Microfabricated Ultrasonic Transducers Monolithically Integrated with High Voltage Electronics

Chris Daft, Sam Calmes, Daniel da Graca, Kirti Patel, Paul Wagner and Igal Ladabaum
Sensant Corp., 14470 Doolittle Drive, San Leandro, CA 94577, USA

***Abstract*—Capacitive micro-fabricated ultrasonic transducers (cMUTs) recently produced clinical quality images, and have the potential to enable true 3-D ultrasound. Much has been written about the value of integrating cMUTs with electronics, and some early work has been published [1, 2]. This paper describes monolithic integration of high-quality imaging cMUTs with analog switching electronics. The switching circuitry used has the same voltage limitations as commercial multiplexing chips (200 V_{PP}). Water tank results demonstrate that cMUTs integrated with controlling switches are fully functional when the capacitance and resistance of the switch are inserted into the cMUT model. The results further demonstrate no measurable effect of the switch on the radiation pattern of the acoustic elements. This verifies the viability of aperture control and channel multiplexing with monolithically integrated electronics. In the short term, such integration can allow for reconfigurable apertures, arrays with many elevation rows, and optimal preamplification. It also represents a step towards a practical 2-D matrix transducer, due to the density of its integration and the freedom to separately optimize the cMUT and the integrated electronics.**

INTRODUCTION

Capacitive micro-fabricated ultrasonic transducers (cMUTs) potentially enable 3-D imaging with full 2-D matrix arrays. To accomplish this, several advances are needed in the transducer. Among these are element switching, and preamplification/signal processing. These can be achieved by integrating electronics at the transducer element, which maximizes the signal integrity. Since cMUTs are built on silicon wafers, we can create an application-specific integrated circuit (ASIC) and form the transducer directly above the IC.

An ideal integration of transducer and electronics would maintain the highest density of acoustic elements. This means the electronics should be under the cMUTs, so as not to reduce the transduction area with interconnect fan-out. It would also allow for independent optimization of the ASIC and cMUT. The micromachining must take place at a low enough temperature that the IC performance is unaffected.

This paper investigates the feasibility of combining a cMUT design that has produced premium-quality images with commercially available analog high-voltage switches[1]. Success in this integration simplifies several image quality improvements, as well as constituting a step towards true 3-D imaging.

Electronically reconfigurable elevation apertures (e.g., [3]) have conclusively proven their clinical worth. However, such arrays need many hundreds of elements combined using extensive electronics in the probe handle. But with integrated electronics, the die and flex would be no more complex than in a 1-D transducer. Besides this, the large bandwidths typical of cMUTs motivate switched changes in elevation and pitch, based on the center frequency in use. A single element size for all imaging is a limitation when the fractional bandwidth exceeds 80%.

Improved spatial sampling, or an increased center frequency, calls for smaller elements with lower capacitance. Since cable and system parasitics are constant, achieving acceptable signal fidelity and noise performance then becomes more complex. Signal conditioning at the transducer element is an obvious solution to maintain signal-to-noise ratio (SNR) while increasing the diagnostic information in the image.

SILICON PROCESSING

Wafers first underwent the normal Supertex high voltage fabrication process. Since high voltage CMOS processing creates considerable surface topography, the wafer surface was planarized. This was accomplished by depositing an oxide passivation layer, followed by a chemical mechanical polishing (CMP) step that planarized the passivation layer. Vias to certain IC pads of the underlying analog switches were lithographically patterned and opened with a subsequent etch step. This established electrical contact with the cMUT electrode layers formed in later thin film deposition processes. The cMUT bottom electrode metal layer made direct contact with the IC top

[1] Supertex, Sunnyvale, CA.

metal layer. This connection differs from, for example, the two wafer bump-bonding approach of [4].

