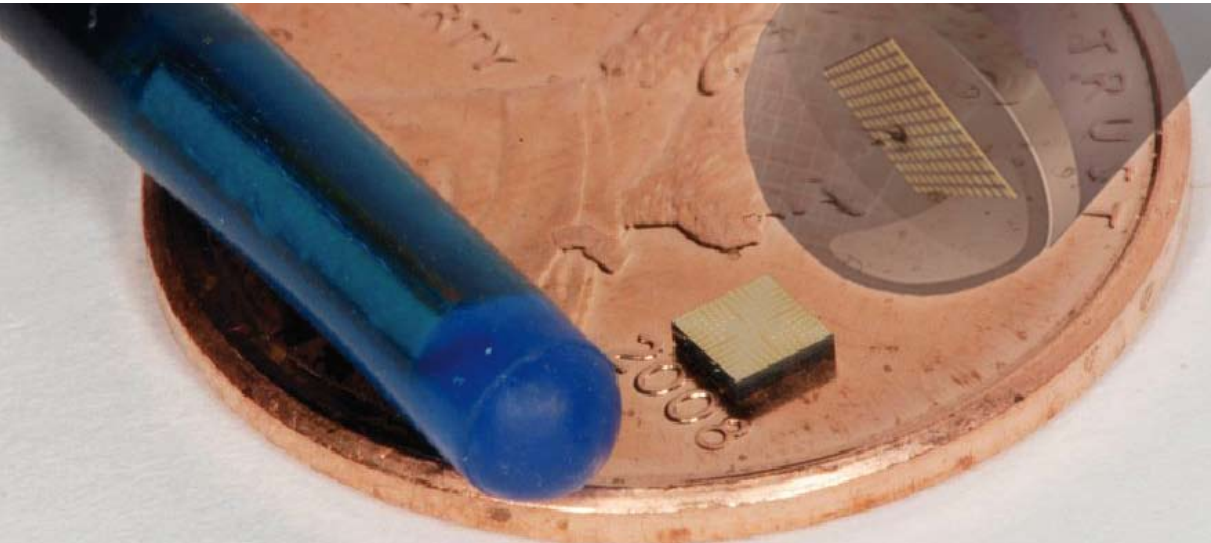


Vibrational Analysis of Ultrasonic Transducers



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Vibrational Analysis of Piezoelectric Micromachined Ultrasonic Transducers

Piezoelectric Micromachined Ultrasonic Transducers (pMUTs) are being used to push the limits of real-time 3D medical ultrasonic imaging in areas such as intravascular ultrasound (IVUS) and intracardiac echocardiography (ICE). A viable alternative to traditional lead zirconate titanate (PZT) bulk ceramic transducers, pMUTs are capable of offering higher operating frequencies with a smaller form factor. Using well-established semiconductor manufacturing processes, the fabrication of pMUTs as a microelectromechanical system (MEMS) provides a cost-effective approach for large volume production of high density 2-D arrays. These can also be constructed to interface directly with on-chip integrated circuits for signal processing, thereby alleviating some of the challenges faced in the field of catheter-based ultrasonic imaging, including the complexity of the interconnect and the performance limitations of bulk PZT transducers, such as high source impedance.

pMUT Structure and Fabrication

The structure of a pMUT consists of a cavity covered by a flexible piezoelectric membrane which deforms mechanically with applied electrical stimulation. A PZT film is deposited using a spin-coating process onto a silicon-on-insulator (SOI) substrate with Ti/Pt electrode layers. The PZT film and electrode layers are photolithographically patterned and etched to form a two-dimensional array of elements. A cavity in the bulk silicon behind each element is etched using a deep reactive ion etch (DRIE) process. In Fig. 1, the basic structure of a pMUT element is illustrated.

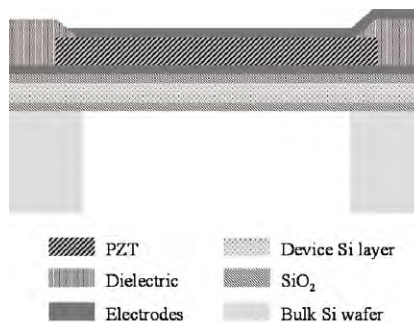


Fig. 1: Cross section of a pMUT laminate structure with component layers.

