SILICON PIEZOELECTRIC SPEAKER

FIELD OF THE INVENTION

The present invention relates to a microelectronic mechanical systems (MEMS) piezoelectric speaker and a method for manufacturing a MEMS piezoelectric speaker.

BACKGROUND OF THE INVENTION

MEMS speakers using silicon based diaphragms are used in the electronics industry in items such as mobile telephones and digital watches. One type of MEMS speaker is a piezoelectric speaker. A piezoelectric speaker uses a piezoelectric material to convert electrical signals into mechanical vibration of a diaphragm. By altering the polarity of a bias applied to a piezoelectric layer sitting on a diaphragm, the diaphragm is made to flex and unflex and so produce sound waves.

Silicon diaphragms have a number of advantages including excellent mechanical properties and reliability, as well as the ready availability of material and of highly accurate processing techniques.

There is desire to keep electronic components, including speakers, as small as possible. One problem is that speaker size affects speaker performance. With existing silicon speakers a smaller size means a reduced sensitivity owing to a reduced diaphragm size.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved piezoelectric silicon speaker and a simple manufacturing process, or at least to provide the public with a useful choice.

In a first aspect, the present invention is a piezoelectric speaker comprising:

a piezoelectric layer;

a diaphragm layer having a first major surface and second major surface, the first major surface of the diaphragm layer being contiguous with the piezoelectric layer;

an intermediate layer having a first major surface and a second major surface, the first major surface of the intermediate layer being contiguous with the second major surface of the diaphragm layer; and

a support layer contiguous with the second major surface of the intermediate layer,

wherein a cavity is formed through both the support layer and the intermediate layer, wherein the diaphragm layer extends over the cavity, and wherein the cavity extends between

the diaphragm layer and the support layer such that a portion of the diaphragm layer directly overlies a portion of the support layer with no intermediate layer between them.

Preferably, the support layer is formed from silicon. Preferably, the diaphragm layer is formed from highly doped silicon. Preferably, the intermediate layer is formed from an oxide. Preferably, the oxide layer is formed by wet thermal oxidation.

Preferably, the diaphragm layer is isolated from edges of the speaker. Preferably, the diaphragm layer has a reduced thickness in a region overlying the cavity.

Preferably, the piezoelectric layer is compressive.

In a second aspect, the present invention is a piezoelectric speaker package comprising:

package walls;

a support layer,

a diaphragm layer overlying the support layer; and

a piezoelectric layer overlying the diaphragm layer,

wherein the support layer, diaphragm layer and piezoelectric layer are all positioned within the package walls, and wherein the diaphragm layer is isolated from the package walls.

Preferably, the support layer is formed from silicon. Preferably, the diaphragm layer is formed from highly doped silicon.

Preferably, the diaphragm layer has a reduced thickness in a region overlying the cavity.

Preferably, the piezoelectric layer is compressive.

In a third aspect, the present invention is a method of manufacturing a piezoelectric speaker from a silicon on insulator (SOI) wafer having a device layer, an intermediate layer and a support layer, comprising the step of:

removing a portion of the support layer and the intermediate layer, to form a diaphragm from the device layer.

Preferably, the method further includes the step of removing a perimeter portion of the device layer, the perimeter portion completely surrounding a portion of the device layer forming the diaphragm.

Preferably, the method includes the step of removing a portion of the intermediate layer directly between the support layer and the device layer so that a portion of the diaphragm directly overlies a portion of the support layer.

Preferably, the step of removing a portion of the intermediate layer includes gas-phase etching with an alcoholic vapour.

Preferably, the method further includes the step of thinning a portion of the diaphragm.

Preferably, the method further includes the step of depositing layer of silicon nitride on the diaphragm.

In a fourth aspect, the present invention is a method of manufacturing a piezoelectric speaker comprising the steps of:

providing a support layer,

providing an intermediate layer overlying the support layer,

providing a diaphragm layer overlying the intermediate layer,

providing a piezoelectric layer overlying the diaphragm layer,

forming a cavity through the support layer and the intermediate layer in a region where the diaphragm layer is intact and removing a portion of the intermediate layer lying between the diaphragm layer and the support layer.

Preferably, the method further includes a step of removing a perimeter portion of the diaphragm outside the extent of the cavity, the perimeter portion forming a closed loop.

Preferably, the step of removing a portion of the intermediate layer includes gas-phase etching with an alcoholic vapour.

Preferably, the method further includes a step of thinning a portion of the diaphragm.

Preferably, the method further includes a step of depositing a layer of silicon nitride on the diaphragm.

Preferably, the method includes using a silicon on insulator (SOI) wafer as a starting material.

