US008531919B2

(12) United States Patent
Cheng et al.

(10) Patent No.: **US 8,531,919 B2**

(45) Date of Patent: **Sep. 10, 2013**

(54) **FLEXIBLE CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCER ARRAY WITH INCREASED EFFECTIVE CAPACITANCE**

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(73) Assignee: **The Hong Kong Polytechnic University**, Hong Kong (HK)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 542 days.

(21) Appl. No.: **12/885,798**

(22) Filed: **Sep. 20, 2010**

(65) **Prior Publication Data**

US 2011/0068654 A1 Mar. 24, 2011

Related U.S. Application Data

(60) Provisional application No. 61/272,404, filed on Sep. 21, 2009.

(51) **Int. Cl.**
H01L 41/08 (2006.01)

(52) **U.S. Cl.**
USPC **367/181**

(58) **Field of Classification Search**
USPC 367/181; 438/22, 48; 257/416; 310/300
See application file for complete search history.

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Primary Examiner — Daniel Pihulic

(74) *Attorney, Agent, or Firm* — Muncy, Geissler, Olds & Lowe, PLLC

(57) **ABSTRACT**

A Capacitive Micromachined Ultrasonic Transducer (CMUT) having a membrane operatively connected to a top electrode and having a bottom electrode having a concave void. When a DC bias voltage is applied, the membrane is deflected towards the bottom electrode such that a peripheral edge region of the membrane is brought into close proximity with the bottom electrode and an electrostatic force proximal to the peripheral edge region of the membrane is increased.

