High-frequency CMUT arrays for high-resolution medical imaging

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ABSTRACT

Applications of ultrasonic imaging in fields such as dermatology, ophthalmology, and cardiovascular medicine require very high resolution. Limitations in existing transducer technologies inhibit the development of high-frequency arrays, which would allow the use of dynamic focusing and enable higher frame rates. As an alternative, capacitive micromachined ultrasonic transducer (CMUT) technology, using integrated circuit fabrication techniques, can provide arrays with the small dimensions required for high-frequency operation. We have designed and fabricated several linear and ring arrays of CMUTs to operate in the 10 to 50 MHz range. These new arrays are made with the wafer bonding process. The ring arrays in particular demonstrate the feasibility of thinning the transducer to aid packaging in intravascular applications. This study shows that CMUTs can be made for high-frequency operation. Both transducers for use in conventional and collapse-mode operation have been designed and characterized. The results demonstrate that CMUT is an appropriate technology for building high-frequency arrays. A linear array of high-voltage pulser and amplifier circuits has also been designed for use with an array of CMUTs to enable real-time imaging applications. Pulse-echo results from the sixteen-channel array have been demonstrated.

Keywords: capacitive micromachined ultrasonic transducer, CMUT, high-frequency ultrasound, ring array

1. INTRODUCTION

The development of high-frequency ultrasonic imaging benefits many fields of medicine. These fields include dermatology, ophthalmology, cardiovascular medicine, and small animal research.[1] The use of high-frequency ultrasound makes it possible to resolve the details of fine features that are close to the transducer. Recent developments have facilitated the fabrication of high-frequency arrays for ultrasonic imaging. The ability to make high-frequency arrays in various configurations also enables new applications for ultrasonic imaging. This paper presents new capacitive micromachined ultrasonic transducers (CMUTs) made using the wafer bonding technique. These transducers were designed in linear and ring array configurations targeted for applications in high-frequency medical imaging. Ring and linear arrays with silicon nitride membranes made with the older surface micromachined process have also been tested in pulse-echo operation with a sixteen-channel, high-voltage, high-frequency electronics chip.

High-frequency ultrasound captures the interest of medical clinicians because it can be used to generate high-resolution images near the surface where ultrasound is applied.[2,3] The finer wavelength in high-frequency ultrasound increases lateral resolution. Increasing the bandwidth of the ultrasonic signal improves the temporal response of the system, thus improving axial resolution. For example, an imaging system using a frequency of 50 MHz and 100% bandwidth can resolve objects in the axial direction on the order of a wavelength in size, which is 30 μm. To achieve high resolutions in an imaging system, transducers and electronic systems with high frequency and wide bandwidth are required. The tradeoff to achieve high resolution is that at high frequencies ultrasound becomes more attenuated in the medium. This prevents high-frequency ultrasound from imaging deep into the body. In addition, it is desirable to have transducers and electronics with low ringdown time after the pulse excitation, because this minimizes the blind spot immediately in front of the transducer.

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High-resolution ultrasound is relevant to disciplines such as the study of the eye, skin, joints, cartilage, cardiovascular system, and small animals.[1] In particular the application of the ring array CMUT is intravascular ultrasound imaging (IVUS). Today the dominant form of imaging the lumen is coronary angiography. This procedure involves inserting a catheter into the vessel to deliver a contrast agent locally. X-ray imaging is performed to acquire a 2-D projection of the vessel profile. The width of the affected lumen is then compared to that of a normal segment and a diagnosis is made based on whether any narrowing of the lumen is found. Imaging by intravascular ultrasound is desirable because it provides detail about the vessel shape and structure.

Ultrasound gives more accurate information about the size of the lumen especially if the vessel does not have a circular cross section. In addition, ultrasound is able to extract information about the material properties of the vessel wall. For example, ultrasound can distinguish between plaque that is made of lipids and plaque that is calcified, making it possible to decide on the appropriate intervention for the case at hand. Ultrasound aids the preinterventional planning stage by giving information about the lesion's shape, size, and composition. IVUS can also provide guidance during the angioplasty (increasing lumen size by ballooning) or atherectomy (mechanically removing plaque using a rotating cutting device) procedure. In addition, IVUS is used in research to learn more about the mechanisms of lumen narrowing and the effects of treatment techniques.[2,3] IVUS is also used as guidance and to perform ablation in procedures to treat fibrillation and arrhythmias in the heart.[4]

