



159159



G00002

Piezoelectric Micromachined Ultrasonic Transducer Array
and Method for Fabricating the Same

Field of the invention

The present invention relates to a micromachined ultrasonic transducer array,
5 which can be manufactured from a silicon wafer using micro electro
mechanical systems (MEMS) technology or other semiconductor processes.
In particular, the present invention relates to a piezoelectric micromachined
ultrasonic transducer array and a method of fabricating the same.

Background of Invention

10

It is known that ultrasonic transducer arrays can be used in medical
diagnostics, industrial measurement and parametric audio systems to
reproduce a highly directional audible sound beam. Conventionally, a
piezoelectric and transducer array having a high ultrasonic carrier frequency
15 is formed by bonding a single bulk piezoelectric sheet onto a backing
substrate that provides acoustic attenuation. The piezoelectric sheet is then
laterally subdivided by cutting or dicing the material to form rectangular
elements of the array. It is noted that it is not easy to use this method to form
a transducer array having smaller element size. Alternatively, a piezoelectric
20 ultrasonic transducer array having a low/middle carrier frequency can be
formed by connecting many individual transducer elements. Unfortunately,
each individual element in this array typically has a slightly different peak
frequency which limits their "arrayability".

25 Some developments have lead to the prospect of manufacturing an ultrasonic
array in silicon by MEMS technology or semiconductor processes. Its
advantages are (i) to suit for high-volume applications, (ii) to assure an
ultrasonic array having reliable and consistent performance with a low cost,

and (iii) to provide a way in integration of mechanical device and electronics into one single chip.

In the course of developing a micromachined ultrasonic transducer/transducer array, U. S. Pat. No. 6,443,901B1, issued to J. D. Fraser disclosed a capacitive micromachined ultrasonic transducer. In this disclosure, the transducer is formed by a plurality of capacitive micromachined ultrasonic transducer (cMUT) cells, each comprising a charged diaphragm plate capacitively opposing an oppositely charged base plate. The diaphragm plate is distended toward the base plate by a bias charge. A narrower gap between capacitive plates is usually adopted in this type of transducer so as to improve its sensitivity. In addition, a dome shaped diaphragm is desirable so as to further improve transducer sensitivity. In a typical capacitive micromachined ultrasonic transducer, a DC bias is used to produce an electrostatic force between two capacitive plates, resulting in the diaphragm being deflected toward the base plate. An AC signal is applied across the capacitive plates to cause the diaphragm to vibrate and emit ultrasonic waves. Conversely, during reception of ultrasonic waves, the diaphragm vibration varies the capacitance of the sensor and thus outputs a current proportional to the input pressure. Note that the DC bias voltage must be carefully controlled so as to maintain high transducer sensitivity without short-circuiting the transducer's capacitance.

As an alternative to such arrangements, a combination of silicon micromachining and piezoelectric film deposition is attractive since piezoelectric coupling strength is significantly higher than electrostatic coupling strength, and also, piezoelectric micro-mechanical devices are not usually restricted to specific geometrical configurations like the electric gap required for electrostatic micro-mechanical devices. All these features provide

the possibility to achieve a more reliable and low cost ultrasonic transducer device. Each ultrasonic transducer element includes a diaphragm/membrane. In most micromachined ultrasonic transducers, the diaphragm/membrane is formed by, firstly, depositing a sacrificial layer 1 such as silicon oxide onto a silicon substrate 3, as shown in Fig. 1(a), and then patterning the sacrificial layer 1, as shown in Fig. 1(b). After that silicon nitride 5 is deposited onto the sacrificial layer 1, as shown in Fig. 1(c). The sacrificial layer 1 is then removed, as shown in Fig. 1(d), thus forming the back cavity and the diaphragm/membrane. Unfortunately, normally a transducer array has many elements, and it is not easy to ensure good consistency among all cells by using this fabrication method, especially to ensure uniform diaphragm thickness among all the elements, which is required for a high performance ultrasonic transducer array.

15 Summary of the Invention

The present invention aims to provide new and useful ultrasonic transducer devices, and methods for forming the devices.