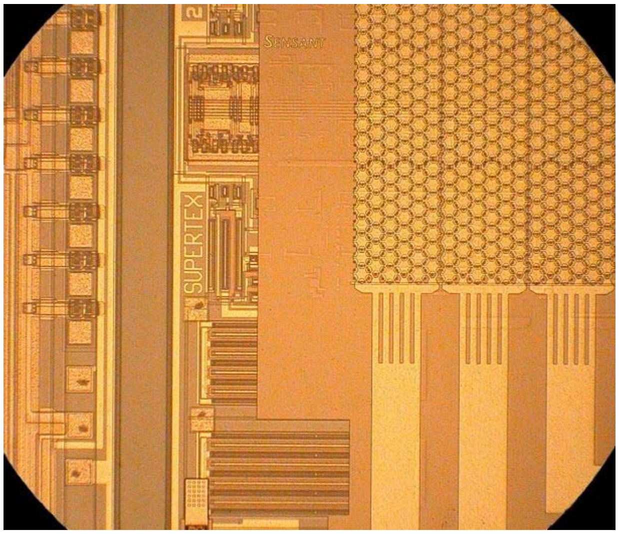

Figure 1: A 3-element cMUT test structure micromachined on a high-voltage switch IC. The CMOS circuit is an unmodified commercial product; the acoustic transduction films are above it.

After our standard cMUT processing, bond pads were opened directly to isolated high voltage chips. This enabled Supertex to conduct comprehensive testing of these ICs to confirm that the CMOS performance was unchanged. Fig. 1 shows a top view of the transducers with their Supertex integrated electronics; Fig. 2 shows a diagram of a cross-section orthogonal to Fig. 1's view.

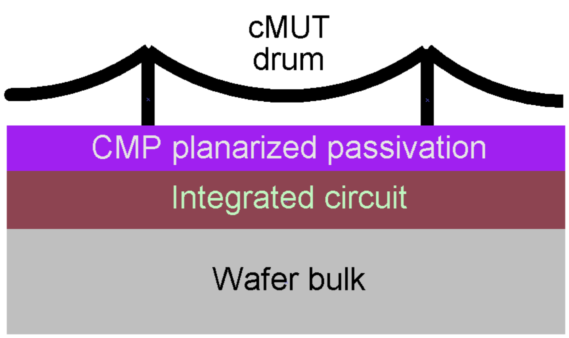

Figure 2: Diagram of a cross-section of the composite structure, with cMUT posts, suspended membrane, passivation layer, CMOS circuit, and silicon substrate.

Experiments

Our initial experiments used a 3-element test structure in which each element can be either connected to, or disconnected from a common terminal. Table 1 lists some parameters of these elements.

TABLE 1
CHARACTERISTICS OF ELEMENTS USED IN TESTING

Element pitch	0.36 mm
Element height	12 mm
Center frequency	3.5 MHz
Half-power bandwidth	110%
-10 dB bandwidth	150%

The elements were initially connected to a network analyzer to check their impedance as a function of frequency. This showed that the capacitance was proportional to the number of elements connected, as anticipated. Then, acoustic performance was tested in two ways using the arrangement shown in Fig. 3.

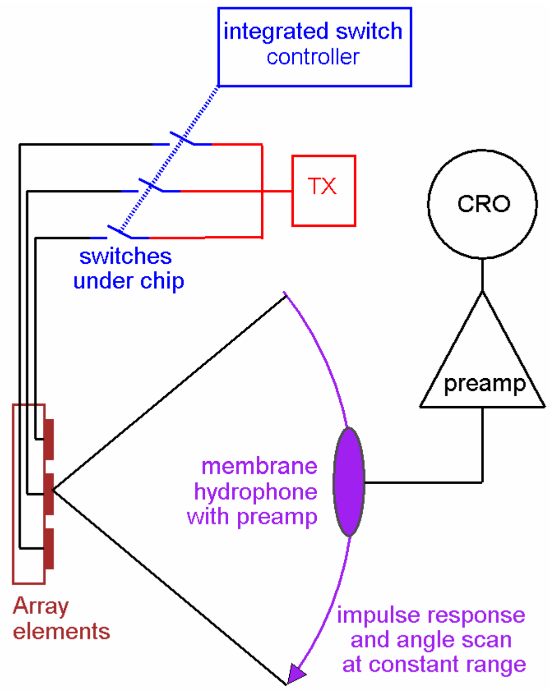

Figure 3: Measuring the performance of the transducer-IC combination in a water tank. The impulse response and angular width were recorded for different apertures created by the switch settings.

The first question was whether the electronic switching had any adverse effect on the sensitivity or axial resolution of the elements. Fig. 4 shows a comparison between the impulse responses of two identically sized elements measured with a membrane hydrophone[2]. One element is directly connected to the transmitter, while its neighbor goes through the switching electronics. The intrinsic variation in sensitivity and bandwidth between different elements on the same die is very small. Increased parasitic

[2] NTR Systems, Seattle, WA.

loading from the switch decreases the expected signal amplitude by 6% in our experiment. The change in impulse response observed is small, and falls within the intrinsic element variability.