16 Claims, 9 Drawing Sheets

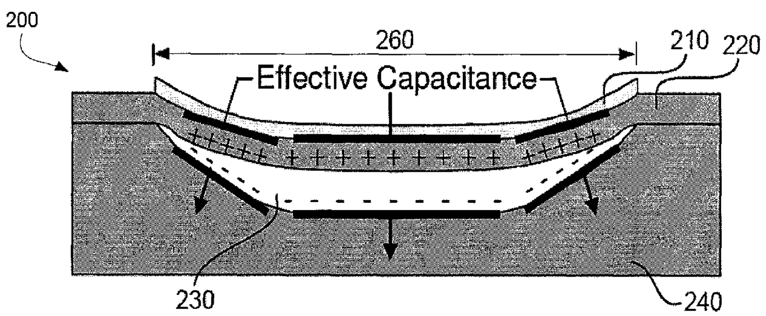

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Figure 1

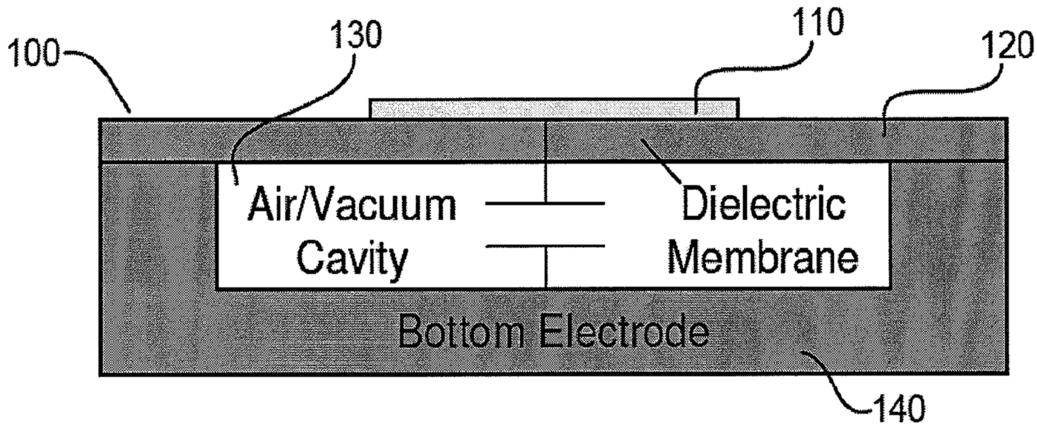


Figure 2

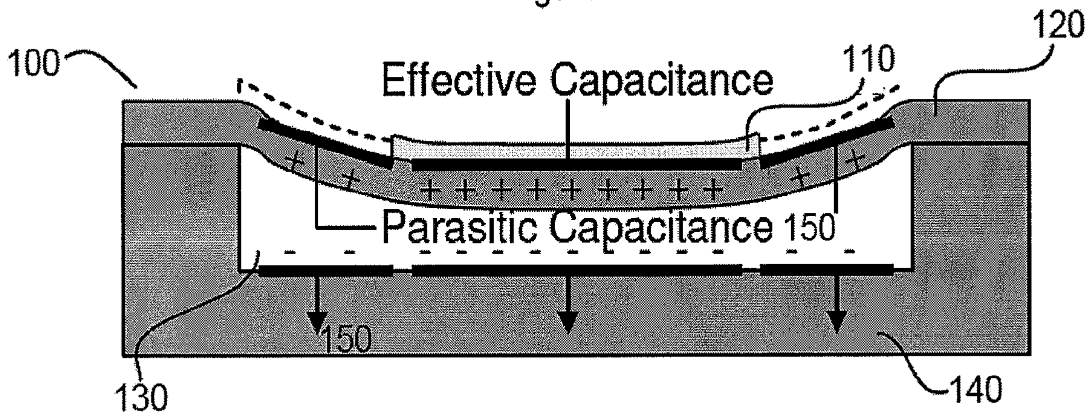


Figure 3

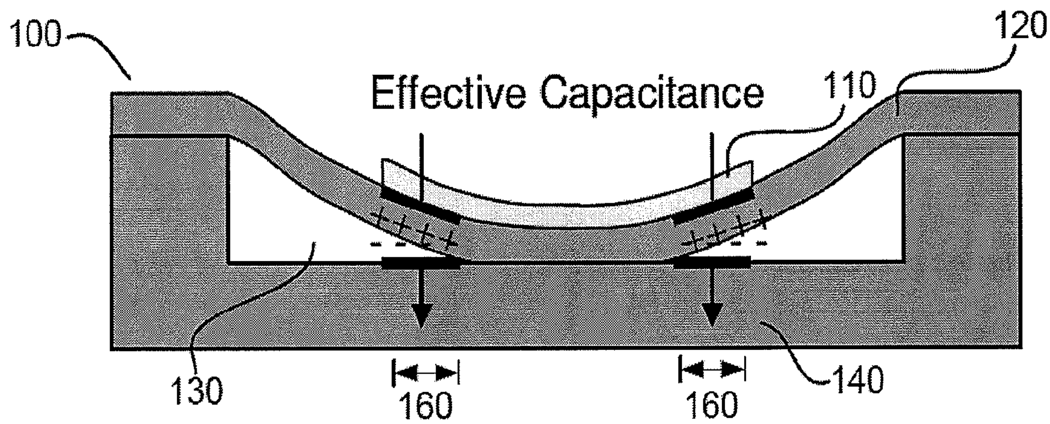


Figure 4

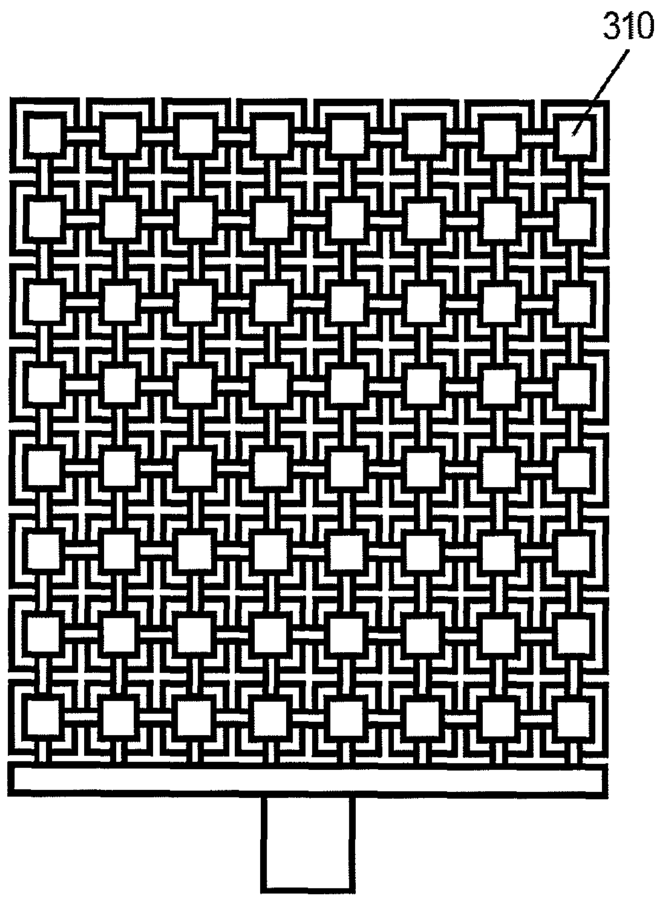


Figure 5

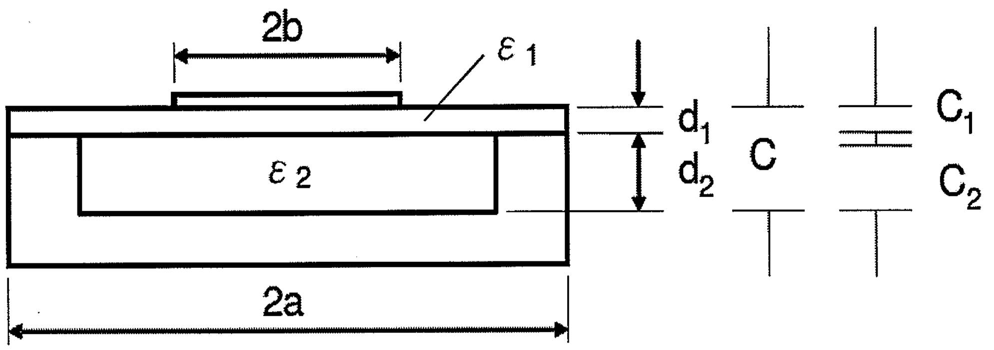