In general terms, the invention proposes that a piezoelectric ultrasonic transducer array is formed by producing one or more trenches in a silicon wafer, and then bonding a silicon layer over the trenches, thereby forming back cavities. The silicon layer acts as a diaphragm, and is provided with a piezoelectric layer and electrode layers sandwiching it, so that deflection of the diaphragm is coupled to (i.e. can be produced by, or alternatively produces) electrical signals in the electrodes.

25 As described in detail below, fabrication of transducer arrays according to the invention may be performed utilizing techniques from micro-electro - mechanical systems (MEMS) technology, especially the techniques of silicon micromachining and piezoelectric film deposition. This means that such

embodiments may be produced with a low manufacturing cost and high performance.

In preferred embodiments, wafer fusion bonding between the silicon wafer and the silicon layer is adopted.

- 5 The silicon diaphragm layer is preferably moved onto the silicon wafer by a handle wafer which is attached to the silicon layer, the handle layer and silicon layer being part of an SOI structure at that time. Subsequently, the handle layer is removed.

10 The term "trenches" is not used here to imply any specific shape when viewed in the direction looking towards the silicon wafer. Thus, although the trenches may be elongate, this is not a requirement of the term as used here.

The array may include many elements. Typically, in each element, there is a diaphragm which is composed of multiple layers, namely, a top electrode, an adhesion layer, a piezoelectric coating, a bottom electrode, another adhesion
15 layer, an insulation layer and the silicon diaphragm layer, bonded to the ridges at the top of the wafer trenches. Between the wafer and the layer are back-trenches, which are preferably substantially vacuums. The vacuum in the back cavities of the transducer array is automatically formed if the wafer is bonded to the layer in vacuum, and the cavities are air-tight.

- 20 In some applications of the invention, the array utilizes an inverse piezoelectric effect to convert electrical energy into mechanical energy, i.e., mechanical strain, displacement, and vibration, thus producing an ultrasonic wave. In other applications, the array uses a direct piezoelectric effect to convert mechanical energy into electrical energy. In this regard, the varying
25 deformation in the piezoelectric coating due to an AC voltage may cause the silicon diaphragm to produce a bending vibration, and thus an ultrasonic wave. Alternatively, the varying deflection/vibration in the silicon diaphragm

due to an external pressure may cause the surface piezoelectric coating to produce an accumulative output charge.

It is possible also to form electronic components in the structure, for example within the silicon wafer. In this case, the mechanical structure and electronics
5 may be integrated in one single chip.

Ultrasonic transducer arrays as proposed above have applications in fields such as medical imaging systems, NDE (non-destructive evaluation) systems, automatic ranging systems, parametric speaker systems and microphone arrays.

10 The invention may be expressed in terms of methods of forming the array devices, or alternatively in terms of the devices themselves.

Brief Description of The Figures

Preferred features of the invention will now be described, for the sake of illustration only, with reference to the following figures in which:

15 FIG. 1, which is composed of Figs. 1(a) to 1(d), shows a prior art method of forming a silicon nitride diaphragm;

FIG. 2, which is composed of Figs. 2(a) and 2(b), shows a piezoelectric micromachined ultrasonic transducer array device which is a first embodiment of the present invention;

20 FIG. 3, which is composed of Figs. 3(a) and 3(b), illustrates two possible operating modes of the transducer array device of Fig. 2;

FIG. 4, which is composed of Figs. 4(a) to 4(l), shows the steps of an array fabrication method for producing the array device of Fig. 3; and

FIG. 5, which is composed of Figs. 5(a) and 5(b), shows respectively
25 views of two further transducer array devices which are embodiments of the present invention.

