Multiple electrode element capacitive micromachined ultrasonic transducer (cMUT) devices and fabrication methods are provided. Some embodiments can include a forward or side looking catheter device having a plurality of cMUT arrays for transmitting and receiving ultrasonic energy. The forward or side looking intravascular device can generally comprise a plurality of cMUT arrays being disposed on a substrate in a spaced apart arrangement. The plurality of cMUT arrays can each comprise a plurality of cMUT elements. At least a portion of the plurality of cMUT elements can comprise a flexible membrane disposed above the substrate and a multiple element electrode. The multiple element electrode can comprise a plurality of electrode elements shaped and sized to have a width less than the width of the membrane, and be further configured to operatively shape the membrane in a reception state to receive ultrasonic energy and a transmission state to transmit ultrasonic energy.

16 Claims, 7 Drawing Sheets
FIG. 5

(a) 

(b) 

(c) 

(d) 

(e) 

(f)
FIG. 6

600  Provide a Substrate

610  Deposit and Pattern an Isolation Layer

615  Deposit and Pattern a First Conductive Layer

620  Deposit and Pattern a Sacrificial Layer

625  Deposit and Pattern a First Membrane Layer

630  Deposit and Pattern a Second Conductive Layer

635  Etch the Sacrificial Layer and, Deposit, Pattern, and Seal a Second Membrane Layer
FIG. 9

FIG. 10

FIG. 11
**FIG. 12**

Hydphone output (mV) vs. input AC voltage (Vpp)

**FIG. 13**

FFT Amplitude vs. Frequency (MHz)
MULTIPLE ELEMENT ELECTRODE CMUT DEVICES AND FABRICATION METHODS

CROSS REFERENCE TO RELATED APPLICATIONS & PRIORITY CLAIMS

This patent application is a continuation of U.S. patent application Ser. No. 11/068,005 (filed 28 Feb. 2005), which claims the benefit of U.S. Provisional Application No. 60/548,193, filed 27 Feb. 2004, and U.S. Provisional Application No. 60/611,049, filed 16 Sep. 2004. All of said patent applications are hereby incorporated herein by reference as if fully set forth below in their entireties.

TECHNICAL FIELD

The present invention relates generally to chip fabrication, and more particularly, to fabricating capacitive micromachined ultrasonic transducers ("cMUTs") having multiple-element electrodes and cMUT imaging arrays incorporating cMUTs having multiple-element electrodes.

BACKGROUND

Capacitive micromachined ultrasonic transducer ("cMUT") devices generally combine mechanical and electronic components in very small packages. The mechanical and electronic components operate together to transform mechanical energy into electrical energy and vice versa. Because cMUTs are typically very small and have both mechanical and electrical parts, they are commonly referred to as micro-electronic mechanical systems ("MEMS") devices.

Conventional cMUTs generally have a ground electrode and a hot electrode. The hot electrode can be used to transmit and receive ultrasonic acoustical waves during ultrasonic imaging. Due to the differing characteristics associated with transmitting and receiving ultrasonic waves, conventional cMUT hot electrodes are commonly optimized to receive or transmit ultrasonic waves with high sensitivity while the maximum transmit power is compromised. This optimization results in sacrificed device performance for the non-optimized action, ultimately sacrificing the quality of data sent or collected by a cMUT having a hot electrode only optimized for receiving or transmit waves.

One approach to address this problem includes using two cMUTs placed side by side. One of the cMUTs can be optimized for transmitting ultrasonic waves while the other cMUT can be optimized for receiving ultrasonic waves. This approach, while addressing the problems associated with a hot electrode optimized for transmitting or receiving ultrasonic waves, has several drawbacks. For example, a major drawback associated with this solution includes the amount of space sacrificed when two cMUTs are used to transmit and receive ultrasonic waves instead of one. cMUTs are often desirable for small scale applications and the increased space associated with using multiple cMUTs would greatly diminish the desirability of using cMUTs.

Another problem associated with conventional cMUTs is that they have lower maximum transmit pressures relative to piezoelectric ultrasonic transducers. Higher transmit pressures are generally desirable to increase signal penetration and to increase the force of ultrasonic waves reflected from media being imaged. In conventional cMUT operation, where the membrane is moved from a rest position to near collapse, the output pressure is limited because the displacement is limited to the one third of the initial gap. To increase the output transmission pressure output for cMUTs to, for example, 1 MPa (Mega-Pascal), which is desired for medical imaging applications, collapse and collapse-snap back operation states for cMUT membranes have been proposed. These proposed approaches, while increasing cMUT output transmit pressures, are nonlinear operational modes limiting the transmit signal shapes, and can cause severe dielectric charging because of the frequent contact between dielectric layers during operation.

Another problem associated with conventional cMUTs is the difficulty in controlling the shape of a cMUT membrane. Since the geometrical shape of a cMUT membrane largely affects overall cMUT device performance, it is desirable to control a cMUT membrane's shape when transmitting and receiving ultrasonic waves.

An additional disadvantage to conventional cMUTs includes the complicated switching circuitry and signal generation and detection circuitry that must be used in concert with the single receive and transmit cMUT electrode. Typically, complicated circuitry is required for single receive and transmit cMUT electrode because protection circuits must be utilized to prevent large transmit signals to be input to the receiver amplifier. These protection circuits increase the parasitic capacitance in parallel with the cMUT, further degrading the received signal. The switching transients may saturate the receiving amplifier and result in dead zones in the images where the regions close to the transducer array can not be imaged.

Therefore, there is a need in the art for a cMUT fabrication method enabling fabrication of a cMUT with at least one multiple-element electrode to increase and enhance cMUT device performance.

Additionally, there is a need in the art for fabricating cMUTs having controllable membranes to increase and enhance cMUT device performance.

Additionally, there is a need in the art for a cMUT device having multiple hot electrodes or separate transmit and receive electrodes so transmitting and receiving ultrasonic wave functions can be simultaneously optimized.

Still yet, there is a need for cMUTs capable of generating multiple output signals from a single transmit event and utilizing the different frequency content of output signals.

It is to the provision of such cMUT fabrication and cMUT imaging array fabrication that the embodiments of present invention are primarily directed.

