Integrated Ultrasound Imaging Systems Based on Capacitive Micromachined Ultrasonic Transducer Arrays

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Abstract— **Capacitive micromachined ultrasonic transducers (CMUTs) overcome many limitations of existing ultrasound transducer technologies enabling new applications of ultrasound, especially for medical imaging and treatment. Some of the most important of these advancements are the ability to fabricate transducer arrays with two dimensional geometries and high operating frequencies. Over the past decade, extensive research has been conducted on the fabrication, characterization, and modelling of CMUTs. Current research efforts focus on the integration of CMUTs in systems for new medical imaging tools. This paper briefly reviews CMUT technology and presents imaging results from two CMUT-based imaging systems. The first system is designed for use within a 5-mm endoscopic channel and is based on a two dimensional, 16-element $\times$ 16-element, 5-MHz CMUT array. To provide a means of integrating the CMUT array with electronics, each element of the array is connected to a flip-chip bond pad on the back side of the array via a through-wafer interconnect. The array is flip-chip bonded to a custom-designed integrated circuit (IC) that comprises the frontend circuitry for the transducer elements. The array and IC are connected to an FPGA-based data acquisition system that can acquire volumetric imaging data in real time. Volumetric pulse-echo and photoacoustic images obtained with this system are presented. The second system is based on a 64-element, 20-MHz, 2-mm diameter CMUT ring array. This array is also designed for use in catheter-based imaging applications. Ring arrays have the advantage of providing space in the center for a guidewire or other catheter-based instrument. Volumetric images obtained with the ring-array system are also presented.**

I. Introduction

Capacitive micromachined ultrasonic transducers (CMUTs) were initially developed in the early 1990's [1]. Over the past decade, there has been extensive research exploring the fabrication [2], [3], characterization [4], and modelling [5] of CMUTs. Recent research has focused on their use in medical imaging systems [6]. For medical imaging, CMUT technology has a number of advantages over existing piezoelectric transducer technology. The silicon micromachining methods used to fabricate CMUTs provide batch fabrication, features with submicron accuracy, and device uniformity. As a result, arrays of transducers with high operating frequencies and widely varying geometries can be fabricated with better performance than comparable piezoelectric transducer arrays. Other advantages of CMUTs include wider bandwidth for better resolution and existing means of compact integration with electronics (either monolithically or in a flip-chip bond package). This paper briefly reviews the design, modelling, and fabrication of CMUTs and then presents imaging results from two transducer arrays: a 256-element 2D array with integrated frontend electronics and a 64-element annular ring array. Volumetric pulse-echo images obtained with both arrays are presented. In addition, photoacoustic images and real-time imaging results obtained with the 2D array are presented.

II. Basic Principles of Operation

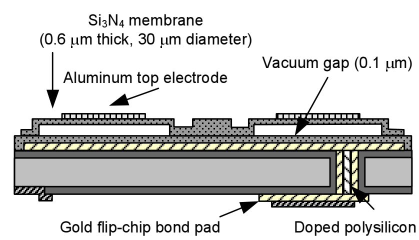

Fig. 1. CMUT fabricated using sacrificial silicon nitride process. A process for CMUT fabrication based on wafer bonding also exists [3].

A CMUT is essentially a vacuum gap capacitor. Typically, the top electrode consists of a metalized membrane and the bottom of heavily doped polysilicon. An illustration of a CMUT fabricated using the sacrificial silicon nitride process is shown in Fig. 1. Pictures of two fabricated CMUT arrays and their individual membranes are shown in Fig. 2. To transmit and detect ultrasound, a DC voltage is first applied across the two electrodes of the CMUT. The electrostic force due to the DC voltage causes the top membrane to deflect towards the bottom electrode. The decreased gap between the bottom and top electrodes increases the electric field in the gap and, as a result, the efficiency of the device. To generate ultrasound, an AC voltage is applied to the membrane. Impinging ultrasound causes the top membrane to move. This movement can be detected as a change in capacitance of the device.