For these pMUT devices, the cavity, PZT film layer, and electrodes are positioned in a specific conformation (Fig. 2) to produce the desired operation. The top electrode layer is patterned smaller than the underlying PZT film to restrict electrical shorting to the ground electrode plane beneath the PZT. The cavity is shorter in one dimension than the other and undercuts the PZT film layer by several micrometers. In the longer dimension, the cavity extends beyond the dimensions of the PZT film. This provides different boundary conditions in the two lateral dimensions and promotes vibration of the structure as a plate bounded

differently on adjacent sides rather than a membrane bounded equally on each side. The rectangular shape and boundary conditions of the pMUTs help to increase the bandwidth of the devices.

Motivation for Optical Measurement of pMUT Vibration

Our current understanding of the operation of pMUT arrays has been formulated by experimental measurement of only their acoustic and electrical response. Conventional theory regarding plate vibration has been insufficient in characterizing the relationship between pMUT structure and performance [1-3]. Modeling of the pMUTs as a transverse resonator in the length dimension was able to describe the vibration of the smaller elements, but the larger elements could not be modeled as a fundamental mode of either a transverse or plate resonator (Fig. 3). No single higher order mode of either model was sufficient in describing the measured high frequency operation (4 to 8 MHz measured, <2 MHz expected); however, a thickness-dependence in operating frequency was observed that suggested operation in a complex

higher-order plate mode [1]. It was determined that direct optical measurement of the pMUT elements in high-frequency vibration would serve as confirmation of fundamental mode operation for smaller elements and complex higher-order mode vibration of the larger elements.

Vibration Measurement Results

The MSA-400 Micro System Analyzer was used to visualize the individual 75 μm and 200 μm pMUT elements in vibration. The 75 μm elements were observed to operate in a fundamental mode (Fig. 4). However, displacement was observed over a larger area than expected, indicating that our assumptions about the vibrational boundary conditions may be incorrect. Measurement of displacement across both axes of the 75 μm elements (Fig. 5) revealed that the dimensions over which the pMUT vibrates may be up to 10% greater than we had anticipated. This increased motion may contribute significantly to the differences we observe between a pMUT's theoretical and measured frequencies of operation. Visualization of the 200 μm pMUT elements confirmed our hypotheses of

higher order operation of these larger elements (Fig. 6). Fundamental mode vibration was observed at frequencies <2 MHz, but additional peaks at 5.5, 5.7, and 7.8 MHz revealed what appeared to be a complex combination of higher order vibrational modes which likely contribute to the acoustic output of the larger devices observed in previous measurements [3].

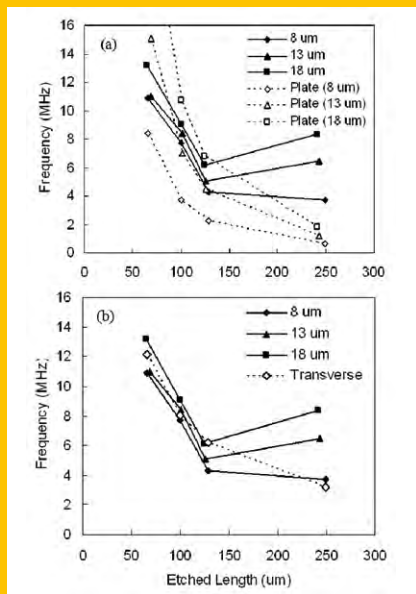


Fig. 3: Measured frequency versus etched length for elements of different thickness (dashed lines) plotted with theoretical calculations for (a) flexensional plate vibration and (b) transverse resonance.

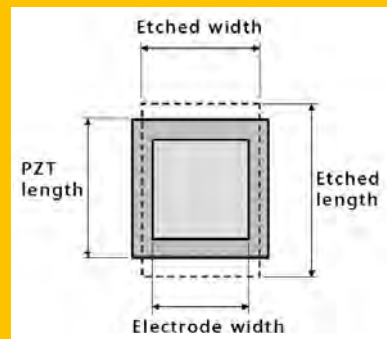


Fig. 2: Top-down diagram of the pMUT structure shown with positioning of the cavity, PZT, and electrode. Cited pMUT sizes correspond to electrode length.