BRIEF SUMMARY OF EXEMPLARY EMBODIMENTS

The present invention comprises multiple-element cMUT array transducer fabrication methods and systems. The present invention provides cMUTs for imaging applications that have multiple-element electrodes for optimizing the transmission and receipt of ultrasonic waves, which can be especially useful in medical imaging applications. The cMUTs of the present invention can also be adapted to generate multiple receive signals from single transmit event by utilizing the frequency content of received signals. The cMUTs can be fabricated on dielectric or transparent substrates, such as, but not limited to, silicon, quartz, or sapphire, to reduce device parasitic capacitance, thus improving electrical performance and enabling optical detection methods to be used, although other translucent or opaque materials can be used. Additionally, cMUTs constructed according to the present invention can be used in immersion applications such as intravascular catheters and ultrasound imaging.
The cMUTs fabricated in accordance with the present invention can comprise a cMUT proximate a substrate. The substrate can be a silicon substrate or formed from transparent materials. A circuit can be embedded in the substrate or located proximate the substrate to receive and direct optical or electric signals to and from the cMUT. The cMUTs can also comprise at least one multi-element electrode, which can aid in shaping the cMUT and in providing an optimal membrane shape for transmitting and receiving ultrasonic waves. The multiple-element electrode can also receive and transmit ultrasonic waves. By properly controlling or adjusting a cMUT membrane's shape when transmitting and receiving ultrasonic waves, it is possible to increase image resolution, enhance transmission signal depth penetration, increase transmit output pressure, and generate multiple output signals with different frequency content.

In a preferred embodiment, the present invention is a cMUT comprising a multi-element first electrode having a first electrode element and a second electrode element, wherein the first and second electrode elements are adapted to transmit an ultrasonic wave. The first electrode element and the second electrode element are typically physically separated, but can be electrically coupled. The multi-element first electrode can be disposed within a membrane. The multi-element first electrode can be disposed proximate a substrate.

The preferred cMUT has a flexible membrane and a membrane shaping means, the membrane shaping means preferably being at least one of the first electrode element and the second electrode element. The cMUT can further include a bottom electrode, wherein the membrane and the bottom electrode are separated by a gap distance in an electrically neutral state, and wherein a side electrode element pair is adapted to flex the membrane by more than one third of the gap distance during transmission of an ultrasonic wave.

A method of transceiving ultrasonic waves according to the present invention preferably comprises the steps of providing a cMUT having a multi-element first electrode incorporating a first electrode element and a second electrode element, the first electrode element separate from the second electrode element, and applying a first voltage to the first electrode element and the second electrode element to transmit an ultrasonic wave. The preferred method of transceiving ultrasonic waves further includes the step of applying a bias voltage to the first electrode element and the second electrode element to receive an ultrasonic wave signal, the step of optically sensing the received ultrasonic wave signal, and the step of electrically sensing the received ultrasonic wave signal.

A method of fabricating a cMUT according to another embodiment of the present invention comprises the steps of providing a top conductor, providing a bottom conductor separated by a gap distance from the top conductor, and configuring at least one of the top and bottom conductors into a plurality of electrode elements physically separated from one another, although at later fabrication steps, two or more of the electrode elements can be electrically coupled. The top and bottom conductor can be formed of the same material(s), or different material(s). The top and bottom conductors can be adapted to both transmit and receive ultrasonic signals.

The method of fabricating the cMUT can further comprise the steps of providing a sacrificial layer proximate the first conductor, providing a first membrane layer proximate the sacrificial layer, providing a second membrane layer proximate the first conductor, and removing the sacrificial layer.

Another preferred embodiment of the present invention includes a cMUT comprising a first electrode that incorporates a first electrode element and a second electrode element proximate the first electrode element. An electrode having a plurality of elements in accordance with the present invention can efficiently transmit and receive ultrasonic wave signals. The electrode elements can be used both to transmit and aid in shaping a cMUT membrane so that the cMUT is optimized for transmitting and receiving ultrasonic acoustical waves. A preferred embodiment of the present invention can utilize leveraged bending to increase the membrane displacement from one third of the initial cMUT cavity to nearly the entire initial cMUT without collapse.

In another preferred embodiment of the present invention, a method to fabricate a cMUT comprises providing a first conductive layer, providing a second conductive layer, and patterning one of the first and second conductive layers into a plurality of electrode elements. The first conductive layer can be proximate the substrate, and can be isolated from the second conductive layer. A cMUT fabrication method can also comprise providing a sacrificial layer proximate the first conductive layer, providing a first membrane layer proximate the sacrificial layer, providing a second membrane layer proximate the second conductive layer, and removing the sacrificial layer to form a cavity. The multiple elements of the first conductive layer and the second conductive layer can be isolated from each other by enveloping the multiple elements in a dielectric material, such as silicon nitride. While the multiple elements are physically separate one from another, later fabrication may electrically couple two or more elements.

In yet another preferred embodiment of the present invention, a method of transceiving an ultrasonic wave using a cMUT comprises applying a first bias voltage to a first electrode element to increase a gap distance and applying an AC signal to a first electrode element to transmit an ultrasonic wave. The method can further comprise applying a second bias voltage to the first electrode element to decrease the gap distance and receiving an ultrasonic wave signal.

This configuration has several advantages including, but not limited to, the maximum pressure amplitude during transmit mode can be significantly increased. By locating the transmit electrodes near the edges of the membrane, leveraged bending can increase the maximum displacement without collapsing the membrane.

In yet another preferred embodiment, the present invention is a cMUT comprising a multi-element first electrode having a first electrode element and a second electrode element, wherein the first and second electrode elements are adapted to shape a membrane.

These and other features as well as advantages, which characterize the various preferred embodiments of present invention, will be apparent from a reading of the following detailed description and a review of the associated drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a cross-sectional view of a cMUT having a multi-element top electrode in accordance with a preferred embodiment of the present invention.

FIG. 2 illustrates a cross-sectional view of a cMUT having a multi-element bottom electrode in accordance with a preferred embodiment of the present invention.

FIG. 3 illustrates a top view of a cMUT having a multi-element electrode in accordance with a preferred embodiment of the present invention.

FIG. 4A illustrates a sample timing diagram of signals provided to a cMUT comprising a multi-element electrode in accordance with a preferred embodiment of the present invention.
The present invention provides cMUTs comprising at least one multiple-element electrode. The top electrode and the bottom electrode can both be fabricated to have multiple elements. Preferably, only one of the top electrode or the bottom electrode has multiple elements. In some embodiments, both the top electrode and the bottom electrode can have multiple elements. The multiple-element electrode can aid in controlling a cMUT to maximize both transmission and receipt of acoustical waves. cMUTs having multiple-element electrodes can aid in shaping or altering cMUT membranes for optimal signal transmission and receipt when varying signals are applied to multi-element electrodes.

Exemplary equipment for fabricating cMUTs according to the present invention can include a PECVD system, a dry etching system, a metal sputtering system, a wet bench, and photolithography equipment. cMUTs fabricated according to the present invention generally include materials deposited and patterned on a substrate in a build-up process. The present invention can utilize low-temperature PECVD processes for depositing various silicon nitride layers at approximately 250 degrees Celsius, which is preferably the maximum process temperature when a metal sacrificial layer is used. Alternatively, the present invention according to other preferred embodiments can utilize an amorphous silicon sacrificial layer deposited as a sacrificial layer at approximately 300 degrees Celsius.

