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(54) ULTRASONIC TRANSDUCER WAFER HAVING VARIABLE ACOUSTIC IMPEDANCE

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(52) **U.S. Cl.** **73/632**; 310/334; 310/336
(58) **Field of Search** 73/628, 632, 644; 310/322, 334, 336; 367/152

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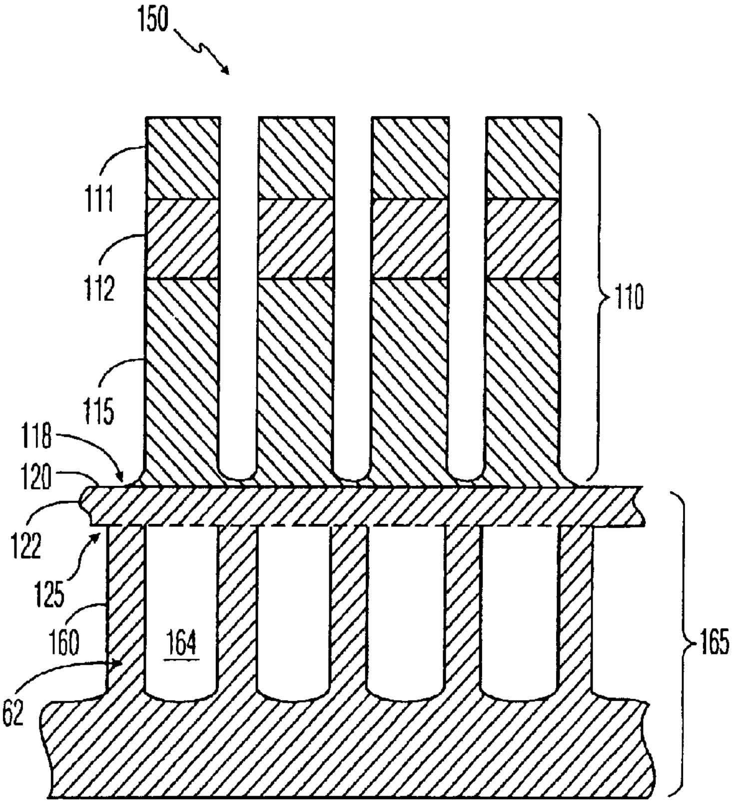
(57) ABSTRACT

The invention is a wafer having variable acoustic properties. The wafer may be used as a substrate over which to form an ultrasonic transducer, an IC, or may be used as a circuit board. An ultrasonic transducer formed on the wafer may include piezoelectric ceramic transducer elements or MUT elements. By controlling the acoustic impedance of the wafer upon which the integrated control circuitry for an ultrasonic transducer is formed, the acoustic impedance of the wafer can be matched to the acoustic impedance requirements of the ultrasonic transducer. Furthermore, by the addition of internal voids, the wafer reduces or eliminates the lateral propagation of acoustic energy through the wafer.

