and 140 μm pitch, respectively, using transmit beam-forming and no beam-forming (PMUTs driven simultaneously). The measurement results demonstrate that beam-forming increases the pressure amplitude \(\sim 3\times\), compared with the pressure produced from which we refer to as the beam-forming pitch. Here, we consider 15-column groups of PMUTs, and study the focused spot diameter at various beam-forming pitches. The time delay of each column is calculated using the differential propagation path divided by the speed of sound. Figure 5 shows the calculated acoustic beam patterns at 1.5 mm axial distance for 15-column groups with various beam-forming pitches. The acoustic beam-width narrows with increasing pitch (70 μm, 140 μm, 210 μm). This is similar to the theory of a single transducer, where larger apertures result in a narrower acoustic beam. The simulation shows that a 15-column PMUT array with 140 μm beam-forming pitch can achieve an 82 μm beam-width at 8 MHz.

While large beam-forming pitch is desirable to achieve a narrow beam diameter, a small pitch between columns is required to allow high fill factor and therefore high acoustic efficiency. To satisfy both of these objectives, a beam-forming and scanning method was developed, as shown in Figure 6. High fill-factor is achieved through a small 70 μm PMUT pitch, while 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 6, 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.
the same 15-column PMUT group without beam-forming (all PMUTs driven with the same phase delay). Furthermore, in agreement with the simulation shown in Figure 5, a larger beam-forming pitch, 140 μm, reduces the peak pressure to 70 kPa compared to the 80 kPa produced with 70 μm beam-forming pitch. Finally, beam-forming results in a short acoustic pulse ∼0.3 μs (−6 dB), corresponding to ∼200 μm wave propagation length.

To study the fluid-immersed bandwidth, the measured pressure signal is analyzed via Fast Fourier Transform (FFT). The beam-formed pressure pulse is analyzed since pulses launched from each PMUT arrive simultaneously at the focus, ensuring that the time-domain signature represents the response of an individual PMUT. To eliminate the contribution of the driving signal, only the ring-down portion is used for FFT analysis. Figure 9 shows the FFT magnitude of the measured acoustic pressure shown in Figure 8 (a), showing an 8 MHz center frequency and a −3 dB bandwidth of 3.4 MHz. For comparison, the PMUT's frequency response measured in air using a laser Doppler vibrometer (LDV) showed a 19 MHz resonance frequency with quality factor Q = 140 and a peak amplitude of 13.7 nm/V.

Figure 10 (a) shows the measured acoustic beam-patterns for a 15-element PMUT array with 140 μm and 70 μm beam-forming pitch at 1.5 mm away from the array. The measured pressure amplitude agrees well with simulation results. Compared with 70 μm beam-forming pitch, the simulation results show that 140 μm pitch reduces acoustic pressure by ∼5%, but narrows −6 dB beam-pattern width from 150 μm to 82 μm; the measurement results demonstrate 140 μm pitch reduces acoustic pressure by ∼13%, but narrows −6 dB beam-pattern width from 200 μm to 90 μm. This difference between simulation and experimental results may be caused by the time-delay resolution of pulse generator or non-ideal measurement positioning. Another possible cause of the difference is that the simulation uses a continuous-wave (CW) model, while measurements were obtained with a pulsed-wave driving signal. This also explains why side lobes shown in the simulation results were not observed in the measurement results. The 2-D acoustic pressure field produced using a beam-forming pitch of 140 μm is measured in the x-z plane and shown in Figure 10 (b). The focused beam demonstrates ∼0.4 mm depth-of-focus, which is suitable for many imaging applications.