Figure 6

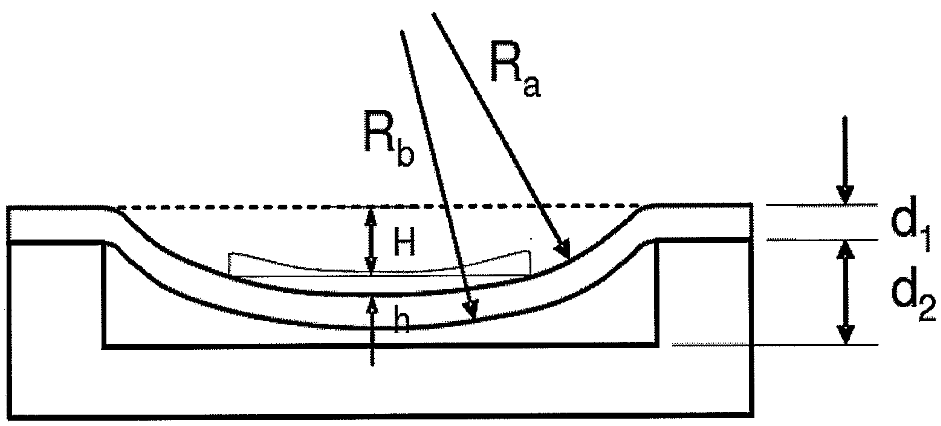


Figure 7

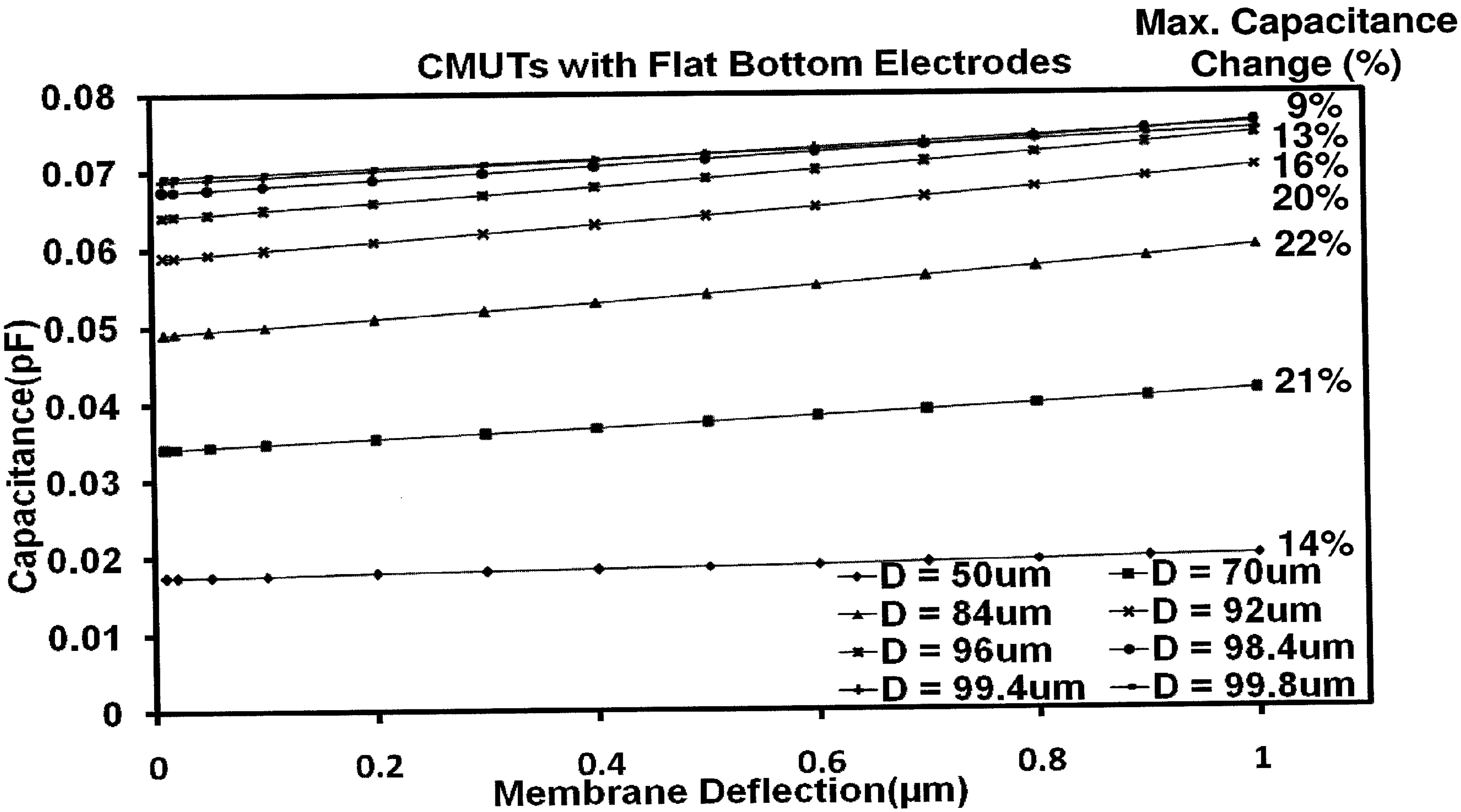

CMUTs with Flat Bottom Electrodes
Max. Capacitance Change (%)
9%
13%
16%
20%
22%
21%
14%
Capacitance(pF)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.2
0.4
0.6
0.8
1
Membrane Deflection(μm)
D = 50um
D = 70um
D = 84um
D = 92um
D = 96um
D = 98.4um
D = 99.4um
D = 99.8um