8 Claims, 3 Drawing Sheets



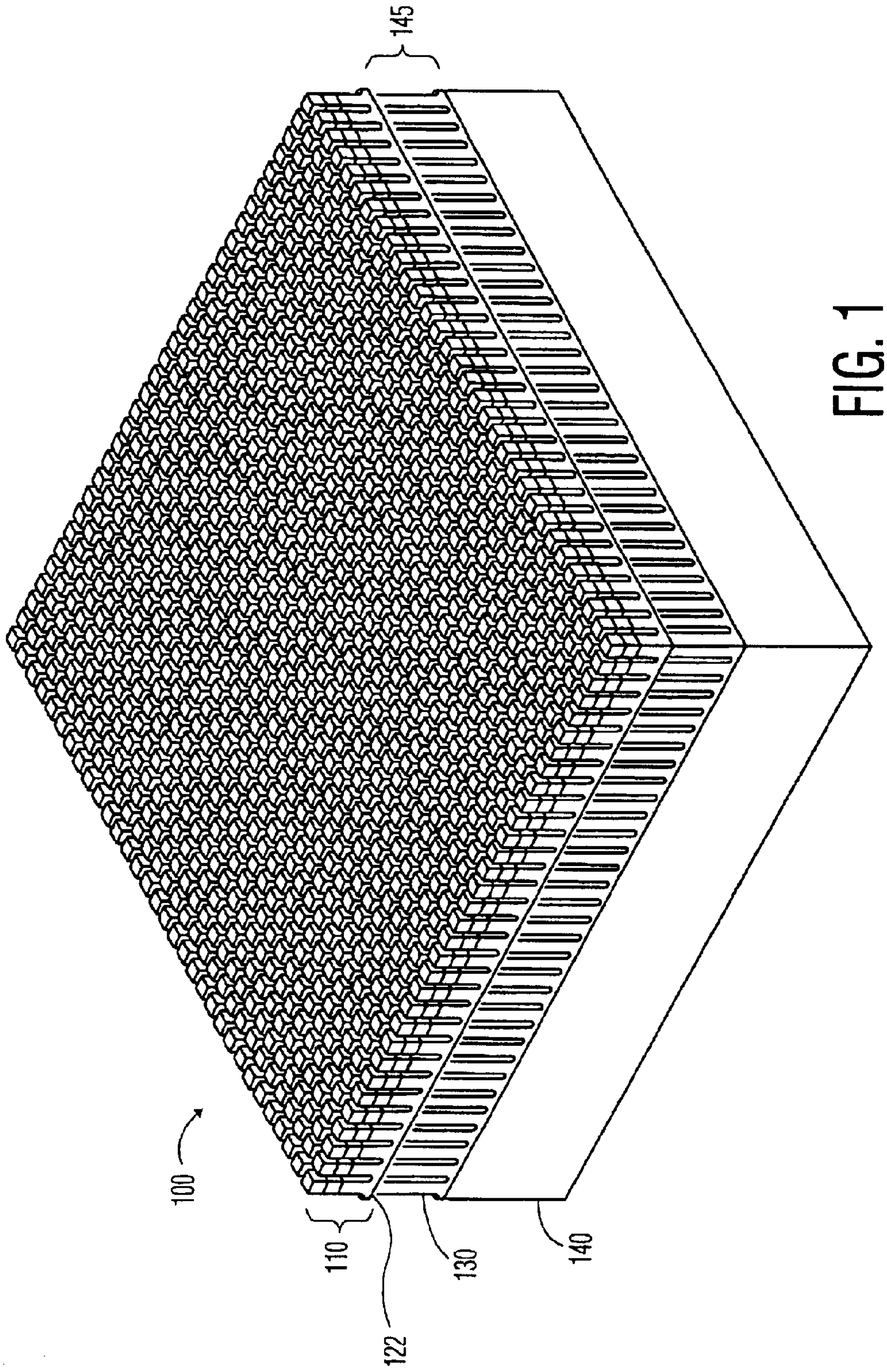
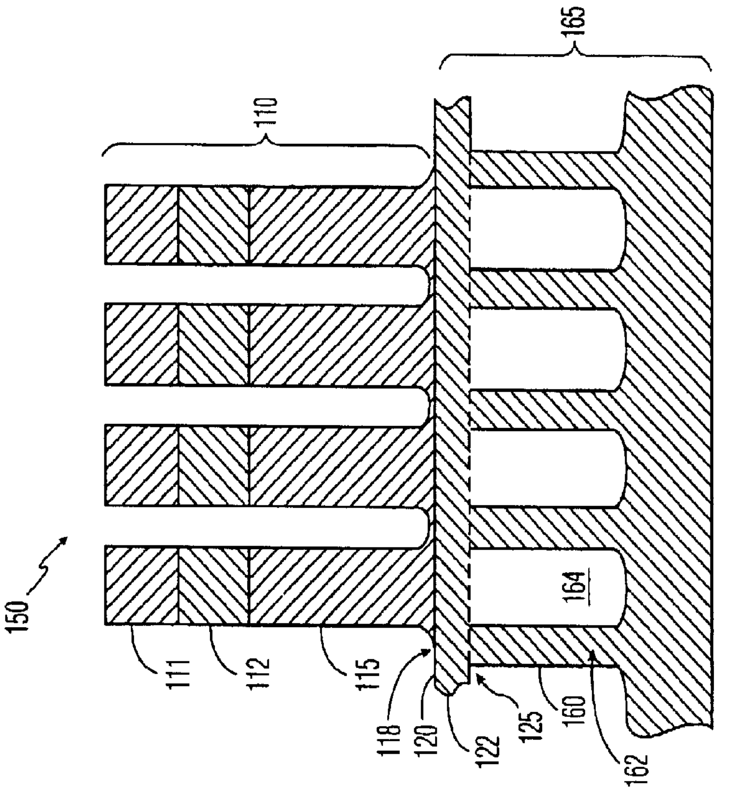