Referring now to the drawings, in which like numerals represent like elements, preferred embodiments of the present invention are herein described.

FIG. 1 illustrates a cross-sectional view of a cMUT 100 having a multi-element top electrode in accordance with a preferred embodiment of the present invention. The cMUT 100 comprises various material layers proximate a substrate 105. The substrate 105 can comprise silicon and can also comprise materials enabling optical detection methods, preferably transparent materials, to be utilized in accordance with the present invention. The material layers can include an adhesion layer 110, a bottom electrode 115, an isolation layer 120, a membrane 130, and a top electrode layer configured into multiple electrode elements 135, 140, 145. The bottom electrode 115 and top electrode elements 135, 140, 145 can be many conductive materials, such as conductive metals or a doped surface of silicon substrate. As discussed in greater detail below, the top electrode layer forming the multiple electrode elements 135, 140, 145 is generally deposited then configured into the multiple electrode elements 135, 140, 145.

The substrate 105 can be formed of silicon and can contain signal generation and reception circuits. For example, the substrate 105 can comprise an integrated circuit 150 embedded in the substrate 105 to enable the cMUT 100 to transmit and receive ultrasonic waves. FIG. 1 illustrates the integrated circuit 150 as embedded, while FIG. 2 illustrates an alternative embodiment wherein the circuit 150 is proximate the substrate, although not necessarily embedded in the substrate. The integrated circuit 150 can be adapted to generate and receive signals and provide the signals to an image processor 155. The integrated circuit 150 can contain both signal generation and reception circuitry or separate integrated generation and reception circuits can be utilized. The image processor 155 can process the signals and create an image from the signals.

The adhesion layer 110 can be placed on the substrate 105 and disposed between the substrate 105 and the bottom electrode 115. The adhesion layer 110 can be Chromium, or many other suitable materials, and is optional in some embodiments. For example, when a doped surface of a substrate, for
example a silicon substrate, forms the bottom electrode 115, the adhesion layer 110 may not be utilized. The bottom electrode 115 is preferably fabricated from a conductive material such as Gold or Aluminum. The adhesion layer 110 can be used to adequately bond the bottom electrode 115 to the substrate 105.

The cMUT 100 can also comprise an isolation layer 120 and a cavity 125 defined by a membrane layer 130. The isolation layer 120 can be deposited on the bottom electrode 115, and can comprise silicon nitride. The isolation layer 120 can be isolated from the bottom electrode 115 by etchants used to form the cavity 125. The isolation layer 120 may not be utilized in some embodiments. As shown, the cavity 125 is generally disposed between the isolation layer 120 and the membrane 130. In embodiments without an isolation layer 120, the cavity 125 would generally be disposed between the bottom electrode 115 and the membrane 130. The cavity 125 can be formed by removing or etching a sacrificial layer generally disposed between the bottom electrode 115 and the membrane 130.

The membrane 130 can have elastic characteristics allowing it to move relative to the substrate 105. The membrane 130 can comprise silicon nitride and can be formed from multiple membrane layers. For example, the membrane 130 can be formed from a first membrane layer and a second membrane layer. In addition, the membrane layer 130 can have sides 131, 132 formed during fabrication by depositing various membrane layers and removing a sacrificial layer to form a cavity 125. As shown, the membrane 130 has a center area 133 generally located equally between the sides 131, 132.

In a preferred embodiment, the cMUT 100 can also comprise the top electrode layer being formed of multiple electrode elements 135, 140, 145 disposed within the membrane 130. Two or more of the multiple electrode elements 135, 140, 145 can be coupled to form an electrode element pair. Preferably, side electrode elements 135, 145 are formed nearer the sides 131, 132 of the membrane 130, and center electrode element 140 is formed nearer the center area 133 of the membrane 130. The electrode elements 135, 140, 145 can be fabricated using a conductive material, such as Gold or Aluminum. The side electrode elements 135 and 145 can be electrically coupled and isolated from the center electrode element 145 to form an electrode element pair in the electrode. The electrode elements 135, 140, 145 can be formed from the same conductive material and patterned to have predetermined locations and varying geometrical configurations within the membrane 130. The side electrode element pair 135, 145 can have a width less than the center electrode 140, and a portion of the pair 135, 145 can be placed at approximately the same distance from the substrate 105 as the center electrode element 140. In other embodiments, additional multiple electrode elements can be formed within the membrane 130 at varying distances from the substrate 105. In a preferred embodiment, each side electrode element 135, 145 has a volume approximately half of the volume of the center electrode element 140 so that the combined volume of the side electrode element pair 135, 145 is approximately equal to the volume of the center electrode element 140.

The electrode elements 135, 140, 145 can be adapted to transmit and receive ultrasonic energy, such as ultrasonic acoustical waves, by receiving signals from different voltage sources. The side electrode elements 135, 145 are shown provided with a first signal from a first voltage source 160 (V1) and the center electrode 140 is shown provided with a second signal from a second voltage source 165 (V2). The side electrode elements 135, 145 can be electrically coupled so that voltage or signal supplied to one of the electrode elements 135, 145 will be provided to the other of the electrode elements 135, 145. These signals can be voltages, such as DC bias voltages and AC signals. Preferably, the side electrode elements 135, 145 are adapted to shape the membrane 130 to have a large displacement swing forming a relatively large gap for the transmission of ultrasonic waves by the side electrode elements 135, 145. It is desirable to use a gap size that during transmission allows for greater transmission pressure. Further the side electrode elements 135, 145 can be adapted to shape the membrane 130 to form a relatively small gap for reception of ultrasonic waves by the center electrode element 140. It is desirable to use a gap size for reception that allows for greater sensitivity of the cMUT 100. Both the center electrode element 140 and the side electrode element elements 135, 145 can also receive and transmit ultrasonic energy, such as ultrasonic waves.

The cMUT 100 can be optimized for transmitting and receiving ultrasonic energy by altering the shape of the membrane 130. As discussed below in greater detail with reference to FIGS. 4A and 4B, the electrode elements 135, 140, 145 can be provided with varying bias voltages and signals to alter the shape of the membrane 130. Additionally, by providing the various voltages, the cMUT 100 can operate in two states: a transmission state and a reception state. For example, during a receiving state, the side electrode elements 135, 145 can be provided a bias voltage from the first voltage source 160 (V1) to optimize the shape of the membrane 130 for receiving an acoustic ultrasonic wave using the center electrode element 140 while providing a bias voltage from a second voltage source 165 (V2). The side electrode elements 135, 145 can also be used for receiving ultrasonic waves. Similarly, during a transmission state, the side electrode elements 135, 145 can be provided with an AC signal from the first voltage source 160 (V1) in addition to a bias from the first voltage source 160 (V1) to optimize the shape of the membrane 130 for transmitting an acoustic ultrasonic wave. An AC signal and a bias voltage may be applied by the second voltage source 165 (V2) to the center electrode element 140 during the transmit state.