Figure 8

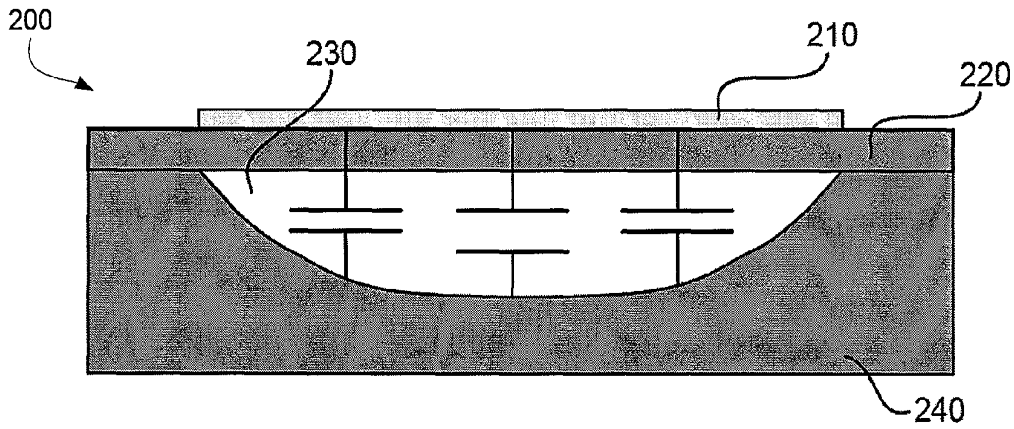


Figure 9

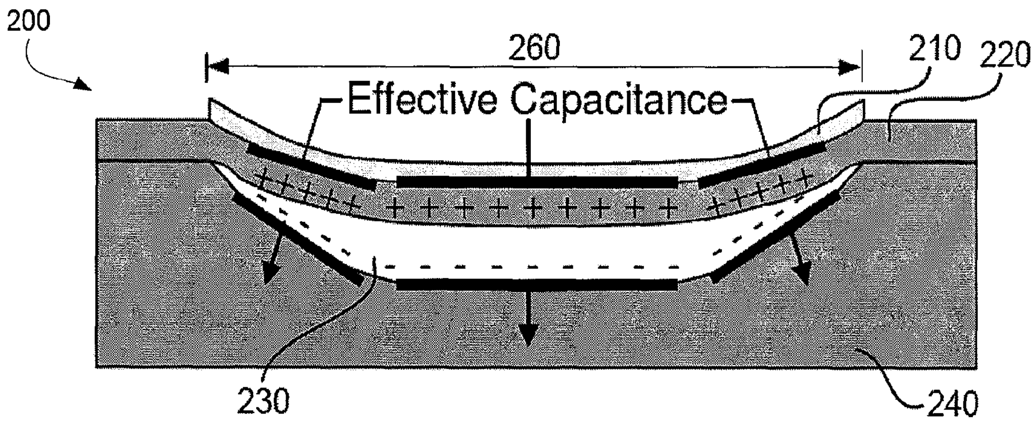


Figure 10

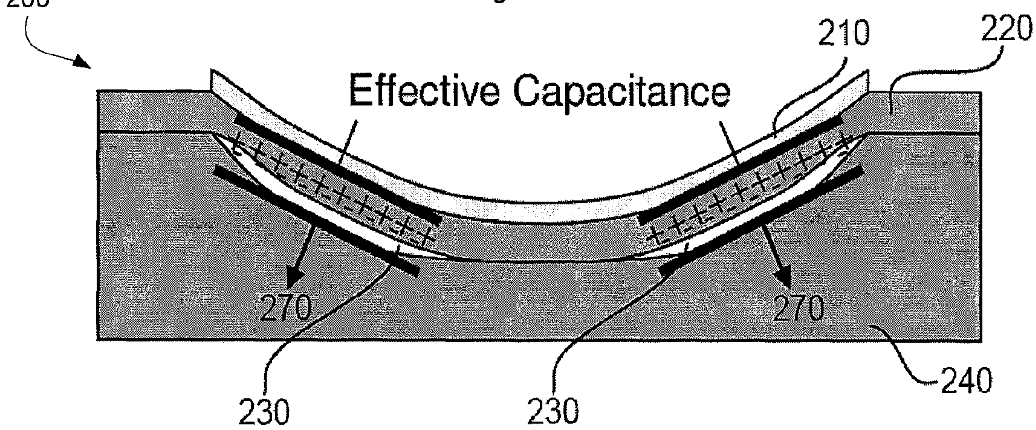


Figure 11

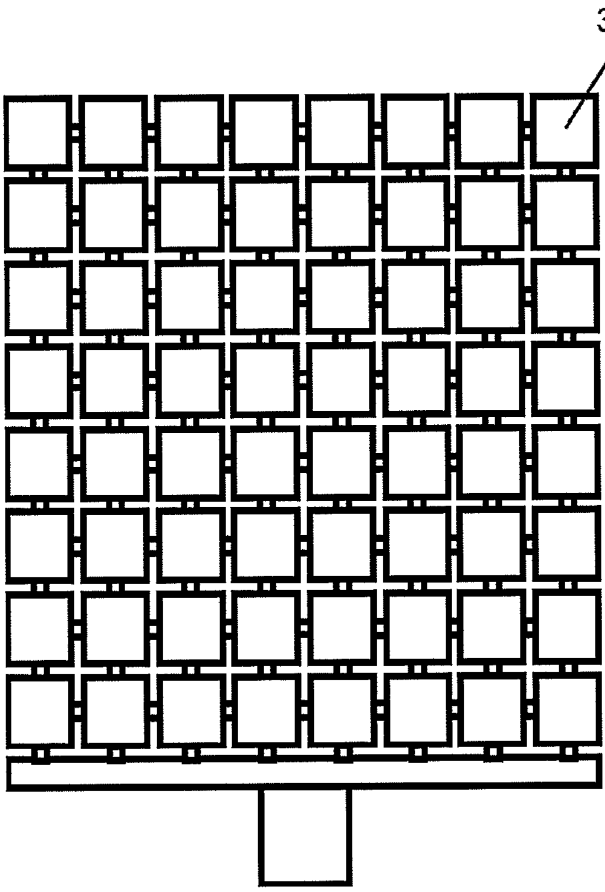


Figure 12

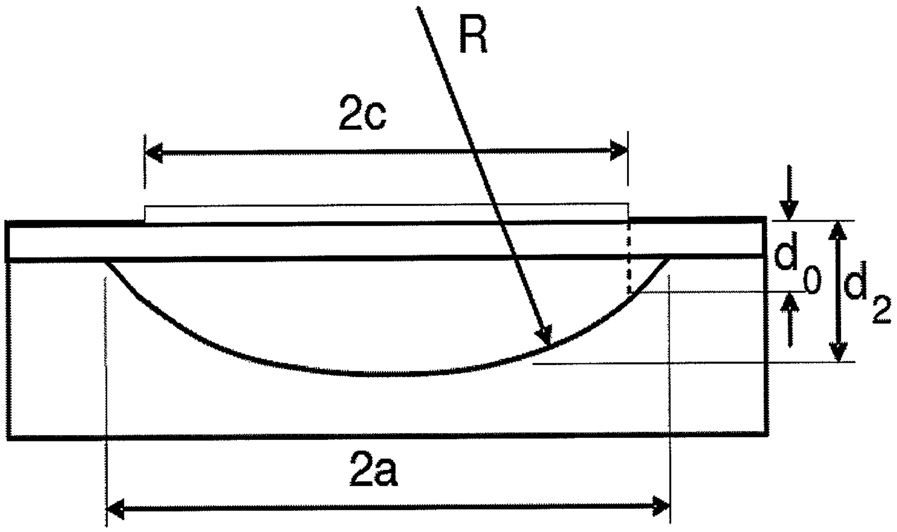


Figure 13

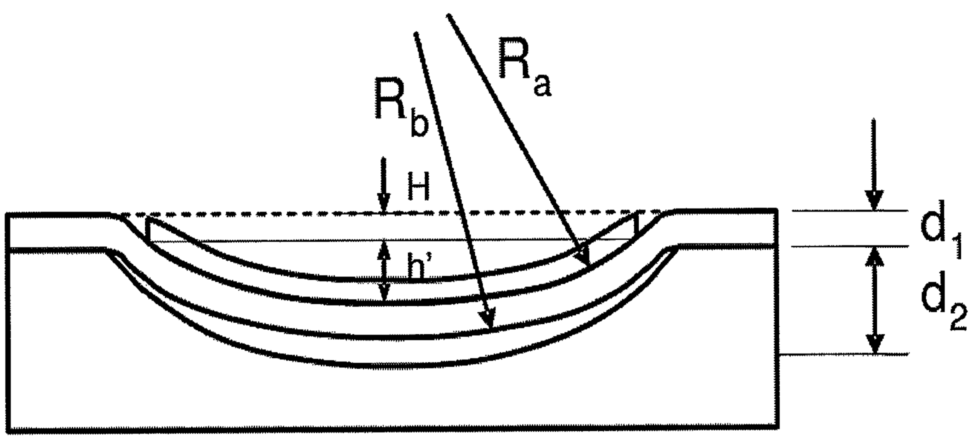


Figure 14

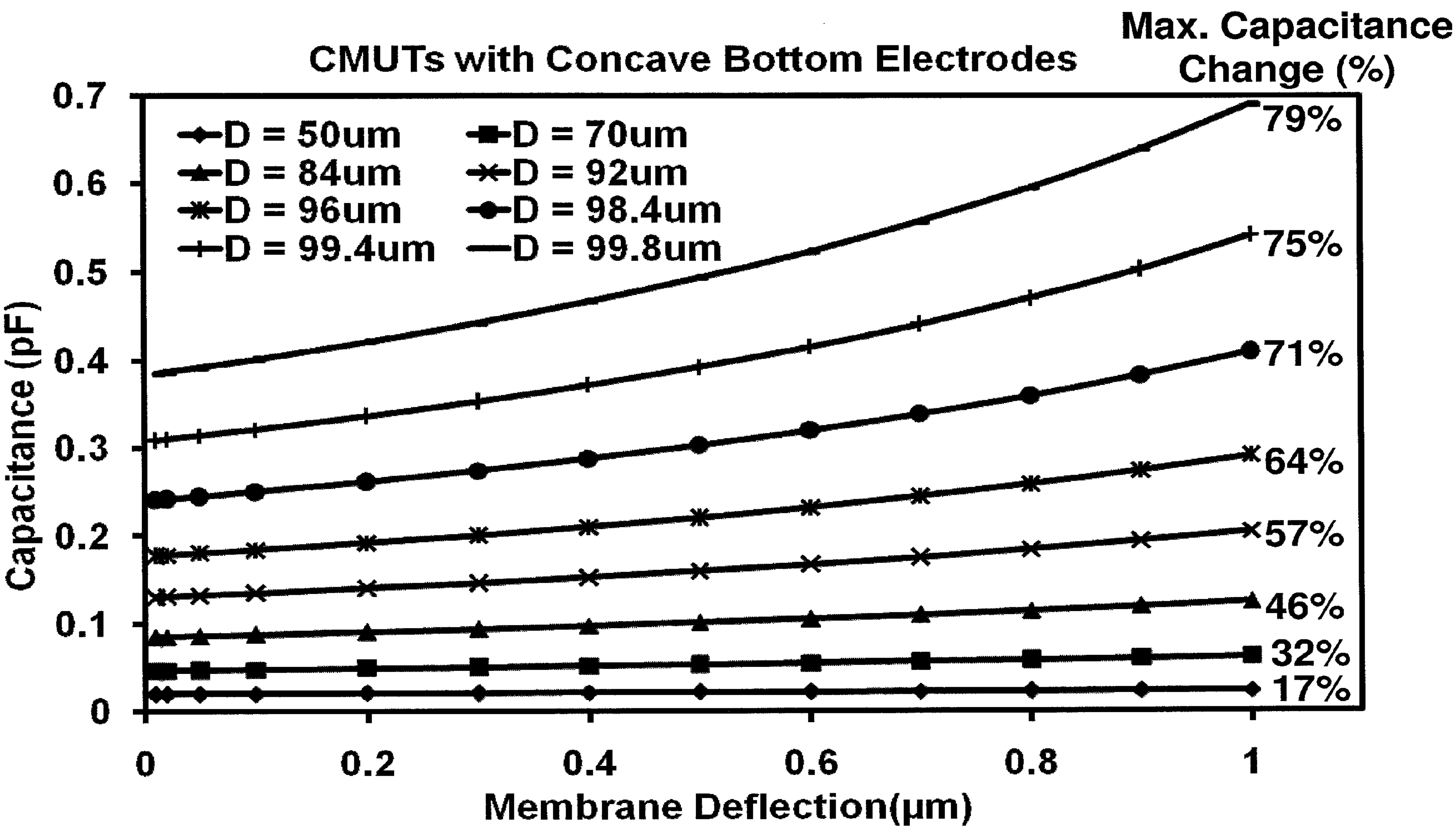
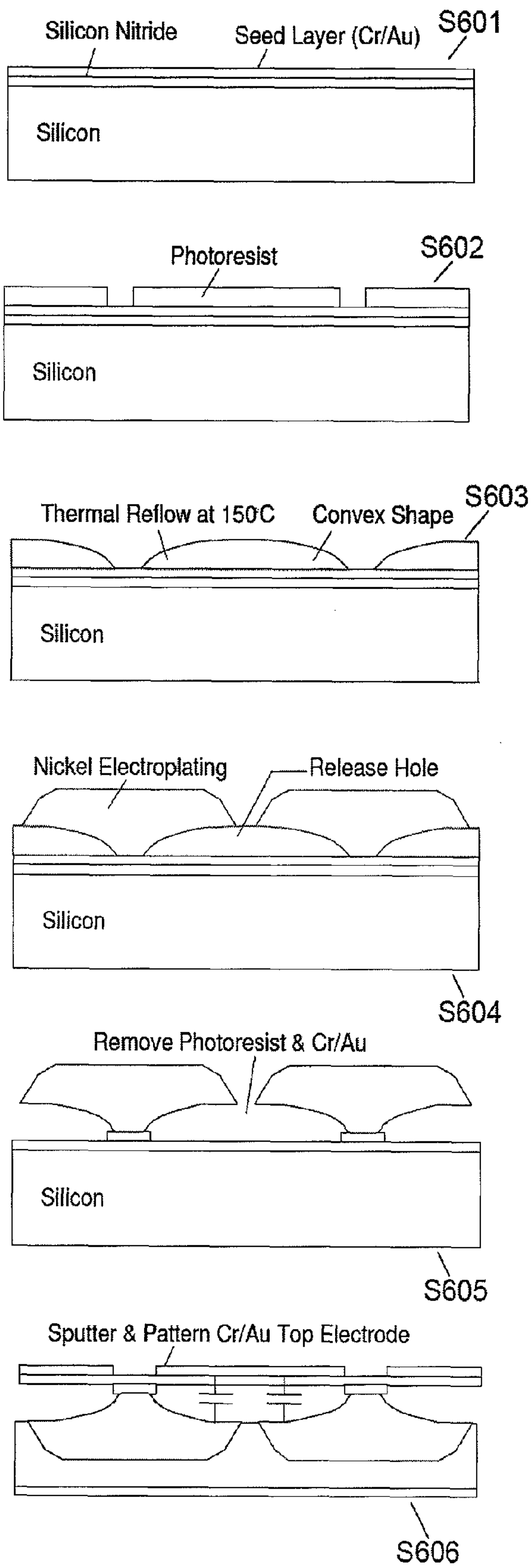

CMUTs with Concave Bottom Electrodes
Max. Capacitance Change (%)
D = 50um
D = 70um
D = 84um
D = 92um
D = 96um
D = 98.4um
D = 99.4um
D = 99.8um
79%
75%
71%
64%
57%
46%
32%
17%
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Capacitance (pF)
0
0.2
0.4
0.6
0.8
1
Membrane Deflection(μm)

Figure 15


Silicon Nitride
Seed Layer (Cr/Au)
S601
Silicon
Photoresist
S602
Silicon
Thermal Reflow at 150C
Convex Shape
S603
Silicon
Nickel Electroplating
Release Hole
Silicon
S604
Remove Photoresist & Cr/Au
Silicon
S605
Sputter & Pattern Cr/Au Top Electrode
S606

FLEXIBLE CAPACITIVE MICROMACHINED ULTRASONIC TRANSDUCER ARRAY WITH INCREASED EFFECTIVE CAPACITANCE

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority of U.S. Provisional Application No. 61/272,404 filed on Sep. 21, 2009 under 35 U.S.C. §119(e), the entire contents of which are hereby incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to an improved a Capacitive Micromachined Ultrasonic Transducer (CMUT) and method for manufacturing the CMUT.

2. Description of the Background Art

FIGS. **1** to **3** illustrate a conventional working principle of a Capacitive Micromachined Ultrasonic Transducer (CMUT) **100** with a flat bottom electrode **140**.

Referring to FIG. **1**, a CMUT **100** is similar to a parallel plate capacitor having a top electrode **110** on a dielectric membrane **120** that is isolated by a vacuum or air cavity **130** to a bottom electrode **140**. The bottom electrode **140** is usually formed on a flat conductive substrate. The top electrode **110** and the bottom electrode **140** may be made from a conductive material such as a conductive silicon substrate. The membrane **120** is made from conductive material or is coated with a conductive material. When actuated by electrostatic force with an AC voltage, the membrane **120** can vibrate to generate ultrasound like a drum diaphragm. Therefore, the CMUT **100** can be used as an ultrasound emitter and receiver. Only 25% of the area near the center of the membrane **120** is patterned with a top electrode **110** since the remaining 75% area has much less capacitance change, which is considered as parasitic capacitance to be removed. In other words, only 25% of the central area of the membrane **120** is patterned with a top electrode **110** to conduct effective capacitance.