FIG. 1


150
110
165
111
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118
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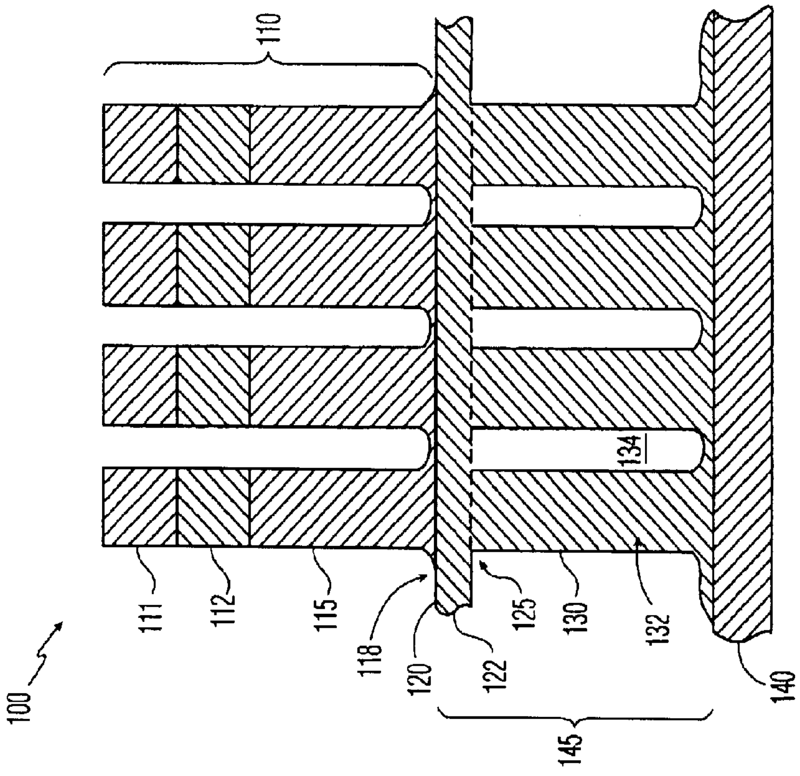
122
125
160
162
164

FIG. 2B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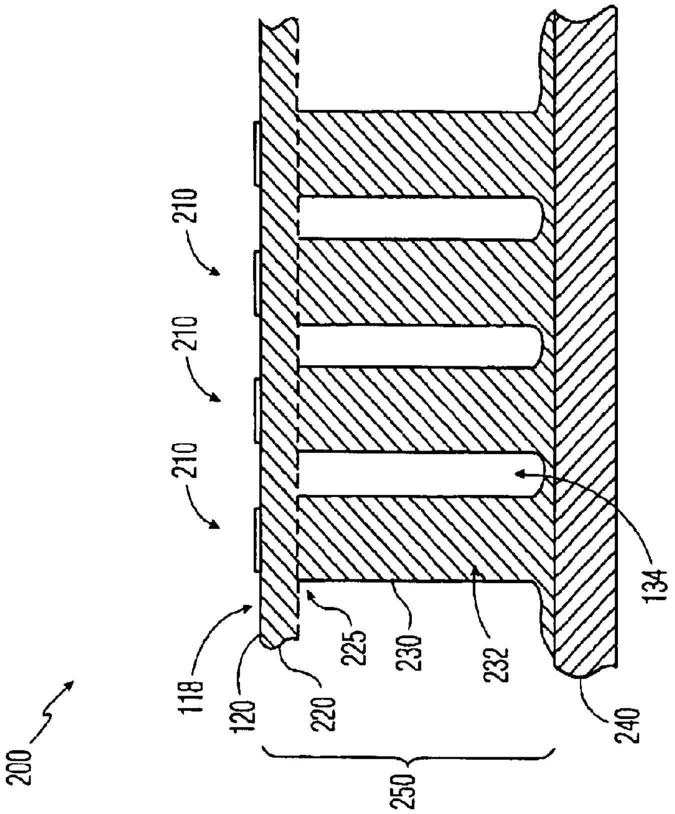
145

FIG. 2A


200
210
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118
120
220
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230
232
134
240
250