In a fifth aspect, the present invention is a method of manufacturing a piezoelectric speaker including the steps of:

providing a support layer,

providing an intermediate layer on the support layer,

providing a diaphragm layer on the layer,

forming a cavity in the support layer and the intermediate layer, and

removing a perimeter portion of the diaphragm layer, the perimeter portion completely surrounding a portion of the diaphragm layer overlying the cavity.

Preferably, the method includes the step of removing a portion of the intermediate layer directly between the support layer and the device layer.

Preferably, the step of removing a portion of the intermediate layer includes gas-phase etching with an alcoholic vapour.

Preferably, the method further includes the step of thinning a portion of the diaphragm.

Preferably, the method further includes the step of depositing layer of silicon nitride on the diaphragm.

Preferably, the method includes using a silicon on insulator (SOI) wafer as a starting material.

In a sixth aspect of the invention, there is provided a speaker manufactured using a method according to the third aspect of the invention.

In a further aspect, there is provided a speaker substantially as herein described with reference to any one or more of the accompanying drawings. In a still further aspect, there is provided a method of manufacturing a speaker substantially as herein described with reference to any one or more of the accompanying drawings.

The term "comprising" as used in this specification means "consisting at least in part of", that is to say, when interpreting independent paragraphs including that term, the features prefaced by that term in each paragraph will need to be present but other features may also be present.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of the present invention will now be described in detail with reference to the accompanying drawings in which:

Figure 1 is a cross-section of one embodiment of the present invention;

Figure 2 is a plan view of the embodiment shown in Figure 1;

Figure 3 is a cross-section of the second embodiment of the present invention;

Figures 4a to 4h illustrate stages in a manufacturing process according to the present invention.

DETAILED DESCRIPTION

The invention will be described with reference to the Figures. It should be noted that the Figures are not drawn to scale and are given for illustrative purposes only. It should also be noted that the description relates to only two preferred embodiments of the invention. Alternative forms of a silicon speaker may also be made in accordance with the invention.

Figure 1 is a cross-sectional view of a piezoelectric speaker in accordance with one embodiment of the present invention. The speaker comprises a support layer 10, an intermediate, oxide layer 11 formed on the support layer, a highly doped silicon device layer 12

formed on the oxide layer 11, a piezoelectric layer 13 formed from aluminium nitride on the device layer 12, a pair of aluminium bond pads 14 and a further oxide layer 15.

The highly doped silicon layer 12 forms a diaphragm which extends over a cavity 16 formed in the underlying support layer 10 and oxide layer 11. The piezoelectric layer 13 is formed or deposited on a top surface of the device layer 12. When electric signals are applied to the piezoelectric layer 13 via aluminium bond pads 14, the piezoelectric layer expands and contracts causing the diaphragm in the device layer to flex and produce sound waves.

In this example, the cavity 16 has angled sidewalls forming a cone shape. The cone shape acts to project the sound waves generated by the diaphragm.

The diaphragm 12 in this example is of reduced thickness in the region overlying the cavity 16. The thickness of the diaphragm can be chosen to provide required speaker performance characteristics.

Figure 2 is a plan view of the speaker shown in Figure 1. In this example the piezoelectric layer 13 is circular and overlies a square shaped cavity 16. However, the shape of the piezoelectric layer and of the cavity can be chosen to provide the required speaker performance.

It can be seen from Figure 2 that the diaphragm layer is isolated from the perimeter of the speaker by a trench 17 formed through the device layer and the overlying oxide layer 15. This ensures that the diaphragm does not pick up stray signals which would interfere with the proper function of the speaker.

Figure 3 shows a cross-section of a second embodiment of the present invention. The speaker shown in Figure 3 is identical to the speaker shown in Figures 1 and 2 except that the speaker shown in Figure 3 includes an undercut 18 of the oxide layer 11 between the support layer 10 and the device layer 12. The undercut 18 extends around the rim of the cavity 16 enlarging the area of oxide that is removed. This increases the effective size of the diaphragm and increases the tonal range and volume of the speaker, without affecting the overall size of the device.

Figure 4 shows an example set of processing steps in the manufacturing of the speakers shown in Figures 1 to 3.

Figure 4a shows a starting material for speaker that is a silicon on insulator (SOI) wafer. Figure 4a shows a cross- sectional view. The SOI wafer has a support layer (or handle wafer) 10 of approximately 500 micrometres thickness, a thermal oxide layer 11 of approximately 2 micrometres thickness and a device layer 12 formed of highly doped silicon of approximately 3 micrometres thickness. The device layer 12 has a resistivity of between 0.01 and 0.02 ohms per

centimetre. Silicon on insulator wafers of this type are standard industry items and are now relatively inexpensive. (However, an SOI wafer can be specially manufactured with materials and dimensions to suit the final speaker design as required.) The SOI wafer is three dimensional and has a substantially uniform cross-section. The major surfaces of the wafer, which are normal to the page in Figure 4, can be of any desired size and shape.