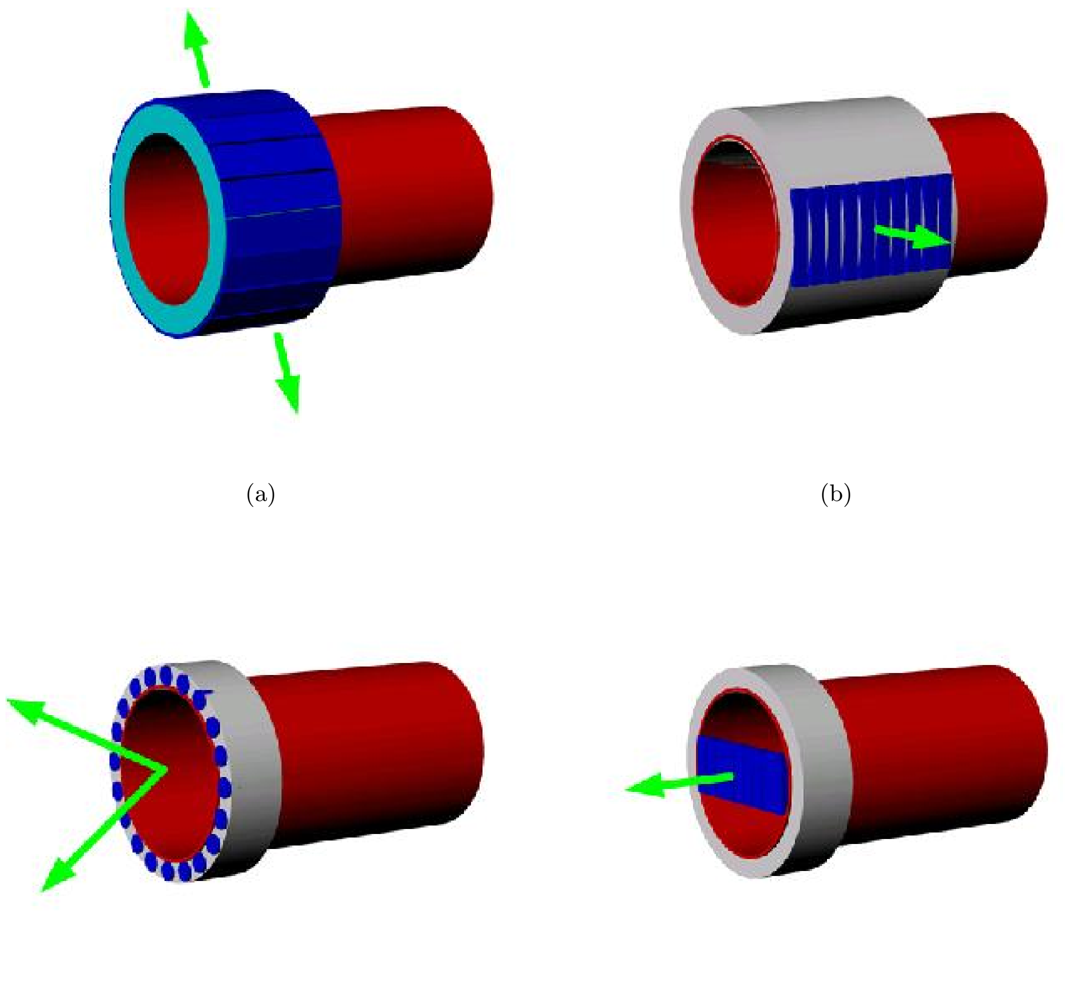
Intravascular ultrasound uses operating frequencies between 20 MHz and 50 MHz to provide resolution on the order of hundreds of microns.[2] The transducer is mounted on a catheter and is guided through the blood vessel. In the commonly used modality, the catheter is pulled back and annular images of the lumen and the vessel wall are recorded.

Traditionally, there are two categories of IVUS transducers for imaging the vessel wall: mechanically rotated transducers, and electronically scanned arrays. In the case of a transducer array, the side-viewing transducer is assembled on the circumference of the catheter as depicted in Fig. 1(a). In the past, mechanically scanned fixed focus transducers provided the best image quality,[2] however electronically scanned arrays offer convenience and flexibility. Recent developments in array technology have greatly improved the quality of images made with arrays. This combined with convenience for the operator makes it the favored technology of the future.

Mechanically scanned systems have a single-element, spherically shaped transducer that provides a fixed focus and eliminates the need to use acoustic lenses, which are difficult to manufacture for this application. Usually the material is the polymer PVDF, or for applications requiring smaller dimensions, a ceramic piezoelectric material like PZT.[1] There are efforts to make high-frequency annular arrays[6–8] that are able to focus along the axis of the concentric rings to replace the fixed-focus, spherical transducer. A drive cable rotates the transducer so that it views the entire lumen wall. The disadvantages of the mechanically scanned approach are that they are difficult to set up because of the mechanical components involved, and the use of a drive cable introduces distortions caused by cyclically non-uniform rotational speed.[2]

Previous attempts at making high-frequency arrays have employed PZT piezoelectric elements.[1,7–9] It has been challenging to manufacture piezoelectric transducer arrays with consistent pitch and kerf at the dimensions necessary for high-frequency operation. High-frequency, (45 MHz) single-element CMUTs have been demonstrated in the past,[12] and, more recently, high-frequency CMUT arrays have been reported.[10] Several array configurations are currently in development for IVUS applications (Fig. 1). The equivalent of the mechanically rotated transducer is the side-viewing ring (Fig. 1(a)).[1] The so-called hockey stick transducer has transducer elements located at the tip on a hinge, so that they may be rotated to look around in the heart.[4] These utilize arrays like those found in Fig. 1(b). Another forward looking device is a tiny 1-D linear array that sits on the end of the catheter (Fig. 1(c)). This paper reports a forward looking ring (Fig. 1(d)),[5,11] which is capable of 3-D imaging in the forward direction. The fine features in cardiovascular imaging require that these arrays be sized appropriately for high-frequency operation (10 – 30 MHz).