FIG. 3A

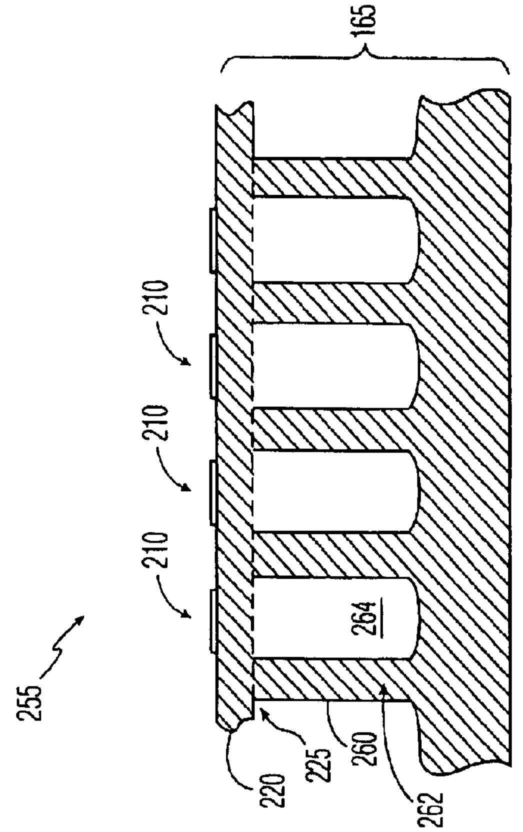
165
255
210
210
210
220
225
260
262
264

FIG. 3B

ULTRASONIC TRANSDUCER WAFER HAVING VARIABLE ACOUSTIC IMPEDANCE

TECHNICAL FIELD

The present invention relates generally to ultrasonic transducers, and, more particularly, to an ultrasonic transducer wafer, or substrate, having variable acoustic impedance.

BACKGROUND OF THE INVENTION

Ultrasonic transducers have been available for quite some time and are particularly useful for non-invasive medical diagnostic imaging. Ultrasonic transducers are typically formed of either piezoelectric elements or of micro-machined ultrasonic transducer (MUT) elements. The piezoelectric elements typically are made of a piezoelectric ceramic such as lead-zirconate-titanate (abbreviated as PZT), with a plurality of elements being arranged to form a transducer array. A MUT is formed using known semiconductor manufacturing techniques resulting in a capacitive ultrasonic transducer cell that comprises, in essence, a flexible membrane supported around its edges over a silicon substrate. By applying contact material, in the form of electrodes, to the membrane, or a portion of the membrane, and to the base of the cavity in the silicon substrate, and then by applying appropriate voltage signals to the electrodes, the MUT may be energized such that an appropriate ultrasonic wave is produced. Similarly, when electrically biased, the membrane of the MUT may be used to receive ultrasonic signals by capturing reflected ultrasonic energy and transforming that energy into movement of the electrically biased membrane, which then generates a receive signal.

The transducer elements may be combined with control circuitry forming a transducer assembly, which is then further assembled into a housing possibly including additional control electronics, in the form of electronic circuit boards, the combination of which forms an ultrasonic probe. This ultrasonic probe, having either bulk wave piezoelectric elements or MUTs and which may include various acoustic matching layers, backing layers, and de-matching layers may then be used to send and receive ultrasonic signals through body tissue.

In the past, joining an acoustic sensor, such as a piezoelectric ceramic transducer element or a MUT element, to the electrical control circuitry required the use of many individual wires to connect each element of the transducer array to the control circuitry. In the case of large transducer arrays having many hundreds or thousands of elements, large wiring harnesses were required. Unfortunately, a large wiring harness increases the bulk and the cost of the ultrasonic probe. For ultrasonic probes that are designed to be used inside the human body, it is desirable to reduce the overall size of the ultrasonic probe and related cabling. One manner of reducing the size of the probe and the cabling is to provide the transducer control electronics on an integrated circuit (IC) assembly or on a circuit board. An IC in proximity to the transducer array may be used to transmit and receive from many small transducer elements and may also be used to multiplex the signals, thereby reducing or eliminating the bulky and expensive cables that typically connect the ultrasonic probe elements to the control electronics.

Placing the transducer array over the IC results in greater packaging efficiency, but often causes undesirable coupling of acoustic energy between transducer elements through the substrate material because the substrate material on which the IC is formed comes into contact with all of the transducer elements.