The next stage in the manufacturing process is to grow a layer of thermal oxide 15 on the device layer 12, as shown in Figure 4b. The thermal oxide layer may be silicon dioxide. A similar layer of thermal oxide 19 is optionally grown on the underside of the support layer 10. In this example, the thermal oxide layer 15 is approximately one micrometre in thickness. The thermal oxide layer 15 is patterned and etched as shown in Figure 4c to isolate a portion of the device layer which will form the diaphragm. The etching forms a perimeter 40 which is a closed loop and entirely surrounds the diaphragm portion of the device layer. The purpose of this step is to minimise any stray, parasitic signals which might otherwise be picked up by the device layer. The perimeter 40 isolates the diaphragm from the package walls and may be formed at the very edge of the device layer, leaving no collar around the periphery.

The next stage is to pattern and etch the oxide layer 15 again, to leave space for a piezoelectric layer 13 and contact pads 14. This is shown in Figure 4d.

Figure 4e shows the device following sputtering of an aluminium nitride layer 13 onto the device layer. Aluminium nitride is a piezoelectric material. The aluminium nitride layer can be formed by other means such as by sputtering/evaporating through a shallow mask or by using a lift off process. An alternative piezoelectric material could be used in place of the aluminium nitride, such as zinc oxide (ZnO). Preferably, the aluminium nitride layer is highly compressive in nature as this leads to better speaker performance. The desirability of a compressive material is described in Seung Hwan Yi and Eun Sok Kim, "Piezoelectric microspeaker with compressive nitride diaphragm", The Fifteenth IEEE International Conference on Micro Electro Mechanical Systems, 2002. Contact pads 14 are formed as shown in Figure 4f. Aluminium or other suitable metal contact pads can be formed using a lift-off process or by depositing the aluminium followed by a patterning and etch step. Any conductive metal may be used to form the contact pads 14.

In order to form a diaphragm, a cavity 16 is etched through the support layer 10 and the thermal oxide layer 11 as shown in Figure 4g. The cavity 16 is formed by first a patterning the oxide layer 19 formed on the underside of the support layer followed by an etching step. The etching can be a dry or wet etch, using KOH for example, up to the oxide layer 11 underneath the diaphragm layer. The oxide layer 11 acts as an etch stop. Following etching of the support

layer, the oxide layer must be etched. This is preferably done as an isotropic dry etch, using an alcoholic vapour. The use of alcoholic vapour prevents stiction problems, as described in Jang et al., "Fabrication of MEMS devices by using anhydrous HF gas-phase etching with alcoholic vapour", *Journal of Micromechanics and Microengineering*, 12 (2002) 297-306.

During this step, the silicon device layer can be thinned to provide the desired final thickness of the diaphragm.

It is also during this step that the undercut 18 that is shown in Figure 3 can be formed. Undercutting can be achieved using the same isotropic dry gaseous etch, using an alcohol such as methanol or ethanol. The extent of the undercut 18 is selected to increase the effective area of the diaphragm while retaining a robust and reliable structure and allowing space for connection of any die attachments or wiring.

A layer of silicon nitride can be sputtered on to the underside of the cavity if needed to balance the stress on the diaphragm.

It should be appreciated that the manufacturing steps need not be carried out in the order described above. Many different orders for the steps are possible. For example, it is possible to form the cavity 16 prior to deposition of the contact pads 14.

It should also be apparent that the isolating trench 40 and the undercut 18 are features that can be independently applied to other speaker designs. In particular, these features are not limited to speakers based on SOI wafers or speakers with a silicon diaphragm. They are equally applicable and are beneficial to speaker with silicon nitride diaphragms for example.

Where in the foregoing description, reference has been made to elements or integers having known equivalents, then such equivalents are included as if they were individually set forth.

Although the invention has been described by way of example and with reference to particular embodiments, it is to be understood that modifications and/or improvements may be made without departing from the scope or spirit of the invention.

CLAIMS

1. A piezoelectric speaker comprising:

a piezoelectric layer;

a diaphragm layer having a first major surface and second major surface, the first major surface of the diaphragm layer being contiguous with the piezoelectric layer;

an intermediate layer having a first major surface and a second major surface, the first major surface of the intermediate layer being contiguous with the second major surface of the diaphragm layer; and

a support layer contiguous with the second major surface of the intermediate layer,

wherein a cavity is formed through both the support layer and the intermediate layer, wherein the diaphragm layer extends over the cavity, and wherein the cavity extends between the diaphragm layer and the support layer such that a portion of the diaphragm layer directly overlies a portion of the support layer with no intermediate layer between them.

2. A piezoelectric speaker according to claim 1, wherein the support layer is formed from silicon.

3. A piezoelectric speaker according to claim 1 or claim 2, wherein the diaphragm layer is formed from highly doped silicon.