This paper presents two types of new high-frequency arrays. These arrays employ CMUTs and are fabricated using the wafer-bonding process. The first type is a high-frequency linear array. The second type is a forward-looking ring array with space in the center for the guidewire in catheter applications. This paper also presents high-frequency ring and linear arrays fabricated with the surface micromachining process. These arrays were tested with a new 16-channel, high-frequency, high-voltage front-end integrated circuit.



(a) (b)

(c) (d)

Figure 1. Catheter probes: (a) Side-viewing ring array; (b) Side-viewing linear array; (c) Forward-viewing ring array; (d) Forward-viewing linear array.

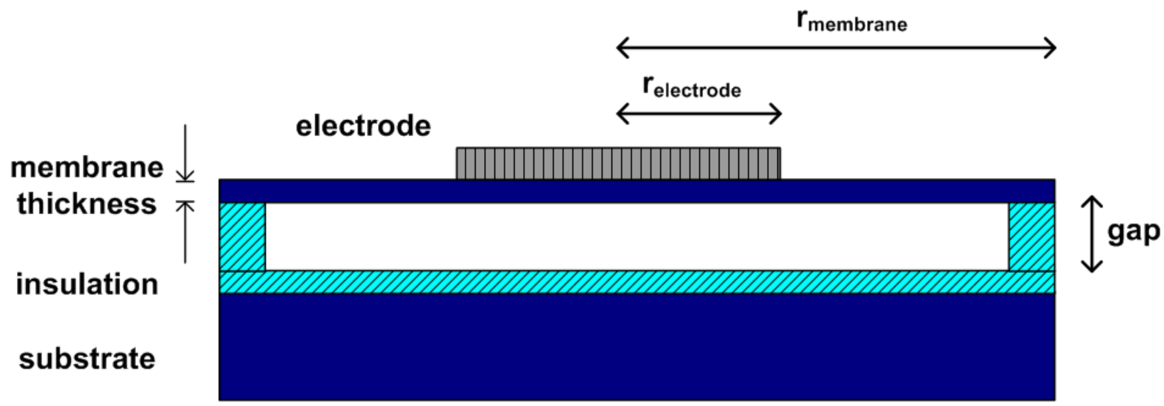


Figure 2. Cross section of CMUT cell

2. HIGH-FREQUENCY CMUT ARRAYS

Arrays of capacitive micromachined ultrasonic transducers operating in high-frequency ranges are reported in this paper in addition to CMUT arrays that have been wafer-thinned. Relative to devices of other transducer technologies, CMUTs are easier to design and to fabricate repeatedly. The feature sizes required for high-frequency ultrasound are readily defined by contact lithography techniques. Because a single mask can contain many patterns, many CMUTs of different operating frequencies and apertures can be fabricated simultaneously on the same wafer. The physical properties of CMUTs are also such that, when loaded by fluid medium, the transducer exhibits very wide bandwidth.

A simple model of the CMUT is a parallel plate capacitor with a movable top plate held in place by a spring. When an excitation voltage is applied between the plates, electrostatic force moves the plate and launches acoustic energy. When used to detect ultrasound, the movable plate converts acoustic motion into a variable capacitance that can be measured with standard electronic techniques. A CMUT is such a device on the ultrasonic scale. Usually the movable plate is a silicon nitride or silicon membrane. The other plate is the bulk substrate, and an insulation layer between protects the capacitor from being shorted. The cavity is vacuum-sealed to make it usable in immersion. A DC bias is applied to increase the electric field between the plates and improve transmit power and receive sensitivity. Fig. 2 depicts the structure of a single CMUT cell.

CMUTs in practice are composed of many membranes, or cells, moving together as one transducer. The operating frequency of the CMUT depends on the membrane radius, elasticity, thickness, and loading. Given a particular material and thickness, CMUTs of different frequencies can be made on the same wafer by varying the radius of the membrane. Cells are spaced closely together to maximize the fill factor of the active transducing area. Simulation has shown that increasing the fill factor of a CMUT improves the bandwidth of the transducer.[10] The characteristics of a CMUT such as input impedance, operating frequency, and bandwidth can be predicted using the CMUT equivalent circuit model,[13] or, if nonlinear effects are significant, by finite element simulation.

The CMUT can also operate in the collapse regime.[14] In this case, the electric force overwhelms the restoring force of the membrane, so it collapses onto the bottom plate. The movable membrane area becomes smaller, increasing the frequency of operation. Furthermore, the electric field becomes greater, increasing the electromechanical coupling efficiency. Collapse mode operation is an alternative way to design CMUTs for high-frequency ultrasound. Exact predictions of the performance of a CMUT in the collapse regime can be made by finite element modeling.[15, 16]

CMUTs with membranes made of silicon nitride by the surface micromachining process have been reported for a decade.[17] This is a mature technology and produces robust devices that can be operated in collapse reliably. The arrays in this paper are made with a new wafer bonding process,[18] which gives greater control over the properties and dimensions of the membrane. In addition, the cells in an element can be made closer to each other, improving the fill factor and bandwidth of these devices.