Therefore, it would be desirable to have a way to connect the elements of an ultrasonic transducer array directly to an integrated circuit or circuit board while reducing or eliminating the undesirable lateral propagation of acoustic energy through the substrate of the IC and the circuit board.

SUMMARY

The invention is directed to a wafer having variable acoustic properties. The wafer may be used as a substrate over which to form an ultrasonic transducer, an IC, or may be used as a circuit board. An ultrasonic transducer formed on the wafer may include piezoelectric ceramic transducer elements or MUT elements. By controlling the acoustic impedance of the wafer upon which the integrated control circuitry for an ultrasonic transducer is formed, the acoustic impedance of the wafer can be matched to the acoustic impedance requirements of the ultrasonic transducer Furthermore, by the addition of internal voids, the wafer reduces or eliminates the lateral propagation of acoustic energy through the wafer.

Other systems, methods, features, and advantages of the invention will be or will become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention, as defined in the claims, can be better understood with reference to the following drawings. The components within the drawings are not necessarily to scale relative to each other, emphasis instead being placed upon clearly illustrating the principles of the present invention.

FIG. **1** is a perspective view of an ultrasonic transducer array formed on a wafer.

FIG. **2A** is a cross-sectional schematic view of a portion of the transducer of FIG. **1**.

FIG. **2B** is a cross-sectional schematic view illustrating an alternative embodiment of the ultrasonic transducer of FIG. **2A**.

FIG. **3A** is a cross-sectional schematic view illustrating a transducer constructed in accordance with an aspect of the invention and including micro-machined ultrasonic transducer (MUT) elements.

FIG. **3B** is a cross-sectional schematic view illustrating an alternative embodiment of the ultrasonic transducer of FIG. **3A**.

DETAILED DESCRIPTION OF THE INVENTION

The invention to be described hereafter is applicable to piezoelectric and micro-machined ultrasonic transducer (MUT) elements connected to a substrate on which an integrated circuit (IC) can be formed.

FIG. **1** is a perspective view of an ultrasonic transducer **100**. For illustration purposes only, the ultrasonic transducer **100** comprises a plurality of elements, referred to as an array, constructed using a piezoelectric material. However, the ultrasonic transducer **100** can also be fabricated using MUT elements, as will be described below with respect to FIGS. **3**A and **3**B. An exemplar one of the plurality of elements is denoted by reference numeral **110**. The collective plurality of transducer elements **110** comprises an ultrasonic sensor Although illustrated as uniformly spaced, the transducer elements **110** need not be spaced as illustrated. The transducer element **110** may include one or more matching layers (to be described below) and is attached to an integrated circuit (IC) (not shown in FIG. **1**). In order to maximize packaging efficiency, it is desirable to assemble the transducer elements **110** over the IC. The IC can be fabricated on an acoustically variable wafer **145** constructed in accordance with an aspect of the invention. The wafer **145** can be fabricated using, for example, silicon (Si), or can alternatively be fabricated using other substrate materials such as, for example, but not limited to, germanium (Ge). As will be described below, the acoustically variable wafer **145** is formed by bonding two wafer components together. The two wafer components can also be referred to as individual wafers.

The first wafer component **130** is formed by dicing grooves with, for example, a dicing saw, or selectively etching to remove material to produce a pattern on the first wafer component **130**. The pattern can be optimized for the particular application and configuration of the transducer array that will be formed over the wafer. In one embodiment the pattern includes a plurality of posts and voids. The second wafer component **122** is preferably an ultra-thin wafer and is bonded to the first wafer component **130**. The first wafer component **130** and the second wafer component **122** form an acoustically variable wafer **145** having adequate stiffness and is useful for subsequent processing into any of an IC, a MUT or a circuit board with traces and vias. As will be explained in further detail below, locating the transducer array elements over the posts or the voids inside the acoustically variable wafer **145** changes the acoustic impedance experienced by each transducer element **110**.

The IC is formed over the acoustically variable wafer **145**. The acoustically variable wafer **145** is constructed having a variable impedance and includes an acoustically variable substrate, referred to herein as the first wafer component **130**, over which is bonded a second wafer component **122**. As will be described below, the first wafer component **130** includes, for example, a waffle patterned structure that allows for variable acoustic impedance. The pattern applied to the first wafer component **130** also reduces the lateral propagation of acoustic energy within the acoustically variable wafer **145**. The IC can be formed on either surface of the acoustically variable wafer **145**. Furthermore, instead of an IC, the acoustically variable wafer **145** could include a circuit board with traces and no active circuitry. Typically, the material from which the first wafer component **130** is formed is the same material as that of the second wafer component **122**. Optionally, backing **140** can be applied behind the first wafer component **130**. The backing **140** acts as an acoustic absorption material.