In FIG. **2**, when a DC bias voltage is applied, the electrostatic force pushes the membrane **120** toward the bottom electrode **140**. The effective capacitance is inversely proportional to the gap distance of the air cavity **130** between the top electrode **110** and the bottom electrode **140**. In other words, effective capacitance can be achieved only when the gap distance is small. Only the middle section of membrane **120** can produce effective capacitance even if the entire membrane **120** is patterned with top electrode **110** because the bottom electrode **140** has a flat bottom. For instance, the capacitance produced in area **150** is considered parasitic capacitance.

To increase the sensitivity, the DC bias voltage is applied to load up the capacitor with charges, which can also pull the membrane **120** closer to the bottom electrode **140** to get a higher capacitance. The maximum sensitivity can be achieved when the membrane **120** is closest to the bottom electrode **140** without collapsing to the bottom electrode **140**.

As the DC bias voltage increases, deflection of the membrane **120** also increases. However, when the DC bias voltage is increased above a certain voltage, electrostatic forces pressure the membrane **120** to collapse on the bottom electrode **140**.

FIG. **3** illustrates a situation where the DC bias voltage is used to collapse the membrane **120**. As a result, the contribution of the affected areas **160** to the effective capacitance is significantly reduced. When the DC bias voltage is large enough to bring the membrane **120** to be deflected to more than ⅓ of the gap distance of the air gap **130**, the membrane **120** will collapse and make contact with the bottom electrode **140**.

FIG. **4** illustrates the conventional CMUT arrays. The top electrodes **310** can only cover part of the membrane.

Referring to FIG. **5**, the capacitance is simply a series combination of two parallel plate capacitors, capacitance C_1 is the capacitance of dielectric membrane, and C_2 is the capacitance of the air cavity, where d_1 is the thickness of the membrane, d_2 is the depth of the air cavity, b is the radius of the top electrode, $\in_1$ and $\in_2$ are the relative dielectric constants, $\in_0$ is the vacuum permittivity.

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{1}{\frac{1}{\varepsilon_0\varepsilon_1\frac{A}{d_1}} + \frac{1}{\varepsilon_0\varepsilon_2\frac{A}{d_2}}} = \frac{\pi\varepsilon_0 b^2}{\frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_2}}$$

Referring to FIG. **6**, for a flat bottom electrode with deflected membrane of a conventional CMUT, the deflected circular membrane is assumed to be a spherical shell partially covered by the top electrode, where R_a is the inner shell radius, R_b is the outer shell radius, and h is the height of the inner shell. C_1 from the deflected dielectric membrane is calculated by the equation of parallel plate capacitor with the area of the partial spherical shell.

$$C_1 = 4\pi\varepsilon_0\varepsilon_1 h\frac{R_a R_b}{d_1}$$

The capacitance in the air cavity between the bottom of the deflected membrane with radius R_b and the flat bottom electrode is calculated as follows.

C_2=(The parallel plate capacitance between the flat bottom electrode and the virtual flat plate (dashed line))−(The capacitance between the spherical shell with radius R_b and the virtual flat plate).

$$C_2 = \frac{1}{\frac{1}{\varepsilon_0\varepsilon_2\frac{\pi b^2}{d_2}} - \frac{1}{2\pi\varepsilon_0\varepsilon_2 R_b \ln\frac{H}{\sqrt{R_b^2 - b^2} - \sqrt{R_b^2 - a^2}}}}$$

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{\pi\varepsilon_0}{\frac{d_1}{4\varepsilon_1 h R_a R_b} + \frac{d_2}{\varepsilon_2 b^2} - \frac{1}{2\varepsilon_2 R_b \ln\frac{H}{\sqrt{R_b^2 - b^2} - \sqrt{R_b^2 - a^2}}}}$$

where

$$R_a = \frac{1}{2H}(H^2 + a^2),\ R_b = R_a + d_1,\ h = R_a - \sqrt{R_a^2 - b^2}$$

FIG. **7** is a graph of effective capacitance with respect to membrane deflection of a conventional CMUT with flat bottom electrodes. The diameter of the silicon nitride membrane is 100 μm, the thickness of the membrane is 0.2 μm, and the depth of the air cavity is 1 μm. These values are applied into the derived equations above. The relative dielectric constant of silicon nitride film is 7.5. For CMUTs with flat bottom electrodes, the capacitance change reaches its maximum of 22% when the diameter of the top electrode is 84 μm. The capacitance change drops to 9% when the top electrode fills the membrane. The maximum capacitance at the collapsed mode can only reach 0.075 pF.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a Capacitive Micromachined Ultrasonic Transducer (CMUT), that includes a membrane operatively connected to a top electrode; and a bottom electrode having a concave void. Whereby, when a DC bias voltage is applied, the membrane is deflected towards the bottom electrode such that a peripheral edge region of the membrane is brought into close proximity with the bottom electrode and an electrostatic force proximal to the peripheral edge region of the membrane is increased.

When the DC bias voltage is applied, the distance between the peripheral edge region of the membrane and the bottom electrode may be less than the distance between a central region of the membrane and the bottom electrode.

When the DC bias voltage applied is above a predetermined amount to collapse the membrane to the bottom electrode, contact between the membrane and the bottom electrode may be minimised to a central region of the membrane.

About 25% of the membrane is in contact with the bottom electrode when the membrane is collapsed to the bottom membrane.

The top electrode may have the same diameter as the void of the bottom electrode.

The membrane may be flat or deflected.

The size of the membrane may be from about 500 μm to 5 μm with a frequency range from 100 kHz up to 100 MHz in air.

The thickness of the membrane may be from about 0.1 μm to 10 μm.

The CMUT may have an array of membranes where each top electrode fills the entire area of each membrane leaving only small voids for anchoring each membrane.

In another embodiment, a method for manufacturing a Capacitive Micromachined Ultrasonic Transducer (CMUT) is provided, whereby the method includes the features of sputtering a layer of Cr/Au as a seed layer on a silicon substrate that includes a layer of silicon nitride to form a CMUT membrane; coating a patterned photoresist to define the active area of a CMUT cell; melting the patterned photoresist to form a spherical profile by surface tension; and electroplating of nickel with the seed layer to form the bottom electrode by over-plating to cover the patterned photoresist.

The Young's modulus of the silicon nitride may be around 200 GPa.

The method may further include sealing released holes caused by the electroplating using a silicone-based polydimethylsiloxane (PDMS) with air trapped in CMUT cavities.

The method may further include coating parylene C in a vacuum chamber.

The method may further include removing the silicon substrate by single-side potassium hydroxide (KOH) etching that stops at the silicon nitride membrane.

The method may further include patterning the PDMS to define a membrane area and array elements.