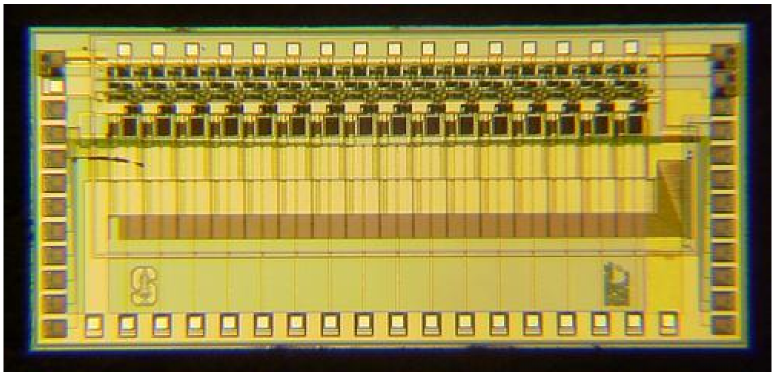


Figure 3. 16-channel electronics die

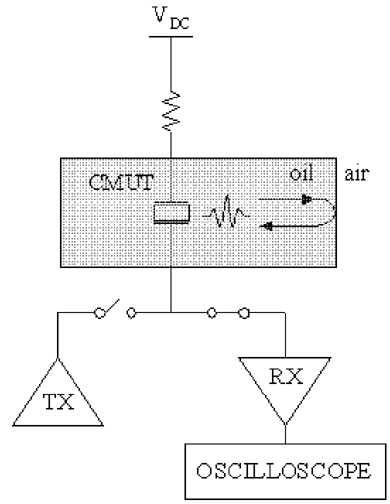


Figure 4. Block diagram of electronics and CMUT for pulse-echo operation

The wafer bonding process used to make these devices is as follows: First a thermal oxide is grown on a prime wafer. This sets the gap distance between the membrane and the substrate. Then the cavity dimensions are defined by lithography in the oxide. The cavity is formed by removing the oxide with buffered oxide etchant. Next a SOI wafer with a thin active layer is bonded to the first wafer. The buried oxide and handle wafer are removed, metal contacts for the CMUT electrodes are patterned, and lithography is performed on the silicon to isolate adjacent array elements.

The wafer-bonded ring array was wafer-thinned to a thickness of 200 μm. The wafer was ground and polished on the back side after all other fabrication steps were completed. Thinning down the device allows it to be assembled in a catheter for intravascular imaging where space is highly constrained.

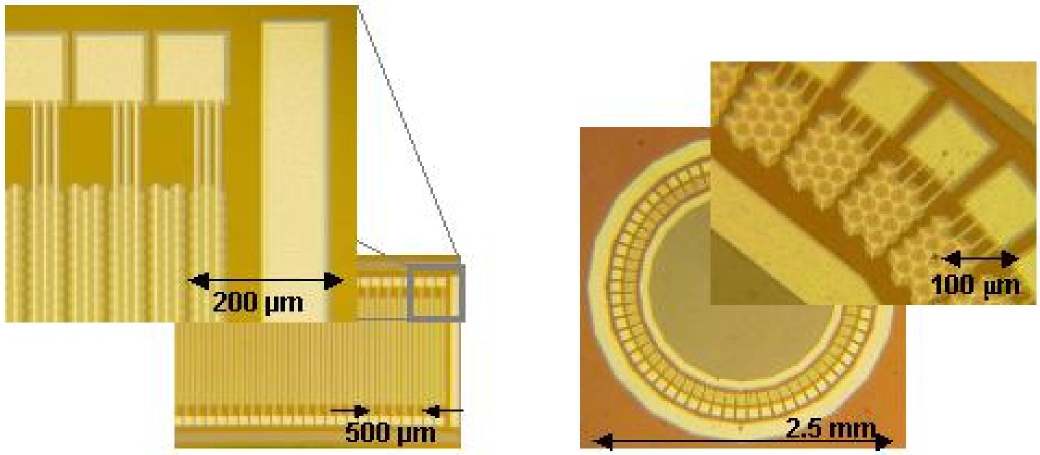
Often CMUTs are paired with custom pulser/receiver circuits that are attached by flip-chip or wirebonding to minimize parasitic capacitance and resistance. This paper presents a new 16-channel pulser/receiver circuit, which is a high-frequency variant of the circuit previously reported in Ref. 19. This circuit consists of sixteen independent channels of 30-V pulsers and transimpedance amplifiers. The layout of the circuit is a linear array as shown in Fig. 3. The circuit was designed to be attached to 16 channels of the CMUT by wirebonding. Fig. 4 depicts the components of this system for pulse-echo experiments.

3. EXPERIMENTAL RESULTS

High-frequency arrays in both linear and ring array configurations have been fabricated and tested. Arrays from the wafer-bonding process (Fig. 5) were measured for electrical impedance in air and pulse-echo response in immersion. These arrays were wirebonded to the single-channel, 5-V electronics for pulse-echo testing. The arrays made using the surface-micromachining process were tested in pulse-echo operation. Sixteen array elements were wirebonded to the 16 channels of the high-voltage electronics array. The surface-micromachined ring array was also tested under collapse-mode bias conditions. These devices are summarized in Table 1.

The electrical impedance measurements were made using a vector network analyzer.(model 8751A, Hewlett-Packard Co., Palo Alto, CA). The arrays were biased using a high voltage DC supply (model PS310, Stanford Research Systems, Inc., Sunnyvale, CA). These measurements determine resonant frequency in air, device capacitance and parasitic capacitance. Results are summarized in Table 1 and the impedance measurements are shown in Fig. 6.