In accordance with an aspect of the invention, and to be described in detail below, the first wafer component **130** includes a number of cavities that define a number of support elements, referred to below as posts. The average, as well as the local, acoustic impedance of the acoustically variable wafer **145** below an array element **110** can be controlled by altering the size, quantity, shape, location, and other parameters of the cavities. Furthermore, the cavities within the first wafer component **130** reduce or eliminate the propagation of acoustic energy, or waves, traveling laterally through the acoustically variable wafer **145**. This arrangement reduces the coupling of acoustic energy between the individual transducer elements **110**. By varying the acoustic impedance of the acoustically variable wafer **145**, the acoustic impedance of the acoustically variable wafer **145** can be matched to the acoustic impedance of the transducer elements **110**. Further, by adding the cavities to the first wafer component **130**, the lateral cross-coupling of acoustic energy between transducer elements **110** is significantly reduced or eliminated. Further still, by varying the acoustic impedance requirement of the acoustically variable wafer **145** to match the acoustic impedance of the transducer elements **110**, the bandwidth of the ultrasonic transducer **100** can be increased.

FIG. **2**A is a cross-sectional schematic view of a portion of the transducer **100** of FIG. **1**. Transducer **100** includes a plurality of transducer elements **110**, each of which include a first matching layer **111**, a second matching layer **112**, and a piezoelectric element **115**. Although shown having two matching layers **111** and **112**, the transducer **100** can be made with only one matching layer or with no matching layers, depending upon the desired application. The matching layer or layers, as known to those having ordinary skill in the art, help to match the acoustic impedance of the piezoelectric element **115** to the acoustic impedance of the tissue being imaged. The piezoelectric element **115** can be fabricated using all PZT ceramic, or can be fabricated using a composite piezoelectric material, depending on the desired impedance matching characteristics of the transducer.

The transducer element **110**, and in particular, the piezoelectric element **115**, is joined to the IC **120** along joint line **118**. For purposes of explanation, the following description will assume that the IC **120** is fabricated on a surface of the acoustically variable wafer **145**. The acoustically variable wafer **145** is fabricated by joining the second wafer component **122** to the first wafer component **130**. The second wafer component **122** is preferably on the order of less than 200 micrometers (μm), sometimes referred to as "microns," thick and can be joined to the first wafer component **130** using, for example, anodic bonding or fusion bonding, which are well known bonding techniques.

A number of different methodologies can be used to join the piezoelectric element **115** to the IC **120**, many of which are disclosed in commonly assigned U.S. Patent Application entitled "System for Attaching an Acoustic Element to an Integrated Circuit," filed on even date herewith, and assigned Ser. No. 09/919,470.

In accordance with an aspect of the invention, the first wafer component **130** includes a plurality of cavities **134**, which define a plurality of pillars, or posts **132**. Preferably, the cavities are cut into the first wafer component **130** using a dicing saw, or are chemically etched into the first wafer component **130** using etching techniques that are known to those having ordinary skill in the art. Preferably, the cavities **134** are formed to be approximately 50–100 micrometers (μm) wide and 250 to 450 μm deep. However, other cavity dimensions are possible, depending upon the desired acoustic properties of the acoustically variable wafer **145**.

In the example shown in FIG. **2**A, each transducer element **110** resides over one of the posts, **132**. By altering the physical characteristics of the cavities **134** the acoustic properties of the first wafer component **130**, and thus, the acoustically variable wafer **145**, can be altered. In this manner, the acoustic properties of the entire ultrasonic transducer **100** can be varied, and thereby controlled. The acoustic impedance of the first wafer component **130** can be designed to match the acoustic impedance of the element **110**.

In another aspect of the invention, the cavities **134** within the first wafer component **130** reduce or eliminate the propagation of acoustic waves that travel laterally through the acoustically variable wafer **145**. In this manner, the coupling of acoustic energy between elements **110** through the acoustically variable wafer **145** can be significantly reduced or eliminated.