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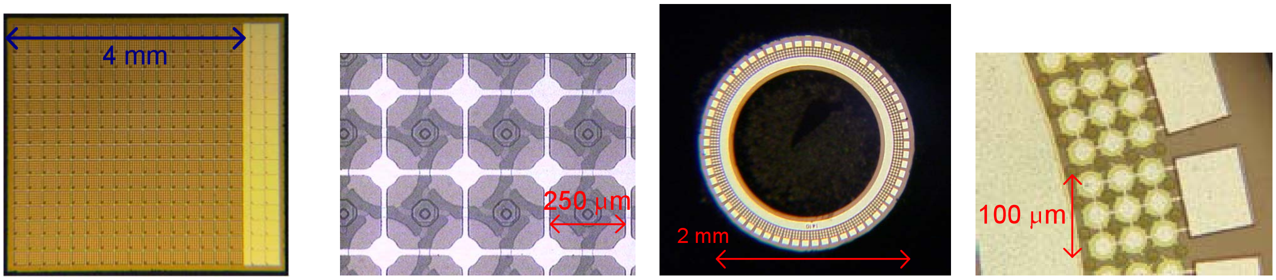


(a) A 16×16-element CMUT array with through-wafer interconnects.
(b) CMUT membranes of device shown in Fig. 2(a).
(c) A 64-element CMUT ring array.
(d) Ring array elements. Each element consists of 9 membranes.

Fig. 2. CMUT arrays.

The size and shape of the membrane and thickness of the gap are designed for a desired operating frequency and DC bias. Modelling has played an important role in this design process and in the development of CMUT technology. Typically, mechanical or electromechanical systems are analyzed in one of two ways: analytical electrical equivalent circuits and finite element models. A transducer equivalent circuit based on Mason's model has been developed for CMUTs [7]. Finite element methods have been developed to study characteristics of the CMUT not captured by the equivalent circuit model.

III. Fabrication

The sacrificial release process and the wafer bonding process are the two dominant methods of CMUT fabrication (Fig. 1). The sacrificial release process has been the traditional method for fabricating CMUTs since its first demonstration in the early 1990s. While there are numerous versions of the sacrificial release process, all are based on the same basic principle. The cavity underneath the membrane is created by depositing or growing a sacrificial layer on the carrier substrate; this layer is selectively removed after the membrane deposition. Etchant, either wet or dry, is carefully chosen to etch the sacrificial layer but not the membrane. A number of sacrificial layer, membrane, and substrate material combinations can be used to fabricate CMUTs. Although the fabrication method remains more or less the same, the choice of material makes a difference in design, process control and overall device yield.

The wafer-bonding method is a relatively new CMUT fabrication technique [3] that uses a combination of bulk and surface micromachining techniques, and a different approach to cavity formation. Fabrication of CMUTs using the wafer-bonding technique begins with two wafers: a prime quality silicon wafer and an SOI wafer. The cavity is first defined on the prime wafer using thermal oxidation and photolithographic patterning. This wafer is then fusion-bonded to the active side of the SOI wafer. The handle portion and the buried oxide layer of the SOI wafer are removed later, leaving a silicon membrane stretched over the cavities.

IV. Integrated Electronics

Integration of ultrasonic transducer arrays with supporting control and data acquisition circuits enables many applications, such as real-time volumetric imaging. The challenges posed by such applications can be itemized as follows: 1. Fabricating 2D transducer arrays and providing electrical connections to each array element are difficult; 2. The small size of a 2D array element causes degradation in output acoustic power and receive sensitivity, making the effect of any parasitic components more pronounced; 3. Data acquisition from a large number of ultrasound channels and processing the resulting data to reconstruct a 3D image are demanding. Integration of the ultrasonic transducer array with supporting electronics minimizes the parasitic components, and consequently, improves the sensitivity and preserves the wide bandwidth of the CMUT. By multiplexing several channels, integration also helps lower the number of interconnects between the transducer array and the signal processing unit. The size of the probe and the number of the cables connected to the probe are especially important for applications such as intraoperative navigation and intravascular diagnostic imaging. A compact probe with a minimum number of external connections can be realized by integrating the electronics with the array. We have proposed an integrated miniature real-time volumetric ultrasound imaging probe for endoscopic use, as shown in Fig. 3. The probe is based on a 2D, 16-element × 16-element CMUT array. An important development made for