Detailed Description of the embodiments

A piezoelectric micromachined ultrasonic array 1 which is an embodiment of the present invention is shown in Fig. 2(a) in a top view. The array 1 includes
5 many elements 11, and Fig. 2(b) is a cross-sectional view of one of them along the line A-A in Fig. 2(a). In each element 11, there is a diaphragm 2 attached to a substrate 20. The diaphragm 2 is a multi-layer structure comprising layers of different respective materials, namely, a top electrode 21, e.g., Au/Pt, an adhesion layer (not shown), e.g., Ti, a piezoelectric coating 22,
10 e.g., PZT, a bottom electrode 23, e.g., Pt, an adhesion layer (not shown), e.g., Ti, an insulation layer 24, e.g., SiO₂, and a substrate 25, e.g., Si. Under the diaphragm and on the major surface of the substrate 20 is a back-cavity 26, which is at a negative pressure (i.e. less than one atmosphere) and preferably substantially a vacuum.

15

The piezoelectric micromachined ultrasonic transducer array may be used in either of two modes. Firstly, it may employ an inverse piezoelectric effect in which electrical energy is applied to the electrodes 21, 23 and converted by the layer 22 into mechanical energy, i.e., mechanical strain, displacement,
20 and vibration, resulting in the generation of ultrasonic waves. Secondly, it may employ a direct piezoelectric effect to convert mechanical energy into electrical energy.

The benefit of effecting a vacuum in the back-cavity 26 is that it removes any
25 need for a back acoustic attenuation layer, as adopted in conventional bulk piezoelectric ultrasonic transducers and capacitive micromachined ultrasonic transducers. In addition, under the negative pressure, the diaphragm 2 is distended toward the back side, resulting in a dimpled shape. This will improve transducer sensitivity. The diaphragms in all elements 11 come from
30 the monolithic and uniform multi-layer membrane, and particularly the

monolithic and uniform silicon membrane 25. This will result in good consistency among all elements 11, and improve their arrayability as well as transducer performance. All elements 11 may be driven in parallel to produce an ultrasonic wave propagating through air, water or biological tissue. This is shown schematically in FIG. 3(a), where an AC voltage signal 31 amplified by a power amplifier 33 is applied to the electrodes 21, 23 to generate an ultrasonic signal. For clarity, only one ultrasonic element 11 is shown in Fig. 3(a). In this regard, the varying deformation in the piezoelectric coating 22 due to the AC voltage causes the silicon diaphragm 25 to produce a bending vibration, which in turn generates an ultrasonic wave.

Alternatively, the element 11 may respond to external pressure (e.g. in the form of parallel pressure fronts) as shown in FIG. 3(b). In this case, varying deflection/vibration in the silicon diaphragm 25 due to an external pressure causes the surface piezoelectric coating 22 to produce an accumulative output charge, leading to an oscillating signal which is amplified by a charge amplifier 35 to produce a measured signal 37.

All the ultrasonic elements 11 in the array share common top and bottom electrodes 21, 23. With semiconductor processes, it is possible to integrate mechanically the transducer array and the electronics (power amplifier 33, as shown in FIG. 3(a), or charge amplifier 35, as shown in FIG. 3(b)) into one single chip. By contrast, the conventional bulk piezoelectric ultrasonic transducer typically has mechanical parts and electronics spaced apart on a circuit board.

Possible steps for fabricating piezoelectric micromachined ultrasonic transducer arrays of the kind shown in Figs. 2 and 3, are shown in FIG. 4. A bare silicon wafer 41 (shown in cross-section in Fig. 4(a)) having an <100> or <111> crystal orientation is used as a starting substrate. In the following

description, we will assume, for the sake of example only, that the wafer 41 is a <100> wafer.

5 In a first step, a masking layer of PECVD silicon dioxide 43 is deposited on both sides of the wafer 41, as shown in Fig. 4(a). Alternatively, thermal oxidation can be used.

Subsequently, the front (top) surface is spin-coated with photoresist. Photolithography on the photoresist layer creates a patterned photoresist
10 layer. An RIE (reactive ion etching) process is then carried out using the Si 41 as an etch stop and the photoresist as a mask. The remaining photoresist is then removed, to give a patterned upper SiO₂ layer 45, as shown in Fig. 4(b).