The first and second voltage sources 160, 165 (V1, V2) can be adapted to provide both AC and DC voltages to the electrode elements 135, 140, 145. These voltage sources 160, 165 (V1, V2) can be controlled by high voltage signal shaping circuitry commonly used in digital ultrasound imaging systems. Vias can be formed in the material layers of the cMUT 100 so that the signals from the first and second voltage sources 160, 165 (V1, V2) can be provided to the electrode elements 135, 140, 145.

FIG. 2 illustrates a cross-sectional view of a cMUT 200 having a multi-element bottom electrode in accordance with a preferred embodiment of the present invention. The cMUT 200 comprises various layers proximate a substrate 205. These layers can include an adhesion layer 210, a dielectric layer 212, a first side electrode element 215, a center electrode element 220, a second side electrode element 225, an isolation layer 230, a membrane 240, and a top electrode 245. The side electrode elements 215, 225 can be electrically coupled in some embodiments forming an electrode element pair of an electrode.

The substrate 205 can comprise silicon and can also comprise materials enabling optical detection methods to be utilized in accordance with the present invention. For example, transparent or translucent materials could be used to enable optical detection methods. The substrate 205 can be formed of silicon and an integrated circuit 250 can be proximate the substrate 205. The substrate 205 can be designed to enable the use of optical signals to transmit and detect capacitance changes associated with cMUT 200. For example, integrated
circuit 250 can be adapted to generate and receive optical signals and provide the optical signals to an image processor 255. The image processor 255 can process the optical signals and create an image from the optical signals. Silicon and many other materials can have beneficial properties with respect to signals having predetermined optical wavelengths. As illustrated in FIG. 2, the adhesion layer 210 can be placed on the substrate 205, and proximate the center electrode element 220. The adhesion layer 210 can be Chromium or many other materials adapted to adequately bond the bottom electrode elements 215, 220, 225 to the substrate 205. In some embodiments, an adhesion layer 210 may not be used if the bottom electrode elements 215, 220, 225 can adequately bond to the substrate 205 during deposition without a separate adhesion layer 210.

The electrode elements 215, 220, 225 can be located at varying positions and formed of many conductive materials. For example, the electrodes 215, 220, 225 can be fabricated using conductive materials, such as Gold or Aluminum. The center electrode element 220 can be proximate a center region of the substrate. The side electrode elements 215, 225 can be proximate side regions of the substrate 205 and the cMUT 200. The electrode elements 215, 220, 225 can also be located in different locations. The side electrode elements 215, 225 can be placed at a greater distance from the substrate 205 than the center electrode element 220. For example, the side electrode elements 215, 225 can be disposed within a dielectric layer 212, such as silicon nitride. The side electrode elements 215, 225 can also be located the same distance from the substrate 205 as the center electrode element 220 in some embodiments. The electrode elements 215, 220, 225 can be orientated substantially parallel to the substrate 205, or each can be orientated differently at varying orientations.

The cMUT 200 can further comprise an isolation layer 230. The isolation layer 230 can isolate the electrode elements 215, 220, 225 from each other physically, although at later steps of fabrication, the elements 215, 220, 225 can be electronically coupled. The isolation layer 230 can also enable the use of certain etchants to fabricate a cMUT that would otherwise harm or degrade unprotected electrode elements 215, 220, 225 or the substrate 205. The isolation layer 230 can comprise silicon nitride, or many other dielectric materials. In some embodiments the isolation layer 230 may not be utilized since certain etchants may not harm or degrade the electrode elements 215, 220, 225 or the substrate 205.

The cMUT 200 can also comprise a cavity 235 defined by a membrane 240. The cavity 235 can be formed by etching or removing a sacrificial layer proximate the isolation layer 230. The sacrificial layer preferably comprises Chromium. Other materials capable of being removed by etching procedures can also be used. The membrane 240 can be deposited on the sacrificial layer before the sacrificial layer is etched. The cavity 235 enables the membrane 240 to fluctuate and move relative to the substrate 205 in response to stimuli. The membrane 240 can comprise multiple layers of membrane materials, such as silicon nitride.

The cMUT 200 can also comprise a top electrode 245 disposed within the membrane 240. The top electrode 245 can be deposited on a first layer of membrane material and then a second layer of membrane material can be deposited on the top electrode 245, thus enveloping the top electrode 245 within the membrane 240. The top electrode 245 is preferably fabricated using a conductive material, such as Gold or Aluminum.

The cMUT 200 can be provided with signals from a first voltage source 260 (V1) and a second voltage source 265 (V2). A first voltage source 260 can provide a first voltage (V1) between the side electrode elements 215, 225 and the top electrode 245, and a second voltage source 265 can provide a second voltage (V2) between the center electrode element 220 and the top electrode 245. The side electrode elements 215, 225, although physically separated by a distance, can be electrically coupled so that a voltage or signal supplied to one of the electrode elements 215, 225 will be provided to the other of the electrode elements 215, 225. By providing these voltages at different time intervals, the cMUT 200 can be optimized for transmitting and receiving ultrasonic acoustic waves.

Additionally, these voltages (V1, V2) can enable the cMUT 200 to operate in a receiving state and a transmission state. Preferably, the first voltage source 260 (V1) is adapted to provide a first voltage (V1) between the side electrode elements 215, 225 and the top electrode 245 in both the transmission state and the receive state. And the second voltage source 265 (V2) is preferably adapted to provide a second voltage (V2) between the center electrode element 220 and the top electrode 245 in the receiving state. The side electrode elements 215, 225 can also receive ultrasonic acoustical waves, and the center electrode element 220 can also transmit ultrasonic energy, such as acoustic waves.

The cMUT 200 can be utilized to sense images. For example, the cMUT 200 can be adapted to receive a fluctuating capacitance between the electrode elements 215, 220, 225 and 245 in response to environmental factors (such as external applied pressures). The cMUT 200 can also be adapted to provide the fluctuating capacitance to a system that produces an image from the received capacitance. An integrated circuit 250 can sense signals produced by the fluctuation of the top electrode 245 relative to the side electrode elements 215, 225 and the center electrode element 220, and provide those electronic signals to an image processor 255.

Those skilled in the art will be familiar with various methods for translating capacitance measurements on a cMUT imaging array into an image using an image processor 255 or similar system. The electrode elements 215, 220, 225 can be coupled to an integrated circuit 250 through vias formed in the layers of the cMUT 200. The integrated circuit 250 can comprise CMOS electronic devices or other transistor-type devices.