The pulse-echo measurements were made on a single array element of each device using the setup depicted by Fig. 4. The array was bonded in a DIP package along with custom pulser and amplifier circuits. The electronics



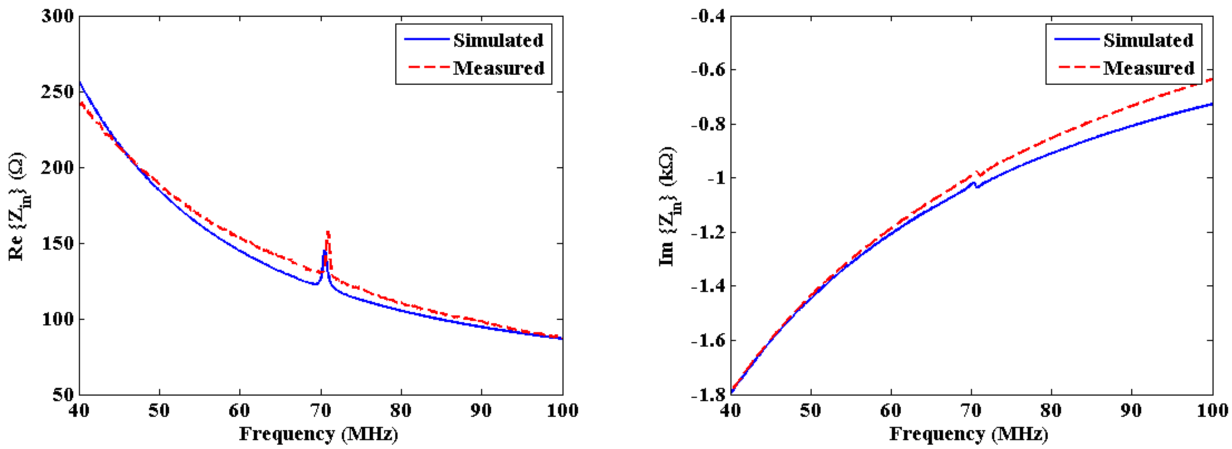
(a) Linear array (b) Ring array

Figure 5. Wafer-bonded arrays.

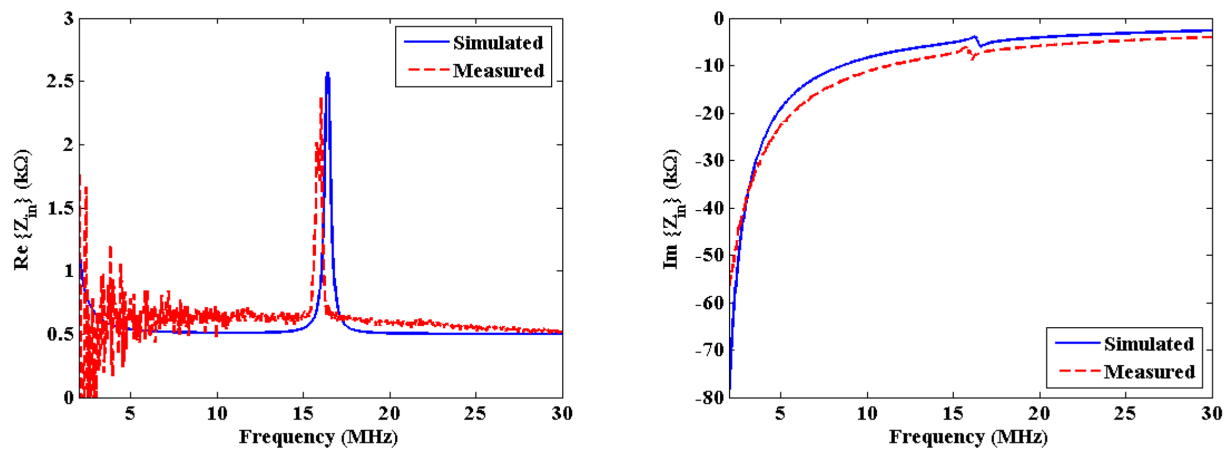
Table 1. Parameters of CMUTs tested

	Wafer bonded		Surface micromachined	
	Linear	Ring	Linear	Ring
Membrane material	silicon	silicon	silicon nitride	silicon nitride
Membrane thickness (μm)	1.0	0.5	0.4	0.4
Insulation thickness (μm)	0.3	0.1	0.08	0.08
Gap distance (μm)	0.2	0.1	0.15	0.15
Membrane radius (μm)	6	10.5	6	13
Cells per element	195	16	110	9
Element pitch (μm)	50	102	36	102
Elements in array	64	64	64	64
Resonant frequency in air (MHz)	70	17	50	28

were wire bonded to a single element of the array. The pulser is capable of driving a 5-V pulse using high voltage circuit techniques in a 0.25-μm, 2.5-V, standard CMOS process. The amplifier has a signal bandwidth of about 50 MHz. The CMUT is biased with the SRS power supply, and a digital pulse generator (model DD50, Stanford Research Systems, Inc., Sunnyvale, CA) provides the signals needed to operate the electronics. A digitizing oscilloscope (model 54825A, Hewlett-Packard Co., Palo Alto, CA) was used to acquire the echo waveform at 2 GS/s. To operate the transducers in immersion, the package is filled with oil. The oil-air interface provides a reflector a few millimeters from the transducer. Waveforms are shown in Fig. 7. The setup for the surface micromachined arrays is identical except for the new electronics array described earlier, which is capable of a 27-V pulse and has a roll-off in the amplifier gain at 45 MHz for capacitive loads of 2 pF or less. Fig. 8 presents the pulse-echo results of the surface micromachined arrays. The results are summarized in Table 2.