Following this, deep trenches 47 and alignment marks (not shown) are formed
15 in the front side of substrate 41 by using DRIE, as shown in Fig. 4(c). It should be mentioned that the trench depth in the present invention is not so critical as that in a capacitive micromachined ultrasonic transducer, as disclosed in the prior arts, for example, U. S. Pat. No. 6,443,901B1. The basic requirement of trench depth in the present invention is not to cause any possible contact
20 between diaphragm and base after deflection of the diaphragm. Aside from this, the trench 47 may be formed as shallow as possible so that the DRIE process can be accelerated. As explained below, the trench 47 forms the basis of the back cavity. Alternatively, in other embodiments, a structure resembling that of Fig. 4(c) can be produced by a process in which the back-
25 cavity is formed by KOH etching of an <100> wafer or an <110> wafer.

Following the formation of the trenches 47, the oxide mask layer 45 is removed by wet etching, to give the structure of Fig. 4(d).

Subsequently, the patterned <100> wafer 41 is bonded to a SOI wafer 50 (on which alignment marks (not shown) have been made. The SOI wafer 50 comprises a silicon handle wafer 51, a buried oxide layer 53, and a silicon layer 55. Preferably, Si-Si fusion bonding is adopted to bond the SOI wafer 50 to the wafer 41, since it can achieve a very high bonding strength and good bonding interface quality. This process is conducted under a vacuum environment. Thus, a vacuum back cavity is automatically formed after wafer bonding. On exposure of transducer array (once completed) to the air, negative pressure will cause the silicon diaphragm 55 to produce a dimpled shape. Formation of a vacuum back cavity in the micromachined ultrasonic transducer array by using silicon wafer fusion bonding process is a valuable feature of the embodiment.

Subsequently, the handle wafer 51 is removed by either DRIE or KOH etching, and the buried oxide layer 53 is removed by HF wet etching, to give the structure shown in Fig. 4(f). By now, a monolithic membrane and the element diaphragms in the ultrasonic transducer array have been formed. Formation of membrane/diaphragm in the micromachined ultrasonic transducer array by using SOI wafer and wafer bonding technology is a valuable feature of the embodiment. The advantage of this process is to maintain good consistency among all transducer elements. In addition, it is easy to control the diaphragm/membrane thickness by selecting the SOI wafer 50 correspondingly.

Subsequently, a layer of oxide 57 is deposited on the bonded wafer stack to insulate the wafer electrically, as shown in Fig. 4(g).

Subsequently, a layer 61 is deposited which will be the bottom electrode, as shown in Fig. 4(h). Different materials may be chosen for the layer 61 (such

as Au, Cu, or Al) as long as it is electrically conductive. Preferably, the layer 61 is composed of Ti/Pt since this gives the good characteristics.

Subsequently, a layer of PZT film 63 is spin-coated over the layer 61 on the
5 wafers via a so-called sol-gel method, as shown in Fig. 4(i). Alternatively, sputtering, CVD or PVD process may be used to form the PZT coating. Besides the ceramic-based PZT, other piezoelectric materials such as ZnO and AlN can be adopted in formation of the micromachined ultrasonic transducer array in the present invention.

10

Subsequently, a layer 65 of Pt or Au is deposited over the PZT film 63 as the top electrode, as shown in Fig. 4(j).

15

A photoresist is applied, and this is patterned photographically. An etching process is then performed to transfer the pattern to the layer 65, in the form of apertures 67. Different etching methods may be chosen, such as ion milling and selective wet etching. Then the photoresist is removed, to give the structure shown in Fig. 4(k). As an alternative, the patterned top electrode 65 may, e.g. if it is formed of Pt, may be evaporated onto the PZT film 63.

20

Finally, as shown in Fig. 4(l), the PZT film 13 is etched through the apertures 67, using as a stop the bottom electrode layer 61. Thus, the bottom electrode is exposed, which means that it can be connected to an external lead wire (not shown).