Additionally, the cMUT 200 can be utilized to sense a variety of real-time information. For example, the device can be adapted to be a pressure sensor, a temperature sensor, a flow sensor, a Doppler flow sensor, an electrical resistivity sensor, a fluid viscosity sensor, a gas sensor, a chemical sensor, an accelerometer, or other desirable sensors. In addition, when used in imaging applications, the cMUT 200 can be a florescence or optical reflectivity sensor adapted to measure reflected and scattered light from surrounding tissue and fluids to monitor optical parameters such as reflectivity and florescence.

The cMUT 200 can be fabricated from a plurality of layers. Conductive materials can form conductive layers, which can be configured to form the electrode elements 215, 225, 220, 245. For example, the conductive material can be a doped silicon surface of the substrate 205, a doped polysilicon layer, a conductive metal, or other suitable conductive materials. The electrode elements 215, 225, 220, 245 can be coupled to signal generation and detection circuits such as the integrated electronic circuit 250. In some embodiments, the signal generation and detection circuits can be embedded within the substrate 205 or can be located on another chip proximate the substrate 205.
embodiment of the present invention. The cMUT 300 generally comprises a substrate 305, a membrane 310, a center electrode element 315, and a side electrode element pair 320.

More electrode elements can be used in other embodiments of the present invention. The center electrode element 315 and side electrode element pair 320 can be proximate the substrate 305 and can be partially disposed within the membrane 310. The membrane 310 can be proximate the substrate 305 and preferably defines a cavity, as illustrated in FIGS. 1 and 2. In addition, the membrane 310 can have side areas 311, 312 on either side of the membrane 310.

The center electrode element 315 and side electrode element pair 320 can have varying geometric shapes and locations within the membrane 310. As shown, the center electrode element 315 can be rectangular-shaped and centrally located within the membrane 310. The side electrode element pair 320 can be rectangular-shaped and as shown, have side electrode elements 320A, 320B. The side electrode element pair 320 can also have more than two electrode elements in accordance with the present invention. The side electrode elements 320A, 320B can be substantially parallel to the center electrode element 315. The side electrode elements 320A, 320B of the side electrode element pair 320 can have a width less than that the center electrode 315, and can be located near sides areas 311, 312 of the membrane 310. The distance between the center electrode element 315 and the side electrode elements 320A, 320B can vary. This distance can aid in controlling the parasitic capacitance between the center electrode element 315 and the side electrode element pair 320 as the distance between the center electrode element 315 and the side electrode element pair 320 affects the capacitance between the electrode elements 315, 320.

The center electrode element 315 and side electrode element pair 320 can be adapted to receive and transmit ultrasonic acoustical waves. In some embodiments, the center electrode element 315 can be adapted to receive ultrasonic acoustical waves and the side electrode elements 320A, 320B can be adapted to transmit ultrasonic acoustical waves. The center electrode element 315 and the side electrode element pair 320 can be adapted to receive ultrasonic acoustical waves. For example, the center electrode element 315 can be adapted to receive ultrasonic acoustical waves and the side electrode element pair 320 can be adapted to transmit ultrasonic acoustical waves. The voltages can be bias voltages as shown in FIG. 4A. For example, a first voltage source 160 (V1) can provide an AC signal 405 and a bias voltage 410 to a cMUT electrode elements, and the voltage sources 160, 165 can provide the signals simultaneously. Additionally, the voltage sources 160, 165 can be adapted to provide the AC signal 405 and the bias voltage 410 during a transmit cycle 406 and a receive cycle 407. During a transmit cycle 406, a cMUT can be optimized for transmitting an acoustic wave, and during a receive cycle 407, a cMUT can be optimized for receiving an acoustic wave. The AC signal 405 can rise to a positive peak at B from a base level A, fall to a negative peak at C, rise to a positive peak at C, and eventually rise to a constant level D approximately equal to the positive peak at B during a transmit cycle 406 and a receive cycle 407. The bias voltage 410 can remain substantially constant during the transmit and receive cycles 406, 407. The level of the bias voltage 410 can be close to the membrane collapse voltage such that while in the receive cycle 406, the membrane is close to collapsing. During a receive cycle 407, the AC signal 405 and the DC voltage 410 can remain substantially constant to shape the membrane 420 for optimal reception.

FIG. 4B illustrates a cMUT membrane 420 fluctuating in response to the signals 405, 410 illustrated in FIG. 4A provided to a cMUT in accordance with a preferred embodiment of the present invention. When a cMUT membrane 420 is not biased with a bias voltage, (electrically neutral) it can be substantially horizontal or planar. Upon the initiation of a transmit cycle 406 and at A, the membrane 420 is biased (pulled) toward a substrate 425 (see 420A). At B, during the transmit cycle 406, the membrane 420 is biased toward the substrate 425, such that the membrane 420 is close to collapsing and contacting the substrate 425 (see 420B). At C, during the transmit cycle 406, the membrane 420 can rebound toward the no bias position (see 420C). As shown, the membrane 420 can have a relatively large fluctuation 430 between 420B and 420C during a transmit cycle 406.

Upon the initiation of a receive cycle 407 and at D, the membrane 420 can be biased so that the membrane 420 moves toward a substrate 425 (see 420D). As shown in FIG. 4B, the membrane 420 can be close to the substrate 425 creating a relatively small gap 435 during the receive cycle. For multiple transmit/receive cycles, the voltage sources can continuously provide the AC signal 405 and the DC voltage 410 to aid in shaping the membrane 420 for transmitting and receiving acoustic ultrasonic waves.

FIG. 5 illustrates a fabrication process utilized to fabricate a cMUT comprising a multi-element electrode in accordance with a preferred embodiment of the present invention. Typically, the fabrication process is a build-up process that involves depositing various layers of materials on a substrate 505 and patterning the various layers in predetermined configurations to fabricate a cMUT on the substrate 505.

In a preferred embodiment of the present invention, a photosist such as Shipley S-1813 is used to lithographically define various layers of a cMUT. Such a photosist material does not require the conventional use of high temperatures for patterning vias and material layers. Alternatively, many other photosist or lithographic materials can be used. A first step in the present fabrication process provides a bottom electrode 510 on a substrate 505. The substrate 505 can comprise dielectric materials, such as silicon, quartz, glass, or sapphire. In some embodiments, the substrate 505 contains integrated electronics 150, and the integrated electronics can be separated for transmitting and receiving signals. Alternatively, a second substrate (not shown) located proximate the substrate 505 containing suitable signal transmission and detection electronics can be used. A conductive
material, such as conductive metals, can form the bottom electrode 510. The bottom electrode 510 can also be formed by doping a silicon substrate 505 or by depositing and patterning a conductive material layer (such as metal) on the substrate 505. Yet, with a doped silicon bottom electrode 510, all non-moving parts of a top electrode can increase parasitic capacitance, thus degrading device performance and prohibiting optical detection techniques for most of the optical spectrum.