(a)



(b)

Figure 6. Electrical input impedance in air of wafer-bonded devices: (a) Linear array real and imaginary impedance; (b) Ring array real and imaginary impedance.

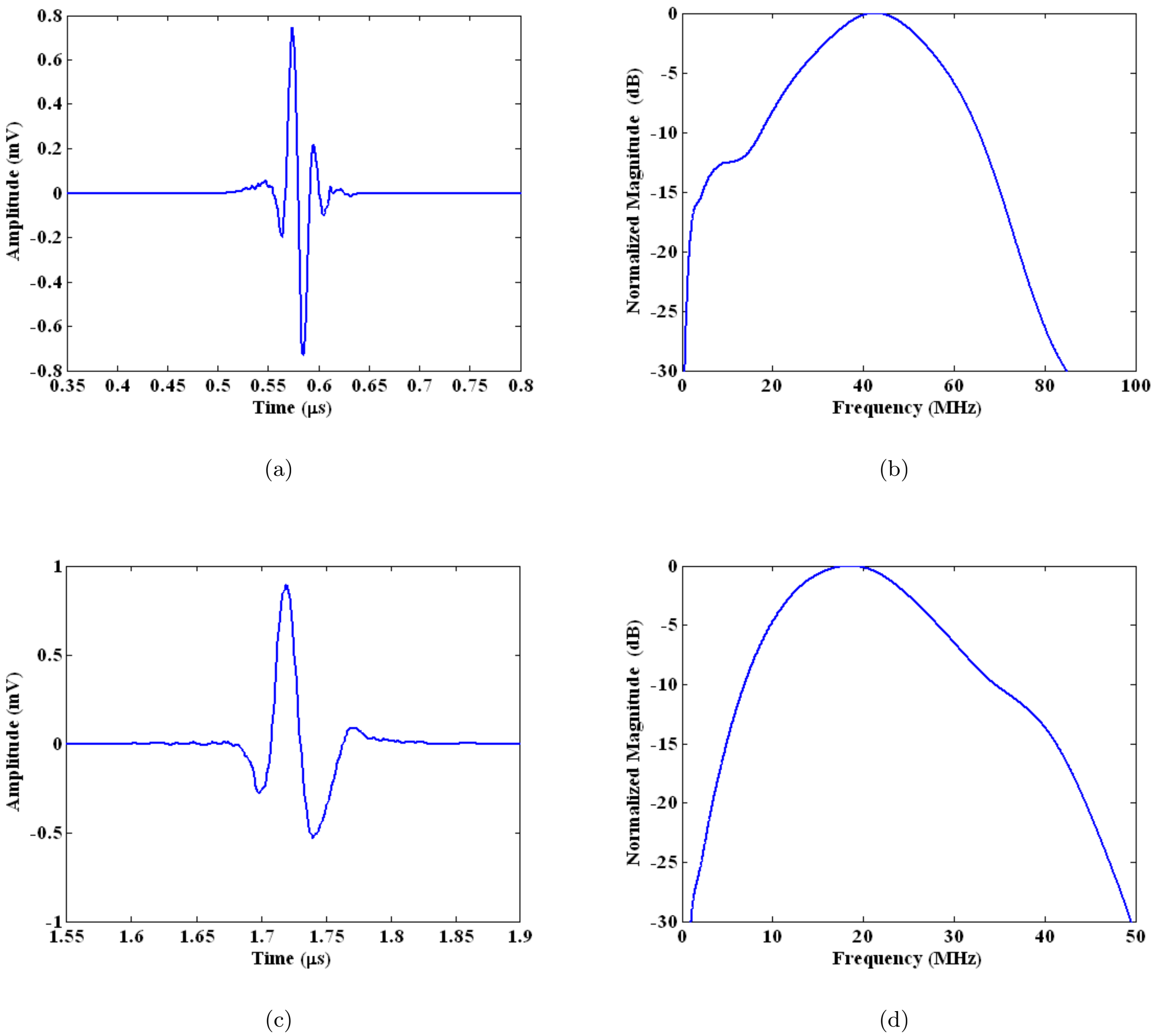


Figure 7. Pulse-echo results for wafer-bonded arrays: (a) windowed echo signal of linear array; (b) FFT of (a); (c) windowed echo signal of ring array; (d) FFT of (c).