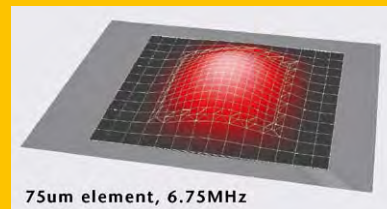


Fig. 4: Vibration of a 75 μm pMUT element at 6.75 MHz in a 14x14 2-D pMUT array.

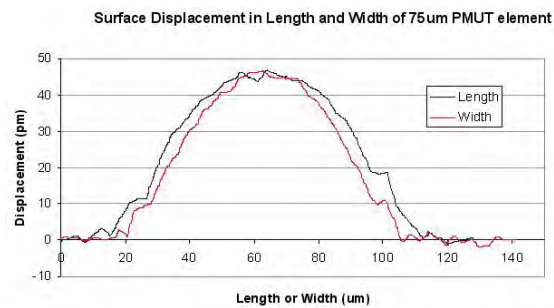
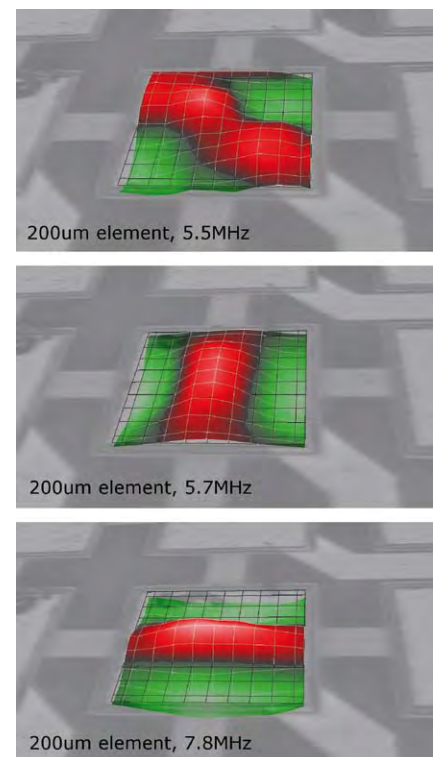


Fig. 5: Measurement of displacement along the length and width dimensions of a 75 μm pMUT element.

Fig. 6: Vibration of a 200 μm pMUT element at a) 5.5 MHz, b) 5.7 MHz, c) 7.8 MHz showing different deflection (mode) shapes. The fundamental mode at frequencies <2 MHz not shown. Single element in a 5x5 2-D pMUT array.



Conclusions

The characterization of pMUT devices presented unusual and demanding measurement conditions, including high speed (~10 MHz) and high resolution (<1 μm), and were made possible by the laser vibrometer capabilities of the MSA-400 Micro System Analyzer.

Visualization of the surface of these pMUT devices in vibration using the MSA-400 laser vibrometer has revealed a wealth of information about their performance. The operation of larger elements in a higher order mode and the revelation of uncertain boundary conditions have increased our understanding of how pMUTs vibrate and will help to advance the theoretical models. Further experimentation may provide even more insight into pMUT vibration characteristics which will allow us to continue to refine their performance as a viable medical ultrasonic transducer.

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References

1. D. E. Dausch, J. B. Castellucci, D. R. Chou, O. T. von Ramm, "Theory and Operation of 2D Array Piezoelectric Micromachined Ultrasound Transducers," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 55(11), 2484-2492 (2008).
2. D. E. Dausch, J. B. Castellucci, D. R. Chou, K. H. Gilchrist, O. T. von Ramm, "Performance of Flexure-Mode pMUT 2D Arrays," Proc. IEEE Ultrasonics Symposium, 1053-1056 (2007).
3. D. E. Dausch, J. B. Castellucci, D. R. Chou, O. T. von Ramm, "Piezoelectric Micromachined Ultrasound Transducer (pMUT) Arrays for 3D Imaging Probes," Proc. IEEE Ultrasonics Symposium, 930-933 (2006).

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