B. Pulse-Echo Imaging Experiments

Pulse-echo imaging was conducted using a custom 1.8V interface ASIC [19], as illustrated in Figure 11(a). The ASIC has a low-noise analog front-end pre-amplifier that is impedance matched to the PMUT. Because the capacitance of the 9 AlN PMUTs in each column is low (∼1 pF, including bond pads), a low-power on-chip 32V charge pump is capable of providing sufficient output current to drive a 15-column PMUT group. As shown in Figure 11(b), the 1mm × 2mm ASIC has 7 identical channels with 6-bit delay control and 5-ns resolution for transmit beam-forming, high-voltage level shifters, and a receive/transmit switch that isolates the low-noise receiver from the 32V transmit voltage. Instead of requiring multiple external high-voltage power supplies, this design generates all the necessary voltage levels from a single 1.8 V supply and is thus amenable to integration with battery powered devices.
Fluid-immersed imaging experiments were conducted using steel phantom targets patterned via laser cutting. 3 cycles of 32-V unipolar pulses with various time delays are used to drive the PMUTs. While beam-forming is used to transmit a focused beam, the echoes were received using a single column of PMUTs in the middle of the transmitting group for simpler signal processing. If all received signals from the PMUTs were collected and processed, receive beam-forming could be used to achieve higher SNR and imaging resolution [30]. Since the 72×9 PMUT array is only 5 mm × 0.6 mm, it is too small to image a large 10 mm × 10 mm phantom using electronic scanning. Instead, mechanical scanning was used to demonstrate the imaging performance. Transmit beam-forming is used to obtain a narrow beam focused at 2 mm away from the PMUT array and a 100 μm scanning step is used to mechanically scan the steel phantom. Figure 12 shows the B-scan image constructed from a lateral scan of this phantom. The phantom with ∼400 μm feature size is clearly imaged with good imaging contrast and a large ∼0.6 V echo signal is obtained. From the image, it is also clear that the phantom is tilted and the leftmost and rightmost bars are wider than the others, as confirmed by the optical image of the phantom.

Figure 13 (a) and (b) show the difference in the pulse-echo responses obtained from a steel strip and space of
the phantom. They correspond to two vertical lines separated by 400 μm distance in lateral direction (x-axis) in Figure 12. The measurements were post-processed with a 4 MHz bandpass filter, after which the envelope was obtained by demodulation and low-pass filtering. Due to beam-forming, good imaging contrast is obtained and the echo from the steel strip is 540 mV, ∼10× of that from the gap (50 mV). In addition, from Figure 13 (a), the second echo is also clearly observed at 12 μs, which is equal to twice the arrival time of the first echo, 6 μs. The 8-cycle ring-down of the pulse-echo response is much larger than 2-cycle ring-down observed in hydrophone measurements. One of reasons for this difference is that the signal is filtered twice by the transducer’s frequency response (once on transmit, and again on receive). In addition, the 5 ns time-delay resolution of the ASIC is relatively coarse, resulting in imperfect focusing of the beam. Finally, there is specular reflection from the neighboring steel strips which produce echoes that return slightly phase-shifted relative to the primary echo. Focusing at a distance equal to twice the imaging depth is a solution to this problem, but is only good for a large planar target and reduces the resolution when imaging small features.

Figure 14 shows a measured pulse-echo C-scan image of a 2-D steel phantom. As with the B-scan image, transmit beam-forming is used to obtain a narrow focused beam and a 100 μm step-size is used to mechanically scan the steel phantom above the PMUT array in a 2-D plane. The 600 μm features of the phantom are clearly imaged with good contrast and a large 1V echo signal is obtained. Compared with the 0.6 V amplitude shown in Figure 12, the relatively larger echo signal observed here is caused by a larger area for specular reflection.

In addition, the echo signal gradually varies in the longitudinal direction because the phantom is tilted. Figure 15 shows pulse-echo time responses obtained from the phantom with and without beam-forming. While the echo signal has comparable amplitude without beam-forming, the contrast ratio is greatly degraded.

IV. CONCLUSION

This work demonstrates short-range and high-resolution ultrasonic imaging using an AlN PMUT array. Until now, most work has focused on PZT PMUTs, since they produce much higher signal levels than AlN PMUTs. Here, we demonstrated that an AlN PMUT array is suitable for pulse-echo imaging when combined with a custom interface ASIC. Because AlN
has a low dielectric constant, lower input currents are needed to drive the array than would be needed for comparably sized PZT PMUTs, and an on-chip 32V charge-pump provided sufficient power for this purpose. 1-D and 2-D pulse-echo imaging was conducted using steel phantoms, and the resulting good contrast ratio (≈10 x) and high spatial resolution (∼100 μm) demonstrate the feasibility of using AIN PMUTs for short-range and high-resolution surface imaging applications.

REFERENCES


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