After the cavities **134** are formed in the first wafer component **130**, the second wafer component **122** is joined to the first wafer component **130** along line **125**, thus forming acoustically variable wafer **145**. In this example, the second wafer component **122** and the first wafer component **130** are both silicon. Therefore, the second wafer component **122** can be joined to the first wafer component **130** using, for example, anodic bonding. Alternatively, fusion bonding, or other techniques known to those having ordinary skill in the art, can be used to join the second wafer component **122** to the first wafer component **130**. This results in an acoustically variable wafer **145** having an acoustic impedance defined by the configuration of the cavities **134**.

After the second wafer component **122** is joined to the first wafer component **130**, the IC **120** is formed on the exposed surface of the second wafer component **122** using conventional IC fabrication methodologies. In profile, the IC **120** is very thin with respect to the thickness of the acoustically variable wafer **145**. After the IC **120** is formed, the material that forms the piezoelectric element **115** is joined to the surface of the IC **120** along line **118** as described above. The matching layers **112** and **111** are then applied over the piezoelectric elements **115** and then the transducer elements **110** are formed by, for example, dicing or etching.

Depending on the desired characteristics of the ultrasonic transducer **100**, prior to assembling the second wafer component **122** to the first wafer component **130**, the cavities **134** can be filled with air or an inert gas. Alternatively, the second wafer component **122** can be joined to the first wafer component **130** in a vacuum so that the gas within the cavities **134** can be at a pressure less than that of the surrounding area.

The following discussion illustrates one manner in which the acoustic impedance of the first wafer component **130**, and therefore, the acoustically variable wafer **145**, can be altered to match the acoustic impedance of the transducer elements **110**. Assume that silicon has an acoustic impedance of approximately 19 Mrayls (a Mrayl is unit by which acoustic impedance is measured) and piezoelectric ceramic (the material from which each piezoelectric element **115** is formed) has an acoustic impedance of approximately 33 Mrayls. Assume that it is desirable to match the acoustic impedance of the acoustically variable wafer **145** (silicon) to the acoustic impedance of the piezoelectric element **115** (piezoelectric ceramic). Reducing the impedance of the piezoelectric ceramic can be done by using a composite of piezoelectric ceramic and various polymers, having an acoustic impedance of approximately 19 Mrayls. This prevents reflections at the interface **118** between the piezoelectric element **115** and the IC **120**. In accordance with an aspect of the invention, to prevent acoustic reflections at the back of the silicon interface (the surface **125** at which the second wafer component **122** is bonded to the first wafer component **130**) the acoustic impedance of the acoustically variable wafer **145** can be defined, by defining the posts **132** and cavities **134**, so that the acoustic impedance of the first wafer component **130** matches the acoustic impedance of the piezoelectric element **115**.

Acoustic backing **140** can be added to the back of the first wafer component **130** in order to absorb any acoustic energy that migrates through the acoustically variable wafer **145**.

FIG. **2B** is a cross-sectional schematic view illustrating an alternative embodiment of the ultrasonic transducer **100** of FIG. **2A**. Ultrasonic transducer **150**, similar to that described above with respect to ultrasonic transducer **100**, includes a first matching layer **111** and a second matching layer **112** over a piezoelectric element **115**. The piezoelectric element **115** can be a piezoelectric ceramic, or can be a piezoelectric composite material as described above. The first matching layer **111**, the second matching layer **112** and the piezoelectric element **115** comprise transducer element **110**. Each transducer element **110** is attached to the IC **120** in similar manner to that described above.

In a similar manner to that described above with respect to FIG. **2A**, the first wafer component **160** has a plurality of cavities **164** formed therein either by dicing, etching, or some other manner known to those having ordinary skill in the art. The cavities **164** define a plurality of posts **162**. However, in the embodiment described in FIG. **2B**, each transducer element **110** resides above one of the cavities **164**. As mentioned above, each of the cavities **164** can be filled with air, inert gas, or can be formed having a vacuum, thus creating a vacuum or gas-backed ultrasonic transducer **150**. The air-backed ultrasonic transducer **150** provides high efficiency and wide bandwidth operation. Similar to that described above, the cavities **164** can be designed to alter the acoustic impedance of the first wafer component **160**, and therefore, the acoustic impedance of the acoustically variable wafer **165**, and also reduce or eliminate the transmission of acoustic energy laterally through the acoustically variable wafer **165**.