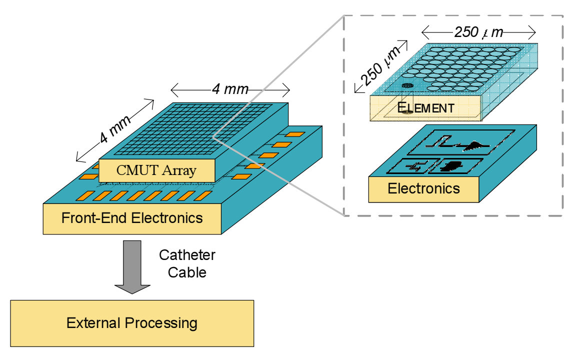
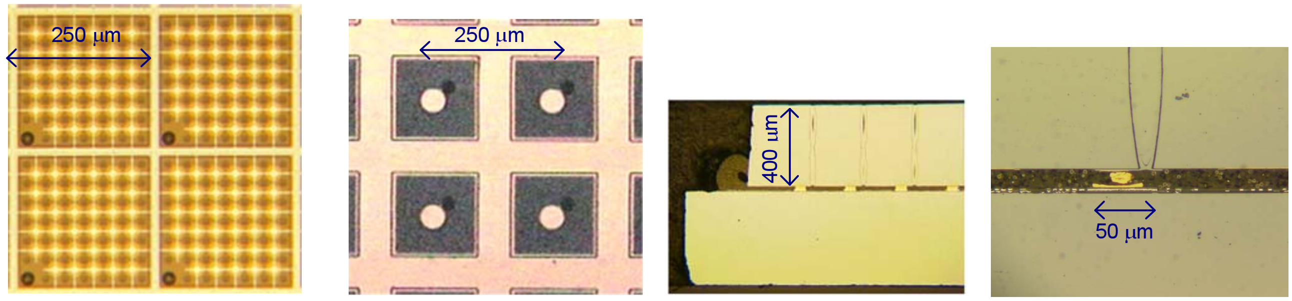


Fig. 3. Catheter-based ultrasound imaging probe with integrated electronics.



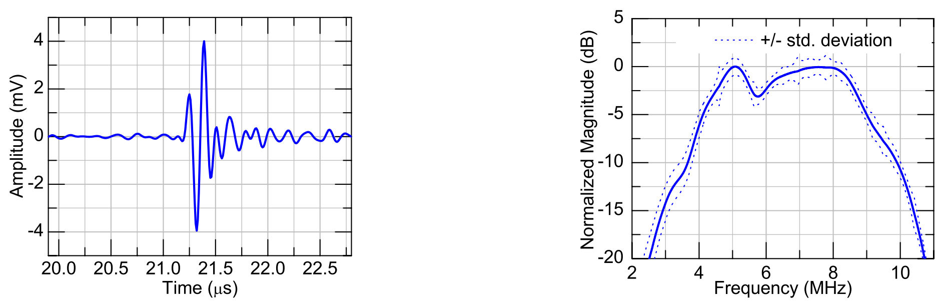
(a) Four elements of a 2D array. A through-wafer interconnect can be seen in the lower left corner of each element.

(b) Back side of four 2D array elements.

(c) Cross section of flip-chip bonded array. The CMUT array is on top of the IC.

(d) A closeup showing the bottom of the through wafer via and the gold bump connecting a CMUT pad to an IC pad.

Fig. 4. Through-wafer interconnects and flip-chip bonding.



(a) Pulse-echo response for a single element of an array flip-chip bonded to a custom-designed IC.

(b) Average Fourier transform of pulse-echo responses for elements in a 256-element array.

Fig. 6. Pulse-echo measurements for a 2D CMUT array with integrated electronics.

this system is the through-wafer interconnect. With through-wafer interconnects, each element of the CMUT array is connected to a flip-chip bond pad on the back side of the array (Fig. 4). An alternative back side interconnect strategy is also being developed [8]. For this technique, deep trenches are etched between the elements to isolate them from one another. Connection to the transducer from the backside can then be made via a highly conductive silicon substrate. Advantages of this trench process include compatibility with the wafer-bonding process and reduced process complexity.

The array is flip-chip bonded to an integrated circuit (IC) that comprises the frontend circuitry. A bonded device is shown in Fig. 5. The IC provides a 25-V pulser and transimpedance amplifier for each element of the array. The pulse-echo response of a single element of an array flip-chip bonded to an IC is shown in Fig. 6(a). In Fig. 6(b), the Fourier transform of the pulse-echo response of all of the elements of the array are averaged and shown with their standard deviation to demonstrate the uniformity in frequency response across the array.