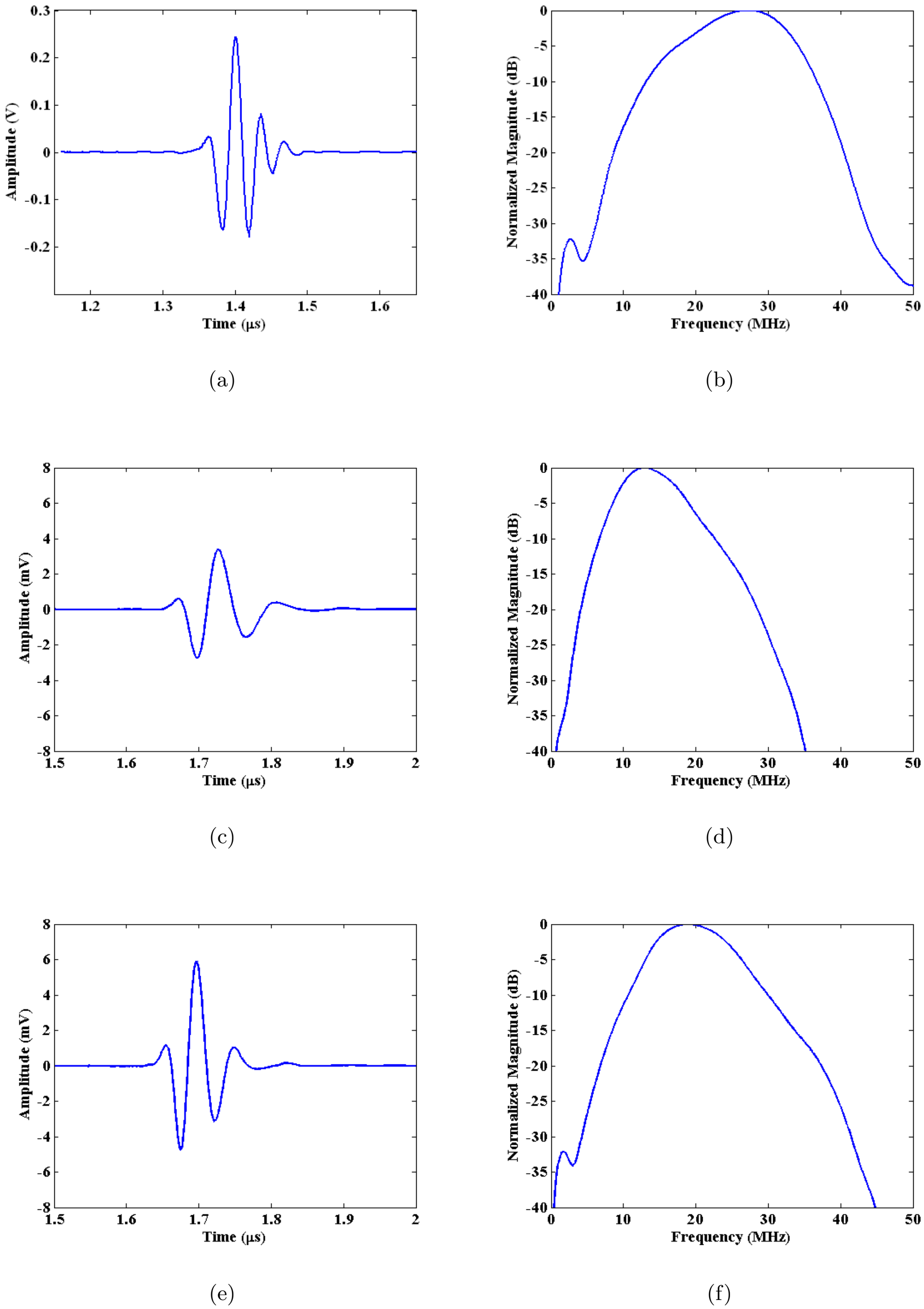


Figure 8. Pulse-echo results for silicon nitride arrays: (a) windowed echo signal of linear array; (b) FFT of (a); (c) windowed echo signal of ring array, conventional mode; (d) FFT of (c); (e) windowed echo signal of ring array, collapse mode; (f) FFT of (e).

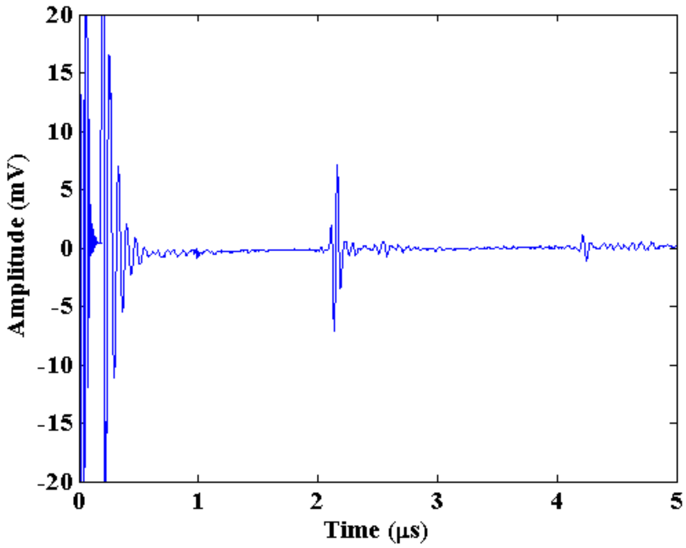


Figure 9. A-scan taken with surface-micromachined ring.

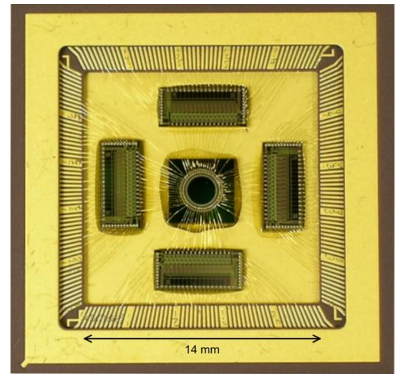


Figure 10. Package for 64-channel ring array imaging.