To overcome these disadvantages, a patterned bottom electrode 510 can be used. As shown in FIG. 5(a), the bottom electrode 510 can be patterned to have a different length than the substrate 505. By patterning the bottom electrode 510, device parasitic capacitance can be significantly reduced.

The bottom electrode 510 can be patterned into multiple electrode elements, and the multiple electrode elements can be located at varying distances from the substrate 505. Aluminum, chromium, and gold are exemplary metals that can be used to form the bottom electrode 510. In one preferred embodiment of the present invention, the bottom electrode 510 has a thickness of approximately 1500 Angstroms, and after deposition, can be patterned as a diffraction grading, and/or to have various lengths.

In a next step, an isolation layer 515 is deposited. The isolation layer 515 can isolate portions of or the entire bottom electrode 510 from other layers placed on the bottom electrode 510. The isolation layer 515 can be silicon nitride, and preferably has a thickness of approximately 50 Angstroms. The isolation layer 515 can aid in forming a chamber, such as a cavity or a via during fabrication. When an isolation layer 515 is deposited onto the bottom electrode layer 510, the isolation layer 515 can be patterned to have a predetermined thickness. In an alternative preferred embodiment, an isolation layer 515 is not utilized.

After the isolation layer 515 is deposited, a sacrificial layer 520 is deposited onto the isolation layer 515. The sacrificial layer 520 is preferably only a temporary layer, and is etched away during fabrication. When an isolation layer 515 is not used, the sacrificial layer 520 can be deposited directly on the bottom electrode 510. The sacrificial layer 520 is used to hold a space while additional layers are deposited during the membrane fabrication. The sacrificial layer 520 can be used to help create a chamber, such as a cavity or a via during fabrication. The sacrificial layer 520 can be patterned into different sections, various lengths, and different thicknesses to provide varying geometrical configurations for a resulting cavity or via.

A first membrane layer 525 is then deposited onto the sacrificial layer 520, as shown in FIG. 5(b). For example, the first membrane layer 525 can be deposited using a Unaxis 790 PECVD system. The first membrane layer 525 can be a layer of silicon nitride or amorphous silicon, and can be patterned to have a thickness of approximately 6000 Angstroms. The thickness of the first membrane layer 525 can vary depending on the particular implementation. Depositing the first membrane layer 525 over the sacrificial layer 520 aids in forming a vibrating cMUT membrane.

After patterning the first membrane layer 525, a second conductive layer 530 can be deposited onto the first membrane layer 525 as illustrated in FIG. 5(c). The second conductive layer 530 can form the top electrode(s) of a cMUT. The second conductive layer 530 can be patterned into different electrode elements 530A, 530B, and 530C that can be separate elements from each other. One or more of the electrode elements 530A, 530B, and 530C can be electrically coupled forming an electrode element pair. The electrodes 530A, 530B, and 530C can be placed at varying distances from the substrate 505. As shown in FIG. 5(d), the second conductive layer 530 can be patterned into a first electrode element 530A and a second electrode element 530B. The first electrode element 530A can be coupled to a third electrode element 530C, forming an electrode element pair. Preferably, the formed electrode pairs 530A, 530B can be isolated from the second electrode element 530B.

The electrode element pair 530A, 530B can be formed from conductive metals such as Aluminum, Chromium, Gold, or combinations thereof. In an exemplary embodiment, the electrode element pair 530A, 530B comprises both aluminum having a thickness of approximately 1200 Angstroms and Chromium having a thickness of approximately 300 Angstroms. Aluminum provides good electrical conductivity, and Chromium can aid in smoothing any oxidation formed on the Aluminum during deposition. Additionally, the electrode element pair 530A, 530B can comprise the same conductive material or a different conductive material than the first conductive layer 510.

In a next step, a second membrane layer 535 is deposited over the electrode elements 530A, 530B, and 530C as illustrated in FIG. 5(d). The second membrane layer 535 increases the thickness of the cMUT membrane at this point in fabrication (formed by the first and second membrane layers 525, 535), and can serve to protect the second conductive layer 530 from etchants used during the cMUT fabrication. The second membrane layer 535 can also aid in isolating the first electrode element 530A from the second electrode element 530B. The second membrane layer 535 can be approximately 6000 Angstroms thick. In some embodiments, the second membrane layer 535 is adjusted using deposition and patterning techniques so that the second membrane layer 535 has an optimal geometrical configuration. Preferably, once the second membrane layer 535 is adjusted according to a predetermined geometric configuration, the sacrificial layer 520 is etched away, leaving a cavity 550 as shown in FIG. 5(f).

To enable etchants to reach the sacrificial layer 520, apertures 540, 545 can be etched through the first and second membrane layers 525, 535 using an RIE process. As shown in FIG. 5(e), access passages to the sacrificial layer 520 can be formed at apertures 540, 545 by etching away the first and second membrane layers 525, 535. When an amorphous silicon sacrificial layer 520 is used, one must be aware of the selectivity of the etch process to silicon. If the etching process has low selectivity, one can easily etch through the sacrificial layer 520, the isolation layer 515, and down to the substrate 505. If this occurs, the etchant can attack the substrate 505 and can destroy a cMUT device. When the bottom electrode 510 is formed from a metal that is resistant to the etchant used with the sacrificial layer, the metal layer can act as an etch retardant and protect the substrate 505. After the sacrificial layer 520 is etched, the cavity 550 can be sealed with seals 542, 547, as shown in FIG. 5(f).

The cavity 550 can be formed between the isolation layer 515 and the membrane layers 525, 535. The cavity 550 can also be disposed between the bottom conductive layer 510 and the first membrane layer 525. The cavity 550 can be formed to have a predetermined height in accordance with some preferred embodiments of the present invention. The cavity 550 enables the cMUT membrane, formed by the first
and second membrane layers 525, 535, to fluctuate and resonate in response to stimuli. After the cavity 550 is formed by etching the sacrificial layer 520, the cavity 550 can be vacuum sealed by depositing a sealing layer (not shown) on the second membrane layer 535. Those skilled in the art will be familiar with various methods for setting a pressure in the cavity 550 and then sealing it to form a vacuum seal.

The sealing layer is typically a layer of silicon nitride, having a thickness greater than the height of the cavity 550. In an exemplary embodiment, the sealing layer has a thickness of approximately 4500 Ångstroms, and the height of the cavity 550 is approximately 1500 Ångstroms. In alternative embodiments, the second membrane layer 535 is sealed using a local sealing technique or sealed under predetermined pressurized conditions. Sealing the second membrane layer 535 can adapt the cMUT for immersion applications. After depositing the sealing layer, the thickness of the composite cMUT membrane can be adjusted by etching back the sealing layer since the cMUT membrane may be too thick to resonate at a desired frequency. A dry etching process, such as RIE, can be used to etch the sealing layer.