FIG. **3A** is a cross-sectional schematic view illustrating a transducer **200** constructed in accordance with another aspect of the invention and including micro-machined ultrasonic transducer (MUT) elements. The ultrasonic transducer **200** includes an acoustically variable wafer **250** over which a plurality of MUT elements **210** are formed. Each MUT element comprises a plurality of MUT cells (not shown). The acoustically variable wafer **250** includes first wafer component **230** and a second wafer component **220**, which also forms the substrate over which the MUT elements **210** are formed. The second wafer component **220** is similar to the second wafer component **122** described above, and may be silicon or another semiconductor substrate material.

In accordance with this aspect of the invention, cavities **234** are formed in the first wafer component **230**, prior to joining the second wafer component **220**, resulting in the acoustically variable wafer **250** having the structure shown. Each cavity **234** can be etched or cut into the first wafer component **230**, creating cavities **234** that are preferably approximately 50–100 micrometers (μm) wide and 250 to 450 μm deep.

After the cavities **234** are formed in the first wafer component **230**, the second wafer component **220** is bonded along line **225** to the first wafer component **230**, thus forming the acoustically variable wafer **250**. After the acoustically variable wafer **250** is thus formed, the MUT elements **210** are fabricated over a surface of the acoustically variable wafer **250** as known to those having ordinary skill in the art. The first wafer component **230** can be either silicon or any other substrate depending upon the acoustic performance desired of the ultrasonic transducer **200**. The second wafer component **220** can be bonded to the first wafer component **230** using, for example, anodic bonding or fusion bonding. Furthermore, in this example, other silicon to silicon bonding techniques can be used.

As described above, the cavities **234** can be filled with air, gas or can contain a vacuum in order to provide acoustic isolation and greatly reduce or eliminate any acoustic energy traveling laterally in the acoustically variable wafer **250**. This greatly reduces acoustic coupling, thus reducing acoustic cross-talk between MUT elements **210**. As shown in FIG. **3**A, each MUT element **210** resides over one of the post **234**. By altering the size, shape, location and quantity of the cavities **234**, the acoustic impedance of the first wafer component **230**, and in particular, the acoustic impedance of each post **232**, can be designed to match the acoustic impedance of a MUT transducer element to a range of backing materials. As described above, backing **240** can be applied to the first wafer component **230** to absorb any acoustic energy that travels through the acoustically variable wafer **250**.

FIG. **3**B is a cross-sectional schematic view illustrating an alternative embodiment **255** of the ultrasonic transducer **200** of FIG. **3**A. As shown in FIG. **3**B, the first wafer component **260** includes a plurality of cavities **264**, which define a plurality of posts **262**. However, in this embodiment, each MUT element **210** resides over one of the cavities **264**.

It will be apparent to those skilled in the art that many modifications and variations may be made to the present invention, as set forth above, without departing substantially from the principles of the present invention. For example, the present invention can be used with piezoelectric ceramic and MUT transducer elements. Furthermore, the invention is applicable to different substrate materials including, for example, silicon and germanium. All such modifications and variations are intended to be included herein.

What is claimed is:

1. An ultrasonic transducer, comprising:

an ultrasonic sensor having a plurality of transducer elements formed on a first wafer component; and

an integrated circuit formed on a second wafer component, said second wafer component including a plurality of cavities defining a plurality of posts such that the cavities are configured and dimensioned to alter the acoustic impedance of said second wafer component in a predefined manner, and wherein the integrated circuit is joined to the ultrasonic sensor on said first wafer component and wherein each of the elements of the ultrasonic sensor is located over a respective one of the plurality of cavities.

2. The transducer of claim **1**, wherein the ultrasonic sensor comprises piezoelectric ceramic material.

3. The transducer of claim **1**, wherein the ultrasonic sensor comprises a micro-machined ultrasonic transducer (MUT).

4. The transducer of claim **1**, wherein the cavities reduce acoustic energy traveling laterally in the wafer.

5. The transducer of claim **1**, wherein the wafer is silicon.

6. The transducer of claim **1**, wherein the wafer is germanium.

7. The transducer of claim **1**, wherein the cavities are designed to allow the acoustic impedance of the wafer to match the acoustic impedance of the transducer elements.

8. The transducer of claim **1**, wherein the cavities are configured and dimensioned in a predetermined manner for the purpose of altering the acoustic impedance of the wafer to increase the effective bandwidth of the transducer elements.

* * * * *

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摘要(译)

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