4. A piezoelectric speaker according to any preceding claim, wherein the intermediate layer is an oxide layer.

5. A piezoelectric speaker according to any preceding claim, wherein the diaphragm layer is isolated from edges of the speaker.

6. A piezoelectric speaker according to any preceding claim, wherein the diaphragm layer has a reduced thickness in a region overlying the cavity.

7. A piezoelectric speaker according to any preceding claim, wherein the piezoelectric layer is compressive.

8. A piezoelectric speaker package comprising:

package walls;

a support layer,

a diaphragm layer overlying the support layer; and

a piezoelectric layer overlying the diaphragm layer,

wherein the support layer, diaphragm layer and piezoelectric layer are all positioned within the package walls, and wherein the diaphragm layer is isolated from the package walls.

9. A piezoelectric speaker package according to claim 8, wherein the support layer is formed from silicon.

10. A piezoelectric speaker package according to claim 8 or 9, wherein the diaphragm layer is formed from highly doped silicon.

11. A piezoelectric speaker package according to claim 8, 9 or 10, wherein the diaphragm layer has a reduced thickness in a region overlying the cavity.

12. A piezoelectric speaker package according to any one of claims 8 to 11, wherein the piezoelectric layer is compressive.

13. A method of manufacturing a piezoelectric speaker from a silicon on insulator (SOI) wafer having a device layer, an intermediate layer and a support layer, comprising the step of:

removing a portion of the support layer and the intermediate layer to form a diaphragm from the device layer.

14. A method of manufacturing a piezoelectric speaker according to claim 13, further including the step of removing a perimeter portion of the device layer, the perimeter portion completely surrounding a portion of the device layer forming the diaphragm.

15. A method of manufacturing a piezoelectric speaker according to claim 13 or 14, further including the step of removing a portion of the intermediate layer directly between the support layer and the device layer so that a portion of the diaphragm directly overlies a portion of the support layer.

16. A method of manufacturing a piezoelectric speaker according to claim 13, 14 or 15, wherein the step of removing a portion of the intermediate layer includes gas-phase etching with an alcoholic vapour.

17. A method of manufacturing a piezoelectric speaker according to any one of claims 13 to 16, further including the step of thinning a portion of the diaphragm.

18. A method of manufacturing a piezoelectric speaker according to any one of claims 13 to 17, further including the step of depositing a layer of silicon nitride on the diaphragm.

19. A method of manufacturing a piezoelectric speaker comprising the steps of:

providing a support layer,

providing an intermediate layer overlying the support layer,

providing a diaphragm layer overlying the intermediate layer,

providing a piezoelectric layer overlying the diaphragm layer,

forming a cavity through the support layer and the intermediate layer in a region where the diaphragm layer is intact and removing a portion of the intermediate layer lying between the diaphragm layer and the support layer.

20. A method of manufacturing a piezoelectric speaker according to claim 19, further including a step of removing a perimeter portion of the diaphragm outside the extent of the cavity, the perimeter portion forming a closed loop.

21. A method of manufacturing a piezoelectric speaker according to claim 19 or 20, wherein the step of removing a portion of the intermediate layer includes gas-phase etching with an alcoholic vapour.

22. A method of manufacturing a piezoelectric speaker according to claim 19, 20 or 21, further including a step of thinning a portion of the diaphragm.

23. A method of manufacturing a piezoelectric speaker according to any one of claims 19 to 22, further including a step of depositing a layer of silicon nitride on the diaphragm.

24. A method of manufacturing a piezoelectric speaker according to any one of claims 19 to 23, further including a step of using a silicon on insulator (SOI) wafer as a starting material.

25. A method of manufacturing a piezoelectric speaker including the steps of:
providing a support layer,
providing an intermediate layer on the support layer,
providing a diaphragm layer on the intermediate layer,
forming a cavity in the support layer and the intermediate layer, and
removing a perimeter portion of the diaphragm layer, the perimeter portion completely surrounding a portion of the diaphragm layer overlying the cavity.

26. A method of manufacturing a piezoelectric speaker according to claim 25, further including a step of removing a portion of the intermediate layer directly between the support layer and the device layer.

27. A method of manufacturing a piezoelectric speaker according to claim 25 or 26, wherein the step of removing a portion of the intermediate layer includes gas-phase etching with an alcoholic vapour.

28. A method of manufacturing a piezoelectric speaker according to claim 25, 26 or 27, further including the step of thinning a portion of the diaphragm.

29. A method of manufacturing a piezoelectric speaker according to any one of claims 25 to 28, further including the step of depositing layer of silicon nitride on the diaphragm.

30. A method of manufacturing a piezoelectric speaker according to any one of claims 25 to 29, further including a step of using a silicon on insulator (SOI) wafer as a starting material.