A final step in the present cMUT fabrication process prepares the cMUT for electrical connectivity. Specifically, RIE etching can be used to etch through the isolation layer 515 on the bottom electrode 510, and the second membrane layer 535 on the top electrode 530 making the electrodes 510, 530 accessible.

Additional bond pads can be formed and connected to the electrode. Bond pads enable external electrical connections to be made to the top and bottom electrodes 510, 530 with wire bonding. In some embodiments, gold can be deposited and patterned on the bond pads to improve the reliability of the wire bonds.

In an alternative embodiment of the present invention, the sacrificial layer 520 can be etched after depositing the first membrane layer 525. This alternative embodiment invests little time in the cMUT device before performing the step of etching the sacrificial layer 520 and releasing the membrane formed by the membrane layers. Since the top electrode 530 has not yet been deposited, there is no risk that pinholes in the second membrane layer 535 could allow the top electrode 530 to be destroyed by etchants.

FIG. 6 illustrates a logical flow diagram depicting a preferred method (600) to fabricate a cMUT comprising a multi-element electrode. The first step involves providing a substrate (605). The substrate can be an opaque, translucent, or transparent substrate. For example, the substrate can be formed of silicon, glass, or sapphire. Next, an isolation layer is deposited onto the substrate, and patterned to have a predetermined thickness (610). The isolation layer is optional, and may not be utilized in some embodiments. An adhesive layer can also be used in some embodiments ensuring that an isolation layer bonds to a substrate.

After the isolation layer is patterned, a first conductive layer is deposited onto the isolation layer, and patterned into a predetermined configuration (615). Alternatively, a doped surface of a substrate, such as a doped silicon substrate surface, can form the first conductive layer. The first conductive layer preferably forms a bottom electrode for a cMUT on a substrate. The first conductive layer can be patterned to form multiple electrodes. At least two of the multiple electrodes can be coupled together to form an electrode having multiple electrode elements.

Once the first conductive layer is patterned into a predetermined configuration, a sacrificial layer can be deposited onto the first conductive layer (620). The sacrificial layer is patterned by selective deposition and patterning techniques so that it has a predetermined thickness. Then, a first membrane layer can be deposited onto the sacrificial layer (625).

The deposited first membrane layer is then patterned to have a predetermined thickness, and a second conductive layer is then deposited onto the first membrane layer (630). The second conductive layer preferably forms a top electrode for a cMUT. The second conductive layer can be patterned to form multiple electrode elements. At least two of the multiple electrode elements can be coupled together to form an electrode element pair. After the second conductive layer is patterned into a predetermined configuration, a second membrane layer is deposited onto the patterned second conductive layer (635). The second membrane layer can also be patterned to have an optimal geometric configuration.

The first and second membrane layers can encapsulate the second conductive layer, enabling it to move relatively to the first conductive layer due to elastic characteristics of the first and second membrane layers. After the second membrane layer is patterned, the sacrificial layer is etched away, forming a cavity between the first and second conductive layers (635). The cavity formed below the first and second membrane layers provides space for the resonating first and second membrane layers to move relative to the substrate. In a last part of this step, the second membrane layer is sealed by depositing a sealing layer onto the second membrane layer (635).

The embodiments of the present invention can also be utilized to form a cMUT array for a cMUT imaging system. The cMUT imaging arrays illustrated in FIGS. 7 and 8 are only exemplary, as other imaging arrays are achievable in accordance with the embodiments of the present invention.

FIG. 7 illustrates a cMUT imaging array device formed in a ring-annular array on a substrate. As shown, the device 700 includes a substrate 705 and cMUT arrays 710, 715. The substrate 705 is preferably disc-shaped, and the device 700 can be utilized as a forward looking cMUT imaging array. Although the device 700 is illustrated with two cMUT arrays 710, 715, other embodiments can have one or more cMUT arrays. If one cMUT array is utilized, it can be placed near the outer periphery of the substrate 705. If multiple cMUT arrays are utilized, they can be formed concentrically so that the circular-shaped cMUT arrays have a common center point. Some embodiments can also utilize cMUT arrays having different geometrical configurations in accordance with some embodiments of the present invention.

FIG. 8 illustrates a cMUT imaging array system formed in a side-looking array on a substrate. As shown, the device 800 includes a substrate 805, and cMUT arrays 810, 815. The substrate 805 can be cylindrically-shaped, and the cMUT arrays can be coupled to the outer surface of the substrate 805. The cMUT arrays 810, 815 can comprise cMUT devices arranged in an interdigital fashion and used for a side-looking cMUT imaging array. Some embodiments of device 800 can include one or multiple cMUT imaging arrays 810, 815 in spaced apart relation on the outer surface of the cylindrically-shaped substrate 800.

In another preferred embodiment of the present invention, the components of the cMUT can be fabricated according to a predetermined geometric configuration. A preferred embodiment of the present invention is described with particular dimensions, but those skilled in the art will recognize that these dimensions are merely examples and are not intended to limit the scope of the present invention. For convenience, the components of the cMUT in this preferred embodiment will be discussed with reference to FIG. 1. However, the description of particular functions of the components or specific arrangement and sizes of the components are
Experiments were performed using a cMUT 100 fabricated in accordance with a preferred embodiment of the present invention. These experimental results are not intended to be limiting but are intended to aid in the understanding of the operation of embodiments of the present invention. The experimental results presented were obtained using a cMUT with an 8 µm center electrode element and 4 µm side electrode elements on a 20 µm wide, 0.9 µm thick silicon nitride membrane. The multi-element element cMUT was first tested in a water tank to determine the shape of the transmit frequency spectrum.

Each electrode element of the cMUT was biased to 60 V and then excited with an 8 ns, 20 V peak pulse. This voltage pulse applied to the center electrode element generated an acoustic pulse in the water which was then recorded with a hydrophone. After recording the waveform for the center electrode element, the electrical connections were switched to test the side electrode elements. The resulting frequency spectra of the received signals under center and side electrode elements are shown in FIG. 11.

As shown in FIG. 11, the spectra are broad-band with a strong resonance at approximately 10 MHz. This resonance is expected since the cMUT membrane was originally designed to generate an acoustic crosstalk mode at 10 MHz. One can also observe that for the same DC bias, the spectrum of the side electrode elements is approximately 10 dB less than that for the center electrode element. This was confirmed using a simple acoustic finite element model. The gains in transmit pressure result from the application of larger swing voltages to the side electrode elements than are possible with the center electrode element.

After determining the transmit frequency response, the cMUT was excited with a tone burst at 9 MHz and a fixed DC bias. The DC bias was set to half of the collapse voltage for either the center or side electrode elements so that the maximum AC, or swing, voltage could be applied. Therefore, the bias was set to 60 V for the center electrode element 140 and 120 V for the side electrode elements. The amplitude of the received signal at the hydrophone was recorded as the swing voltage was varied and the resulting data is plotted in FIG. 12.