The method may further include wire bonding to front-end electronics.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus, are not limitive of the present invention, and wherein:

FIG. **1** illustrates the conventional working principle of CMUT with a flat bottom electrode;

FIG. **2** illustrates the conventional working principle of CMUT with a flat bottom electrode when DC bias is applied;

FIG. **3** illustrates the conventional working principle of CMUT with a flat bottom electrode when DC biasing is applied to collapse the membrane;

FIG. **4** illustrates the conventional CMUT array arrangement;

FIG. **5** illustrate the conventional working principle of CMUT with a flat bottom electrode;

FIG. **6** illustrate the conventional working principle of CMUT with a flat bottom electrode;

FIG. **7** illustrates a graph of effective capacitance with respect to membrane deflection of a conventional CMUT with a flat bottom electrode;

FIG. **8** illustrate a CMUT with a concave bottom electrode in accordance with an embodiment of the present invention;

FIG. **9** illustrate a CMUT with a concave bottom electrode in accordance with an embodiment of the present invention when DC bias is applied;

FIG. **10** illustrate a CMUT with a concave bottom electrode in accordance with an embodiment of the present invention when DC biasing is applied to collapse the membrane;

FIG. **11** illustrates an exemplary CMUT array arrangement in accordance with an embodiment of the present invention;

FIG. **12** illustrate the working principle of CMUT with a concave bottom electrode in accordance with an embodiment of the present invention;

FIG. **13** illustrate the working principle of CMUT with a concave bottom electrode in accordance with an embodiment of the present invention;

FIG. **14** illustrates a graph of effective capacitance with respect to membrane deflection of a CMUT with a concave bottom electrode in accordance with the present invention; and

FIG. **15** illustrates an exemplary fabrication process of CMUT arrays with concave bottom electrodes.

DETAILED DESCRIPTION

Referring to FIGS. **8** to **10**, a Capacitive Micromachined Ultrasonic Transducer (CMUT) **200** with a concave shaped bottom electrode **240** is depicted. A concave air cavity **230** is defined by the concavity of the bottom electrode **240**. Turning to FIG. **8**, the top electrode **210** covers 100% of the area **260** of the membrane **220** above the air cavity **230**. Consequently, the effective capacitance for the CMUT **200** can be significantly higher than the conventional CMUT **100** of FIG. **1** with a top electrode **110** which covers only 25% of the membrane area **120**.

Turning to FIG. **9**, when direct current (DC) bias is applied, the entire area **260** of the membrane **220** above the air cavity **230** is considered to produce effective capacitance. The concavity of the bottom electrode **240** substantially conforms to the deflection of the membrane **220** when a DC bias voltage is applied.

If the bottom electrode **240** is defined with a concave shape or curved profile, and when the membrane **220** is deflected, the membrane **220** can fully comply and conform to the top surface of the bottom electrode **240**, especially around the outer edge **270** of the membrane **220** above the air cavity **230**. This can increase the electrostatic force around the edge **270** of the membrane **220** to pull down the membrane **220** so a smaller DC bias voltage can be used. Using a smaller DC bias voltage is essential when inserting the transducer probe into the human body for an intravascular application. The bandwidth of the CMUT **200** can also be improved since most of the membrane **220** is under the electrostatic force from the DC bias voltage, which can increase the tensile stress on the membrane **220** to reduce the ringing tail.

Turning to FIG. **10**, when a DC bias voltage exceeds a certain voltage level, the membrane **220** is collapsed to the bottom electrode **240**. In this situation, only approximately 25% of the membrane **220** is in contact with the bottom electrode **240**. Hence, 75% of the membrane **220** which is the area **270** proximal to the peripheral edge (that is, the area **270** of the membrane **220** that is not in contact with the bottom electrode **240** above the air cavity **230**) is considered as effective capacitance.

A CMUT can also operate at the collapsed mode to have an increased sensitivity and bandwidth. The sensitivity is increased from the increased capacitance at the minimum gap distance around the contacting area. The bandwidth can be improved because the movement of the membrane **220** can be damped by the bottom electrode **240** to reduce the ringing tail. When implementing the concave shaped bottom electrode **240** to operate CMUTs **200** at the collapsed mode, the whole membrane **220** is barely touching the bottom electrode **240** to increase the bandwidth and sensitivity. In particular, around the central area of the membrane **220** is damped by the bottom electrode **240**. Thus, the CMUT **200** can increase effective capacitance to improve fill factor, output pressure, bandwidth, and sensitivity of the transducer.

The resonant frequency of the CMUT depends on the size and thickness of the membrane. The size of the membrane can range from 500 μm to 5 μm with a frequency range from 100 kHz up to 100 MHz in air. The thickness of the membrane can range from 0.1 μm to 10 μm. Since each membrane of the CMUT is very small, it requires an array of membranes for the CMUT to fill the area of a single transducer element.

FIG. **11** illustrates exemplary CMUT arrays. The top electrode **320** can fill the whole area of the membrane leaving only small voids for anchoring the membrane, which increases the fill factor four times more than conventional CMUTs. The top electrode **320** can also be patterned to make a 1-D CMUT array for 2-D ultrasonic imaging. In addition, the electroplated bottom electrode can also be patterned to isolate 2-D array elements for 3-D ultrasonic imaging.

The capacitance of a parallel plate capacitor can be determined from the area of the effective capacitance A and the distance between the top and bottom electrodes d, which is expressed as follows:

$$C = \frac{Q}{V_{ab}} = \varepsilon_0 \varepsilon_r \frac{A}{d},$$

for series capacitor

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

Based on the geometry of the CMUT, the capacitance of the CMUT can be calculated as follows, where the electrode diameter is much greater than the cavity depth (2c>2b>>d_2) and the capacitance C_2 is assumed to be a parallel-plate capacitor.

Referring to FIG. **12**, for a concave bottom electrode with a flat membrane, the capacitance from dielectric membrane C_1 is calculated by the parallel-plate capacitor equation. The capacitance C_2 between the bottom surface of the flat membrane to the concave bottom electrode with spherical surface is calculated also using the spherical shell to flat plate capacitance equation:

$$C_1 = \varepsilon_0 \varepsilon_1 \frac{\pi c^2}{d_1}$$

$$C_2 = 2\pi \varepsilon_0 \varepsilon_2 R \ln \frac{d_2}{d_0}$$

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{\pi \varepsilon_0}{\frac{d_1}{\varepsilon_1 c^2} + \frac{1}{2\varepsilon_2 R \ln \frac{d_2}{d_0}}}$$

where

$$R = \frac{1}{2d_2}(d_2^2 + a^2),\ d_0 = \sqrt{R^2 - c^2} - R + d_2$$

Referring to FIG. **13**, for a concave bottom electrode with a deflected membrane, the membrane is assumed to deform into a spherical shape similar to the case of FIG. **6**. The concave bottom electrode is also assumed to have a spherical surface. For membrane capacitance C_1, it is calculated similar to FIG. **6** as described above. As to C_2, the cavity capacitance is first calculated relative to the virtual flat plate. Then, the cavity capacitance is subtracted with the capacitance between two spherical surfaces to obtain C_2. The equations for obtaining C_1 and C_2 are as follows:

$$C_1 = 4\pi \varepsilon_0 \varepsilon_1 h' \frac{R_a R_b}{d_1}$$

C_2=(The capacitance between the bottom electrode and the virtual flat plate (dashed line))−(The capacitance between the spherical shell with radius R_b and the virtual flat plate).