25

Compared with other fabrication methods in the prior arts, the fabrication method in the present invention is simple and involves only a few main steps. The shape of the transducer elements 11 may be a circle (when viewed from the front), as shown in Fig. 2(a). However, other shapes are also possible,
30 such as a polygon element 71 as shown in Fig. 5(a) (which is a view

corresponding to Fig. 2(a) but showing a second embodiment of the invention) or narrow rectangle elements 81 as shown in Fig. 5(b) (which is a view corresponding to Fig. 2(a) but showing a third embodiment of the invention). Improvements in performance and cost of an ultrasonic transducer in the present invention may enable a wide range of applications. By selection of various dimensions of diaphragm, the peak frequency in the transducer array is tunable.

We now list several application examples of piezoelectric micromachined ultrasonic transducer arrays which are embodiments of the present invention. However, the applicability of the invention is not limited to these.

1. Medical imaging

In this regard, the transducer array may be used in an ultrasonic medical diagnosis system as a transmitter/receiver.

2. Non-destructive evaluation (NDE)

3. Ranging (e.g. detection of an objective position in an intelligent system)

4. As an ultrasonic micro fluid delivery device

5. As an ultrasonic speaker. In this case, it may act as a "parametric speaker" which utilizes a non-linear coupling of ultrasonic waves in air to reproduce a demodulated audible sound.

6. As a microphone array. In this case, it may be used as a wide-band microphone array working in the air or water. In this application, the transducer may work in an either resonance or non-resonance mode.

Although only a few embodiments of the invention have been described, the invention is not limited to these, and many other embodiments may be formed within the scope of the claims as will be clear to a skilled reader.

Claims

1. A method of forming a piezoelectric ultrasonic transducer array, the method comprising:

forming trenches in a first major surface of a silicon wafer;

5 bonding a layer of silicon to the first major surface of the wafer, the layer extending over the trenches, thereby defining back-cavities; and

forming first and second electrode layers on the silicon layer, the first and second electrode layers being spaced apart by a layer of piezoelectric material, whereby deflection of the silicon layer is coupled by the piezoelectric material to a voltage difference between the first and second electrodes.

10 2. A method according to claim 1 in which the silicon layer is placed onto the wafer at a time when the layer is a part of an SOI structure, the structure further comprising a handle wafer, the method comprising removing the handle wafer from the silicon layer after the bonding of the silicon layer to the silicon wafer.

3. A method according to claim 1 in which the silicon layer and silicon wafer are bonded by a silicon fusion bonding process.

4. A method according to claim 1 in which the piezoelectric layer is formed by a deposition process.

20 5. A method according to claim 1 in which the silicon layer is bonded to the silicon wafer at a pressure lower than one atmosphere, whereby the pressure within the back cavities is less than one atmosphere.

6. A method according to claim 5 in which the silicon wafer is bonded to the silicon layer in vacuum, whereby the back-cavities are vacuums.

7. An ultrasonic transducer device comprising:

a silicon wafer including one or more trenches on one of its major surfaces,

a silicon layer extending over the trenches and bonded to the silicon wafer, and thereby defining back cavities between the silicon layer and the silicon wafer, and

respective top and bottom electrode layers formed on the silicon layer and sandwiching a piezoelectric layer, the piezoelectric layer coupling deflection of the silicon layer to a voltage difference between the electrode layers.

8. A device according to claim 7 in which the piezoelectric layer is spaced from one or both of the electrodes by a, or a respective, adhesion layer.

9. A device according to claim 7 or claim 8 in which there are a plurality of trenches, defining respective back cavities.

10. A device according to claim 7, claim 8 or claim 9 in which said cavities have a circular cross-section when viewed perpendicular to the major surface of the wafer.

11. A device according to any of claims 7 to 9 in which said cavities have a polygonal cross-section when viewed perpendicular to the major surface of the wafer.

12. A device according to any of claims 7 to 9 in which said cavities have an elongate cross-section when viewed perpendicular to the major surface of the wafer.

13. A device according to any of claims 7 to 12 in which said wafer further includes at least one electronic amplifier component.

14. A device according to any of claims 7 to 13 in which said wafer further includes one or more electronic components for generation of a voltage signal for application to at least one of the electrodes.

5 15. A device according to any of claims 7 to 14 in which said wafer further includes one or more electronic components for measurement of a voltage signal derived from at least one of the electrodes.