As shown in FIG. 12, one can see that the transmit pressure is 6.8 dB higher under side electrode element excitation than under center electrode element excitation. This comes at the expense of higher DC bias voltages which can be reduced by moving the electrode elements closer to the substrate. Those skilled in the art will recognize that the area of the center electrode element was equal to that of the side electrode elements. Alternatively, the electrode elements can be alternative dimensions to achieve desired characteristics.

The Fourier transform of the received tone burst was calculated for signals resulting from center and side electrode element excitation. The AC amplitude was adjusted so that the pressure output side electrode element excitation was equal to the maximum pressure output under center electrode element excitation. The spectra indicate that side electrode element excitation generates 4 dB less of the second harmonic. This is expected since the cMUT operates far from collapse under side electrode element excitation.

A pulse-echo experiment was performed using the center electrode element and then the side electrode elements. An aluminum reflector was placed 1.5 mm from the substrate and the gap was filled with water. The electrode elements were biased to 90 V and then excited with an 8 ns, 16 V peak pulse. The reflected waveform was amplified and then recorded. The frequency spectra for center electrode element and side electrode element excitation are shown in FIG. 13.
As shown in FIG. 13, the spectra for center electrode element and side electrode element excitation have a similar shapes for frequencies up to 35 MHz. However, in the range of 50 to 70 MHz, the frequency spectra are quite different. The curve for side electrode element excitation exhibits a large peak at approximately 58 MHz, which corresponds to the second resonant mode of the 20 µm wide membrane. This behavior compares well with a simple acoustic finite element model.

While the various embodiments of this invention have been described in detail with particular reference to exemplary embodiments, those skilled in the art will understand that variations and modifications can be effected within the scope of the invention as defined in the appended claims. Accordingly, the scope of the various embodiments of the present invention should not be limited to the above discussed embodiments, and should only be defined by the following claims and all applicable equivalents.

1. In a forward or side looking catheter device having a plurality of cMUT arrays for transmitting and receiving ultrasonic energy, the forward or side looking catheter device comprising:
   a plurality of cMUT arrays being disposed on a substrate in a spaced apart arrangement so that the cMUT arrays are disposed at differing locations on the substrate, the plurality of cMUT arrays each comprising a plurality of cMUT elements,
   at least a portion of the plurality of cMUT elements comprising a flexible membrane disposed above the substrate a first electrode disposed on the membrane and a second electrode disposed on the substrate, at least one of the first and second electrodes being a multiple element electrode, the multiple element electrode comprising a plurality of electrode elements, and the plurality of electrode elements being shaped and sized to have a width less than the width of the membrane, and being further configured to operatively shape the membrane in a reception state to receive ultrasound energy and a transmission state to transmit ultrasonic energy.

2. The forward or side looking device of claim 1, wherein the cMUT arrays are arranged as concentric annular rings on the surface of the substrate.

3. The forward or side looking device of claim 1, wherein the substrate is disc-shaped and the plurality of cMUT arrays are disposed on the surface of the disc-shaped surface.

4. The forward or side looking device of claim 1, wherein the plurality of cMUT arrays comprises a first cMUT array and a second cMUT array, the first cMUT array being disposed proximate an outer periphery of the substrate, and the second cMUT array being in a position different than the first cMUT array.

5. The forward or side looking device of claim 1, wherein the plurality of electrode elements are further configured to receive ultrasonic signals for transmission and to receive bias voltages for positioning the membrane for transmission and reception of ultrasonic waves.

6. The forward or side looking device of claim 1, wherein the plurality of cMUT arrays are distributed at different positions on the substrate.

7. The forward or side looking device of claim 1, wherein at least some of the electrode elements are disposed within the membrane at varying locations across the membrane including a first location, a second location, and third location, the first location being proximate one edge of the membrane, the second location being proximate a middle portion of the membrane, and the third location being proximate a second edge of the membrane.

8. The forward or side looking device of claim 1, wherein the electrode elements include first, second, and third electrode elements, the first and third electrode elements being coupled together to form an electrode pair and forming part of a circuit that does not include the second electrode element, and wherein the first and third electrode elements are operatively configured to control displacement of opposing edge portions of the membrane, and the second electrode element is operatively configured to control displacement of a center region of the membrane.

9. The forward or side looking device of claim 1, wherein the electrode elements include first and second electrode elements, the first and second electrode elements being spaced apart from each, forming part of different circuits, and operatively configured to transmit or receive an ultrasonic wave separately from each other such that the first electrode element can transmit or receive an ultrasonic wave separately from the second electrode element receiving or transmitting an ultrasonic wave.

10. The forward or side looking device of claim 1, wherein the electrode elements are configured to transmit and receive ultrasonic at differing frequencies so that the cMUT arrays are configured to transmit and receive ultrasounds at differing frequencies.

11. The forward or side looking device of claim 1, wherein the first and second voltages comprise only a DC biasing component in the reception state; and wherein one or more of the first and second voltages comprise a DC biasing component and an AC signal in the transmission state.

12. A cMUT-based device configured as a forward or side looking ultrasonic array device that comprises a plurality of cMUT devices, the forward or side looking ultrasonic array device comprising:
   a plurality of cMUT devices formed in a plurality of array portions, the array portions being disposed at differing locations on a substrate that carries the cMUT devices; and
   at least some of the cMUT devices comprising a membrane that defines a cavity situated between the membrane and the substrate a first electrode disposed on the membrane and a second electrode disposed on the substrate, at least one of the first and second electrodes comprising a plurality of electrode elements, each having a cross-sectional width less than the membrane, the electrode elements being spaced apart from each other and forming part of different circuits and being operatively configured for displacement of the membrane for reception and transmission of ultrasonic waves, and wherein the electrode elements can receive and transmit ultrasonic wave energy independent of each other due to being part of different circuits.

13. The forward or side looking ultrasonic array device of claim 12, wherein the cMUT devices are configured to transmit and receive ultrasonic waves at separate frequency ranges.

14. The forward or side looking ultrasonic array device of claim 12, further comprising integrated electronics associated with the array portions to enable cMUT devices within the array portion to transmit and receive ultrasonic energy.

15. The forward or side looking ultrasonic array device of claim 12, wherein the electrode elements are configured to enable the array portions to transmit and receive ultrasonic energy at differing frequencies.
16. The forward or side looking ultrasonic array device of claim 15, wherein the electrode elements include first, second, and third electrode elements disposed within the membrane, and wherein the first and third electrode elements are coupled together to form an electrode pair, and wherein the first and third electrode elements are operatively configured to control displacement of opposing edge portions of the membrane, and the second electrode element is operatively configured to control displacement of a center region of the membrane.