$$C_2 = \frac{1}{\frac{1}{2\pi\varepsilon_0\varepsilon_2 R \ln \frac{d_2}{d_0}} - \frac{1}{2\pi\varepsilon_0\varepsilon_2 R_b \ln \frac{H}{\sqrt{R_b^2 - c^2} - \sqrt{R_b^2 - a^2}}}}$$

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{\pi\varepsilon_0}{\frac{d_1}{4\varepsilon_1 h' R_a R_b} + \frac{1}{2\varepsilon_2 R \ln \frac{d_2}{d_0}} - \frac{1}{2\varepsilon_2 R_b \ln \frac{H}{\sqrt{R_b^2 - c^2} - \sqrt{R_b^2 - a^2}}}}$$

where

$$R_a = \frac{1}{2H}(H^2 + a^2),\ R_b = R_a + d_2,\ h' = R_a - \sqrt{R_a^2 - c^2}$$

FIG. **14** illustrates a graph of effective capacitance with respect to membrane deflection of a CMUT with concave bottom electrodes. CMUTs using concave bottom electrodes the capacitance change can increase up to 79% when enlarging the diameter of the top electrode up to 99.8 μm. The maximum capacitance at the collapsed mode can reach up to 0.7 pF, which is almost ten times more compared to the CMUT using flat bottom electrodes. From Coulomb's Law, the electrostatic force of a parallel capacitor is expressed as follows, where Q is the electrical charge, E is the electrical field, and V is the voltage.

$$F = Q \cdot E = Q\frac{Q}{2A\varepsilon_0} = \frac{\varepsilon_0 A V^2}{2d^2}, \text{ where } Q = A\varepsilon_0\frac{V}{d}$$

For output pressure, since the electrostatic force is inversely proportional to the square of the cavity depth, which means shorten the cavity depth can estimate to have two orders of magnitude increase on the output pressure when the capacitance increase is one order of magnitude.

FIG. **15** illustrates a method of fabricating CMUT arrays with concave bottom electrodes. The fabrication starts with step **S601** using a silicon wafer that includes a layer of silicon nitride to serve as the CMUT membrane. The Young's modulus of the silicon nitride is around 200 GPa. In step **S602**, a layer of Cr/Au is sputtered to serve as the seed layer for electroplating. Photoresist is coated by a spin coater to get a thickness of around 1 μm and patterned to define the active area of the CMUT cell. Next, in step **S603**, a thermal reflow process is carried out at 150° C. for 30 minutes to melt the patterned photoresist to form a spherical profile by surface tension. In step **S604**, electroplating of nickel is performed with the Cr/Au seed layer to form the bottom electrode by over-plating to cover the photoresist sacrificial layer. Step **S605** illustrates that the electroplating leaves a small hole for removal of photoresist and Cr/Au in the cavity.

Finally, in step **S606**, the released holes are first sealed by silicone-based polydimethylsiloxane (PDMS) with air trapped in CMUT cavities. This is followed by a coating of parylene C in a vacuum chamber. The vacuum chamber sucks the trapped air out through the gas permeable PDMS for vacuum sealed cavities since parylene is not gas permeable. The silicon substrate is then removed by single-side potassium hydroxide (KOH) etching that stops at the silicon nitride membrane. This eliminates the membrane stiction problem because the cavity remains dry during the wet etching with the protection of the PDMS and parylene coating. The PDMS now serves as the flexible substrate with silicon nitride membrane ready to be deposited with the metal for the top electrode. The PDMS is then patterned to define the membrane area and array elements. After wire bonding to front-end electronics, the CMUT array is ready to be used.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the scope or spirit of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects illustrative and not restrictive.

What is claimed is:

1. A Capacitive Micromachined Ultrasonic Transducer (CMUT) comprising:

a membrane operatively connected to a top electrode; and

a bottom electrode having a concave void;

wherein the membrane is configured to deflect towards the bottom electrode when a DC bias voltage is applied such that a peripheral edge region of the membrane is brought into close proximity with the bottom electrode and an electrostatic force proximal to the peripheral edge region of the membrane is increased.

2. The CMUT according to claim **1**, wherein when the DC bias voltage is applied, the distance between the peripheral edge region of the membrane and the bottom electrode is less than a distance between a central region of the membrane and the bottom electrode.

3. The CMUT according to claim **1**, wherein when the DC bias voltage applied is above a predetermined amount to collapse the membrane towards the bottom electrode, contact between the membrane and the bottom electrode is minimized to a central region of the membrane.

4. The CMUT according to claim **3**, wherein about 25% of the membrane is in contact with the bottom electrode when the membrane is collapsed towards the bottom membrane.

5. The CMUT according to claim **1**, wherein the top electrode has the same diameter as the void of the bottom electrode.

6. The CMUT according to claim **1**, wherein the membrane is flat or deflected.

7. The CMUT according to claim **1**, wherein the size of the membrane is from about 500 μm to 5 μm with a frequency range from 100 kHz up to 100 MHz in air.

8. The CMUT according to claim **1**, wherein the thickness of the membrane is from about 0.1 μm to 10 μm.

9. The CMUT according to claim **1**, wherein the CMUT has an array of membranes where each top electrode fills the entire area of each membrane thereby leaving only small voids for anchoring each membrane.

10. A method for manufacturing a Capacitive Micromachined Ultrasonic Transducer (CMUT), the method comprising:

sputtering a layer of Cr/Au as a seed layer on a silicon substrate that includes a layer of silicon nitride to form a CMUT membrane;

coating a patterned photoresist to define an active area of a CMUT cell;

melting the patterned photoresist to form a spherical profile by surface tension; and

electroplating of nickel with the seed layer to form the bottom electrode by over-plating to cover the patterned photoresist.

11. The method according to claim **10**, wherein a Young's modulus of the silicon nitride is around 200 GPa.

12. The method according to claim **10**, further comprising the step of sealing released holes caused by the electroplating using a silicone-based polydimethylsiloxane (PDMS) with air trapped in CMUT cavities.

13. The method according to claim **10**, further comprising the step of coating parylene C in a vacuum chamber.

14. The method according to claim **10**, further comprising the step of removing the silicon substrate by single-side potassium hydroxide (KOH) etching that stops at the silicon nitride membrane.

15. The method according to claim **12**, further comprising the step of patterning the PDMS to define a membrane area and array elements.

16. The method according to claim **10**, further comprising the step of wire bonding to front-end electronics.

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