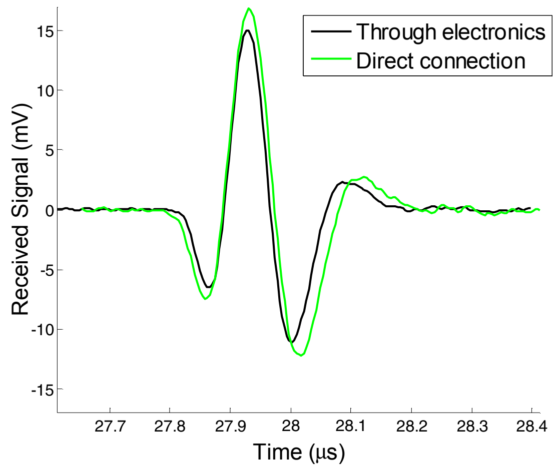

Figure 4: Measured impulse responses for a directly connected element and one that passes through the switching electronics.

In the second experiment, the maximum pressure in the time waveform was recorded as a function of azimuth angle, for different combinations of switch settings. This was done at a fixed range of 30 mm. Data were extracted at 3.5 MHz and 6.0 MHz for comparison with theory. The far-field, continuous-wave angular response of a rectangular element mounted in a pressure-release baffle is derived by the method of stationary phase in [5]:

$$p(\theta) \propto \sqrt{\frac{\lambda}{r}} \cos\theta \frac{\sin([\pi w/\lambda]\sin\theta)}{\pi \sin\theta}$$

where r is the range, w is the width of the element, and θ is the azimuth angle. The angular width is inversely proportional to the element's width in wavelengths λ.

Fig. 5 compares this equation with experimental data. Note especially the correlation in the widths of the curves at both frequencies and apertures. It seems clear at both frequencies that the aperture is changing from 1 element to 3 elements wide. In Fig. 5, the theoretical amplitudes have been adjusted to account for the voltage division caused by parasitic capacitance in our apparatus, and the analog switches themselves. This scales down the 1-element and 3-element data by 6% and 16% at 3.5 MHz. At 6.0 MHz these figures are 15% and 33%, respectively. The theoretical plots were further scaled so that the amplitudes of the 1-element data (only) matched the experiment.

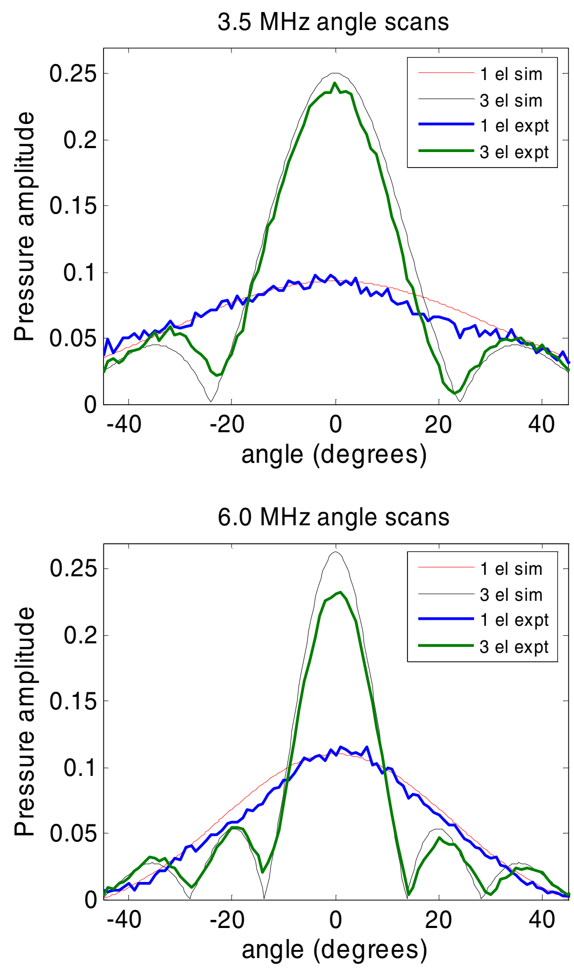

Figure 5: Angle scans in azimuth at 3.5 and 6.0 MHz, comparing measured and predicted responses.

