AIR-COUPLED ALUMINUM NITRIDE PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCERS AT 0.3 MHZ TO 0.9 MHZ
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ABSTRACT
Air-coupled piezoelectric micromachined ultrasonic transducers (PMUTs) operating at frequencies ranging from 0.3 MHz to 0.9 MHz were designed, fabricated and characterized. We increased the fractional bandwidth by 51% and improved the piezoelectric coupling over 80% by patterning the diaphragm center into a ring or structural ribs, resulting in a reduction of the PMUT’s mass. Pulse-echo testing was conducted in air using PMUTs at frequencies up to 0.9 MHz and the measured acoustic loss versus path-length was compared to theoretical models. Devices were fabricated in an industrial foundry process using wafer-level bonding of a MEMS PMUT wafer to a CMOS wafer using a conductive metal eutectic bond. This process allows for close integration of PMUT arrays and signal processing circuitry and is used here to study the effects of wafer-level packaging on acoustic performance.

INTRODUCTION
Typically, fluid-coupled micromachined ultrasonic transducers (MUTs) used in medical imaging operate at 5 MHz or more, while air-coupled ultrasonic transducers usually operate at relatively low frequencies, 40 to 200 kHz [1], in order to maximize the range by reducing the thermal losses in air [2]. Increasing the operating frequency allows the MUT diameter to be decreased and improves the angular resolution of a MUT array with a given area [3], both of which are crucial characteristics for ultrasonic sensors used in consumer electronics as well as in non-destructive evaluation (NDE) applications [4].

Here, we present piezoelectric MUTs (PMUTs) fabricated in an industrial foundry process in which the MEMS wafer is wafer-bonded to a CMOS wafer containing signal processing circuitry. While the direct bonding of CMOS to MEMS affords high signal integrity, it imposes acoustic boundary conditions on the PMUT membrane that may lead to poor performance due to squeezed film damping or other loss mechanisms. We demonstrate that proper acoustic design of the CMOS-MEMS assembly can lead to acoustic performance that is equivalent to that of previous single-chip PMUTs.

To enable small, low-cost arrays of PMUTs, we investigate the acoustic performance of PMUTs with up to 25% smaller area and 400% higher frequency than earlier 200 kHz PMUT designs. High frequency arrays are expected to have shorter range due to increased acoustic absorption in air and this was characterized experimentally using pulse-echo measurements. Because reducing the PMUT diameter leads to increased quality factor (Q) and poor pulse response, we investigate patterned membrane designs as a means to reduce Q, thereby increasing the bandwidth [5].

DESIGN
We designed PMUTs, shown in Figure 1, at four different center frequencies from 200 kHz to 900 kHz by adjusting the diameter between 360 µm to 780 µm. Three different membrane designs were investigated: (1) a flat diaphragm with a center electrode; (2) a partially-etched diaphragm with an outer ring electrode; and (3) a diaphragm with radial stiffening ribs and an outer ring electrode. The ring and ribs were designed to reduce the diaphragm’s mass while enhancing its stiffness, therefore increasing the...
fractional bandwidth [5]. The ring and wedge-shaped ribs were patterned by a 3.5 µm deep partial etch of the 5 µm thick Si elastic layer.

The air-filled cavity between the MEMS and CMOS wafers results in squeeze-film damping, the real part of which is modeled by [6]

$$R_{cav} = \frac{3\mu r^4}{2h^3}$$ (1)

where \(r\) and \(h\) are the radius and depth of the cavity and \(\mu\) is the dynamic viscosity of air. Since the damping term \(R_{cav}\) decreases with the cavity depth, the quality factor will increase. However, the backside cavity impedance also includes imaginary components corresponding to the mechanical compliance and inertial mass of the cavity, [7]

$$c_{cav} = \frac{h}{\rho_0 c^2 \pi r^2}$$ (2)

$$l_{cav} = \frac{\rho_0 r^2 h}{3}$$ (3)

where \(\rho_0\) and \(c\) are air density and speed of sound, respectively. The effect of \(l_{cav}\) and \(c_{cav}\) is that the PMUT’s resonance frequency changes with the cavity depth. The modeled and measured \(Q\) factor as a function of cavity depth are shown. Figure 2 shows that \(Q\) reaches an approximately constant value for cavity depths greater than 20 µm. Note that while low quality factor is generally a positive characteristic [3, 5] of PMUTs, as it indicates efficient transfer of mechanical energy to the air, the energy should be transmitted as the ultrasonic output, and not lost to other mechanisms such as squeeze-film damping.