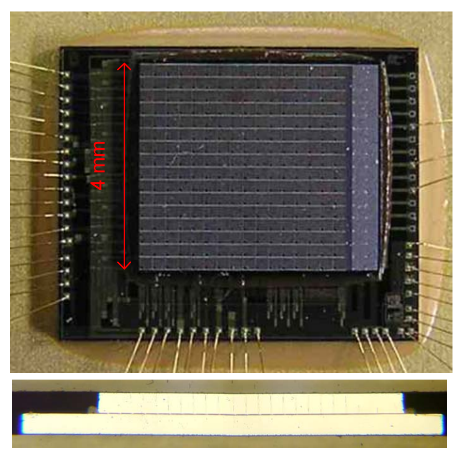
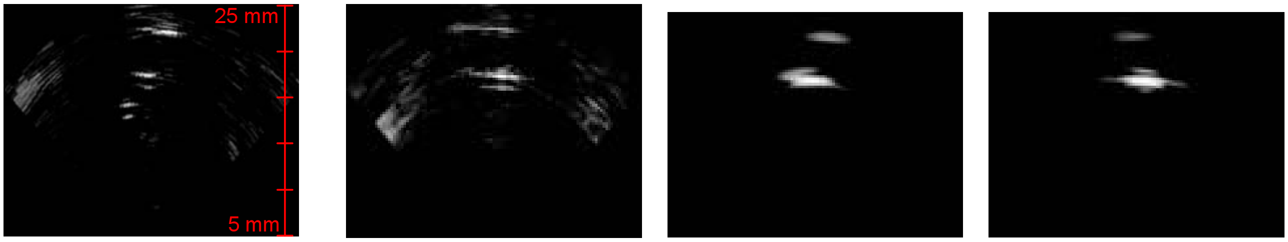


Fig. 5. Photograph of a CMUT array flip-chip bonded to the frontend IC. A cross section of the device is shown below the picture.

V. Ultrasound Imaging

Recently, imaging results have been presented for high frequency (20 MHz - 40 MHz) linear arrays [9], a 64-element ring array [10], and a two-dimensional array with integrated electronics [11]. A 16-channel pulser/receiver IC was designed for the high frequency and ring arrays. These arrays were wire bonded to the ICs for imaging. A volume rendered image of a stent obtained with the ring array is shown in Fig. 7. An IC was also designed for flip-chip bonding to a 2D array with through-wafer interconnects. The IC contains a pulser/amplifier circuit



(a) X-Z cross section of pulse-echo image.

(b) Y-Z cross section of pulse-echo image.

(c) X-Z cross-section of photoacoustic image.

(d) Y-Z cross section of photoacoustic image.

Fig. 8. Pulse-echo and corresponding photoacoustic images of three 1.3-mm diameter polyethylene tubes in tissue mimicking material. The center tube is filled with black ink so that it is identified in the photoacoustic images.

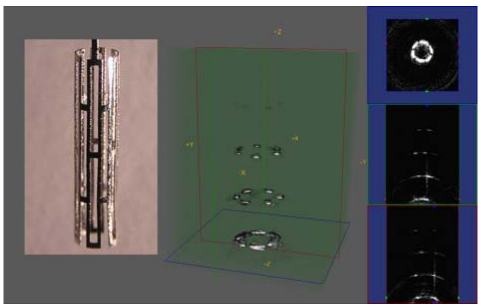


Fig. 7. Volume rendered ultrasound image of a stent obtained with a 64-element ring array. A photograph of the stent is shown beside the rendered image.

for each of the 256 elements of the array. In the initial implementation of the circuit, pulse-echo is done on a single element at a time for classic synthetic aperture imaging. An IC capable of using multiple elements for transmit and receive is being developed. Cross-sections of a volumetric pulse-echo image and photoacoustic image obtained with the 2D array and IC are shown in Fig. 8. Volumetric pulse-echo images acquired in real-time (30 fps) have also been demonstrated with this system.

CMUTs for photoacoustic imaging is also being explored. In photoacoustic imaging, the ultrasound generated by a material illuminated by a short laser pulse is detected [12]. Photoacoustics shows promise in medical imaging, because different materials in the body have different optical absorption characteristics. For example, at some wavelengths blood is more absorbing than the surrounding tissue. Photoacoustic images are shown in Fig. 8(c) and Fig. 8(d).

VI. Conclusion

CMUT technology has important fabrication and performance advantages over existing piezoelectric transducer technology. This paper provides a brief review of CMUT technology and presents imaging results from a ring array and 2D array with integrated electronics. These images are a result of considerable technological advances in CMUT fabrication, interconnect technology, and frontend circuitry. Imaging systems suited for new applications of ultrasound and with larger apertures and improved axial resolution are made possible by these advancements.

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