DISCUSSION

The results show that we have succeeded in creating a clinical quality cMUT process that is fully compatible with integrated circuit fabrication. This is primarily due to careful attention to the thermal budget during surface micromachining. We have confirmed that there are no alterations to the IC performance, and the acoustic behavior of the elements is as predicted by our models. The present data indicate the potential for incorporating a high-voltage switching function beneath the cMUT elements.

There are many ways in which this can be exploited to improve image quality. To fully take advantage of the cMUT's bandwidth, the pitch and elevation apertures should be adjusted to maintain an optimal beam as the excitation frequency changes in response to differing clinical needs. For example, B-mode and flow imaging are undertaken with transmit signals that vary substantially in center frequency. B-mode scanning is performed at the highest feasible frequency for the best resolution, while color flow is done at a much lower frequency due to SNR considerations. Harmonic imaging may also benefit from an aperture that changes its size between transmission and reception.

Varying the elevation aperture with focal depth has become a popular method for improving image quality in recent years [3]. Such schemes are straightforward to implement with our present approach. Fig. 6 shows part of a 192-element linear array that has 5 elevation rows, also controlled with high-voltage switches:

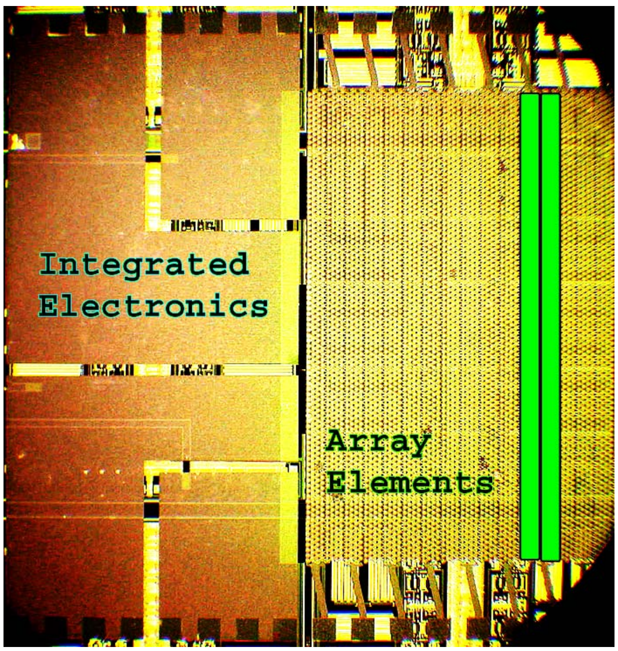

Figure 6: Micrograph of part of a 5-row, 192-element, 1.25-D array controlled with integrated electronics. 16 elements at one end of the array are shown together with the switching area, visible at the left-hand side.

An attractive feature of this method of realizing a multi-row array is that going well beyond 5 rows does not present difficulties in die design, or complicate the interconnect. From the system's perspective, the 1.25-D cMUT array has the same complexity as a 192-element 1-D array. One practical consideration is the severe lack of space in the nosepiece of current ultrasound probes. This stems from the desirability of minimizing patient contact area, while ensuring that the probe handle is comfortable for sonographers. Our technique is efficient in this regard.

The integration of transducers with support electronics on a single wafer creates several other advantages in image quality. Parasitic capacitance and resistance exist in several places between the probe and the system front-end preamplifier. The attenuation suffered by a signal traversing this path affects the signal-to-noise ratio, even in imagers with high-performance preamplification. Therefore, we can expect penetration improvements from eliminating these losses by integrating amplification directly under the transducer element.

Many other kinds of intriguing electronic designs could be realized under the cMUT element. From an IC perspective, the area beneath a typical ultrasonic array element is large, so the circuit can contain many functions. We have found that even 2-D array elements with areas less than λ^2 can accommodate sophisticated signal conditioning when paired with modern mixed-signal IC processes.

CONCLUSIONS

One of the earliest motivations for the capacitive micro-machined transducer was the promise of much easier electronics integration than is possible with piezoelectric devices. This has been achieved by combining an unaltered, commercial high-voltage switch with a typical curved-array cMUT element. Further work can proceed in several directions. One avenue we have already pursued is to fabricate a 1.25-D array whose elevation height can be manipulated with integrated electronics. This allows for some optimization of the slice thickness at different imaging ranges. Full 2-D array electronics is currently in process. The future of the cMUT-IC combination looks promising.

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