**FABRICATION**

PMUTs were fabricated in an industrial foundry process in which the MEMS wafer is bonded to a CMOS wafer using a conductive Al-Ge eutectic bond, as shown in Figure 1. Following bonding, the MEMS wafer is DRIE etched to release the AlN-Si PMUT membrane and the bonded wafer is diced to expose bondpads on the CMOS wafer. To investigate the effect of cavity depth on squeeze-film damping, devices from two different wafers were tested. On the first wafer, the cavity between the PMUT and the CMOS wafer was approximately 2.5 µm. On the second wafer, a 50 µm cavity was etched into the CMOS wafer in the region beneath the PMUT, as shown in Figure 3.

**RESULTS**

The displacement frequency response was measured by laser Doppler Vibrometry (LDV). The center frequency and quality factor were found by fitting the frequency response to a second-order transfer function, and are presented in

![Figure 2: Simulated and measured quality factor as a function of cavity depth for a flat, 360 µm radius PMUT. Cavity depth of the measured devices is the nominal value and can vary by ±10 µm.](image1)

![Figure 3: SEM image of a die cross section showing the cavity etched into the CMOS wafer. The pillars in the cavity area formed due to an error on the layout](image2)

![Figure 4: Simulated and measured quality factor and center frequency of for PMUTS with back side cavities depths of 2.5µm and 50µm.](image3)
Figure 4. In devices with a 2.5 µm cavity, the system bandwidth is governed by squeeze-film damping, instead of energy transfer to the acoustic output. In comparison, devices with a 50 µm cavity show high $Q$ (up to 350 in devices operating from 600 kHz to 800 kHz), similar to MEMS devices lacking the CMOS wafer. Additionally, the devices with a cavity show more die-to-die variation in the center frequency than those without the cavity. The source of this variation is not entirely clear but may be caused by particulate in the cavity resulting from imperfect DRIE caused by a layout error.

As shown in Figure 5, the Ribs design, in which a partial etch is used to reduce the membrane mass, achieves lower quality factor than that of the Flat design. The reduction in $Q$ achieved by the Ribs and Ring designs is summarized in Table 1. The Ribs design shows the most improvement, reducing $Q$ by up to 51% relative to the Flat diaphragm design. Moreover, the displacement normalized by the quality factor was compared as a measure of the piezoelectric coupling. For all designs, the average normalized displacement of the ribs design was 27-80% higher than that of the flat design.

**Table 1: Reduction in $Q$ relative to flat PMUT design**

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<th>300 kHz</th>
<th>400 kHz</th>
<th>600 kHz</th>
<th>800 kHz</th>
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<tr>
<td>Ribs</td>
<td>35%</td>
<td>51%</td>
<td>31%</td>
<td>13%</td>
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<tr>
<td>Ring</td>
<td>10%</td>
<td>18%</td>
<td>12%</td>
<td>14%</td>
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PMUT arrays require close matching between the center frequencies of the PMUTs in the array. Using dice selected from various locations across the 200 mm wafer, we compared the range of center frequencies of 10 identical 400 kHz Ribs designs on the same die. For six dice with 50 µm cavities and five with 2.5 cavities, the worst matching observed on a single die was 6.7% and 2.5% and the best matching was 0.8% and 1% respectively.

We also studied the frequency variation across the entire wafer, which is an important metric for manufacturing yield. The across-wafer frequency variation was 23% for the 800 kHz devices and 29% for the 400 kHz devices. Using FEM simulations for the frequency variation induced by AlN residual stress and Si device layer thickness variations, we estimate the AlN residual stress varies by 170 MPa to 350 MPa across the wafer, and the Si device layer total thickness variation (TTV) is in the range of 0.7-1 µm, which agree well with the known fabrication tolerances.
Pulse-echo measurements were conducted to evaluate the acoustic performance at each frequency. The received signal was cross-correlated with the measured transmit burst pattern and is shown in Figure 6. The propagation loss is a function of path-length and the loss increases strongly with frequency, Figure 7, e.g. a 900 kHz transducer at 15cm exhibits 35 dB greater loss than a 300 kHz transducer over the same path-length. The absorption loss at each frequency has been extracted from the difference in slope of the lines in Figure 7, and agrees well with theoretical absorption loss [7] for air at room temperature and 50% relative humidity, Figure 8.

Finally, we measured the transducers directivity, Figure 9, by rotating the PMUT relative to a flat reflecting target. The measured directivity is narrower than simulated. The origin of this effect is under investigation.

CONCLUSIONS
We have designed, fabricated, and characterized air coupled PMUTs at frequencies ranging from 0.3 MHz to 0.9 MHz. Pulse-echo measurements showed that the loss as a function of frequency agrees well with theory. We found that the Rib design decreases the quality factor by up to 51% and improves the coupling coefficient by up to 80% compared to the Flat design. A backside cavity depth of 50 µm was proven to be a sufficient in order to minimize the influence of squeeze film damping on acoustic output.

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REFERENCES

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