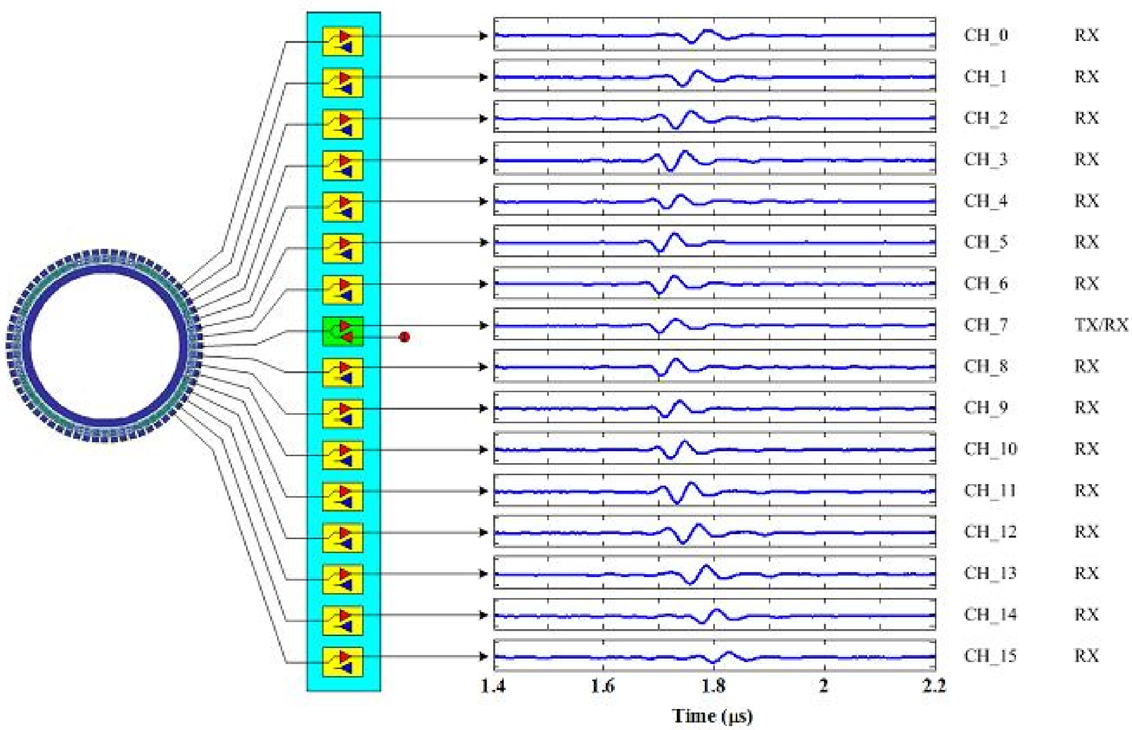


Figure 11. Demonstration of 16 channel transducer array.

Table 2. Pulse-echo results

	Wafer bonded		Surface micromachined		
	Linear	Ring	Linear	Ring	
				Conventional	Collapse
V_{DC}	150	90	110	35	100
V_{AC}	5	5	27	27	27
Pulse width (ns)	15	25	20	30	20
Center frequency (MHz)	41.9	19.2	25.5	13.9	19.8
Bandwidth (MHz)	36.4	20.4	18.4	11.5	14.5
Fractional Bandwidth	87%	106%	72%	83%	73%

4. DISCUSSION

The impedance plots from the wafer-bonded devices have been plotted along with the results from simulation with the equivalent circuit model. Appropriate parasitics were used in the model, and the close match between the simulation and actual results demonstrates the accuracy of the equivalent circuit model. The high-frequency linear array exhibits a parasitic DC leakage as evidenced by the low frequency rise in the real part of its input impedance. The wafer-thinned ring array does not have this characteristic. The performance of the ring array proves the feasibility of the wafer-thinning technique. The pulse-echo measurements for both arrays show high-frequency operation, a short impulse response, and very good bandwidth.

The linear surface-micromachined array exhibits high signal levels because of its large element size compared to that of the ring array. The ring array is operated in both conventional and collapse modes, demonstrating the increase in center frequency and higher output pressure when the CMUT is in the collapse regime.

An A-scan taken with the surface-micromachined ring array is shown in Fig. 9 This plot shows a reflector at 1.5 mm. The ringdown present at the beginning of the scan ends by 500 ns, corresponding to a dead zone of 375 μm.

Finally, the transducer is demonstrated as an array by Fig. 11. The center element was pulsed, and data was collected from all the channels. This shows that this system is ready to be used as an imaging array. The setup for imaging is shown in Fig. 10. It consists of 64 channels of independent pulsers and amplifiers wirebonded to a 64 element ring array. Present work aims to create a data acquisition and image synthesis system to generate 3-D images from this setup.

5. CONCLUSIONS

This work demonstrates high-frequency CMUT arrays from a variety of CMUT technologies operating in 10 MHz to 50 MHz range. CMUT technology is adept at fabricating transducers with very fine pitch, high frequency, and wide bandwidth. Integrated circuits custom designed for this application were presented and bring this work one step closer to the vision of CMUTs being closely integrated with electronics in a complete imaging system. The results shown here support the conclusion that CMUT technology holds great promise for making high-frequency ultrasonic arrays. Progress in the fabrication of CMUT arrays and the corresponding development of high-frequency ultrasonic arrays will enable new applications for high-resolution medical ultrasound.

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