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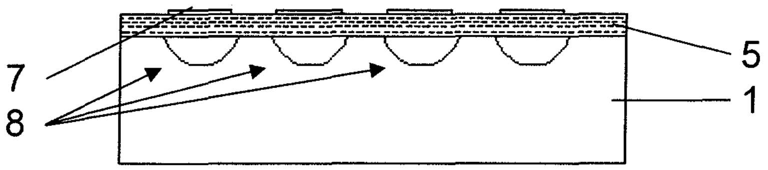
(54) Capacitive micromachined ultrasonic transducer and its fabrication method

(57) The invention relates to an electro-acoustic transducer (8) comprising a substrate (1) of a substrate material, a cavity (3) and a membrane (5) extending over at least a portion of the cavity. The cavity is arranged in the substrate material and the membrane is supported above the cavity by the substrate material. The invention further relates to a method of fabrication such an electro-acoustic transducer.

Fig. 1H



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Description

[0001] The present invention relates to electro-acoustic transducers, in particular capacitive Micromanufactured Ultrasonic Transducers, and a method of fabrication thereof.

[0002] Capacitive Micromanufactured Ultrasonic Transducers, generally referred to as cMUTs, and methods of fabricating them are known in the art. Surface micromachined ultrasound transducers are e.g. described in US 5,619,476, US 5,650,572, US 5,870,351, US 5,894,452, and US 6,004,832.

[0003] Such surface micromachined transducers comprise a substrate and one or more membranes which are supported above the substrate by support structures, forming cells. The thus formed membrane cells are combined to single or multiple element transducer(s). In the prior art, surface micromachined transducer membrane cell cavities and support structures are fabricated by selectively etching a sacrificial film, which film is deposited or grown between the membrane and the surface of the substrate. Such methods involve multiple complex fabrication steps, which compromise the repeatability and uniformity of the membranes and thus of the transducers.

[0004] A modification of the above-described method is disclosed in US 7,074,634, which teaches how to improve the planarity of a cMUT device. The method of US 7,074,634 comprises deposition of silicon monoxide to form a supporting layer with subsequent lift-off and grinding procedures to form uniform cavities for cMUT cells in the supporting layer. However, a method including mechanical grinding and polishing into the micromachining process is not technically feasible. Furthermore, the method still comprises the major disadvantages of surface micromachining, such as poor repeatability and uniformity.

[0005] Another option is disclosed in US 2004/0085858, which teaches bulk micromachining and wafer bonding technology. This method comprises providing a substrate with an oxide layer, etching cavities in the oxide layer down to the substrate and fusion bonding of membrane material to the oxide layer. This provides a number of advantages over surface micromachining, because most of the etching processes involved are self-stopping. Further, epitaxially grown monocrystalline silicon may be used for the membranes. However, such a method is relatively complex and costly.

[0006] It is therefore an object of the present invention to provide an improved method of fabricating an electro-acoustic transducer, in particular a capacitive Micromanufactured Ultrasonic Transducer.

[0007] To that end a method is provided comprising the steps of providing a substrate having a surface;
providing a cavity in the surface of the substrate;
providing a layer of membrane material on the surface of the substrate to form a membrane over at least a portion of the cavity.

[0008] The method facilitates controlled fabrication of the cavity and thus of the shape and volume of the cell of the transducer. The method allows fabrication without requiring a supporting layer for supporting the membrane in the finished transducer, which facilitates the process and improves repeatability and uniformity. The resulting electro-acoustic transducer is ideally suited for use as a cMUT in case an electrode is arranged on the membrane over at least a portion of the cavity. Using the method a plurality of electro-acoustic transducer cells or electro-acoustic transducers, e.g. arranged in one or more arrays, may be provided in a substrate in one process.

[0009] The method of claim 2 provides a reliable method for fabricating a membrane over at least a portion of the cavity. A substantially closed cell may be fabricated by providing the membrane material on the sacrificial material over substantially the entire cavity.

[0010] With the method of claim 3 cavities may be formed with a well-defined shape. It also allows fabricating a plurality of cavities arranged in a well-defined pattern.

[0011] The patterned resist layer comprises openings through which the substrate material is removable, preferably by an etching method, e.g. plasma etching or reactive ion etching (RIE). Preferably, the removal method is a self-stopping process which improves reliability of the method.

[0012] The method of claim 4 allows accurate structuring of the sacrificial material.

[0013] It has been found that silicon comprising substrate material, in particular a silicon wafer, provides a suitable substrate for an electro-acoustic transducer.

[0014] It is useful that -if applied- the resist layer comprises an oxide layer, in particular when the substrate material contains silicon, especially when it is a silicon wafer, since an oxide layer may be provided relatively easily such as by being thermally grown and it may be processed by various techniques. The resist layer may also suitably comprise a photo-resist layer. Reactive ion etching (RIE) is particularly suited for etching a silicon substrate, and it has been found that such a process is self-stoppable.

[0015] It has been found that silicon nitride has excellent properties as a membrane material. The membrane material may be provided with various techniques, e.g. plasma enhanced chemical vacuum deposition (PECVD).

[0016] A method for providing such a membrane is defined in claim 8. Further layers may be added.

[0017] The physical properties of the membrane, in particular the residual stress inside the material and its default shape, i.e. its shape when the transducer is not in operation, may be controlled by adjusting the composition of the membrane, e.g. layer thicknesses for a multilayered membrane, and/or adjusting deposition process parameters such as temperature, pressure, plasma frequencies etc.

[0018] It has been found that copper presents a suitable sacrificial material; it may be etched with various relatively reliable etchants and it provides a relatively large etching selectivity against most substrate and membrane materials, in particular against silicon, silicon oxide and/or silicon nitride. Thus, a sacrificial etching step is relatively reliable and uncritical.

[0019] Another aspect of the invention is an improved electro-acoustic transducer. The transducer comprises a substrate of a substrate material, a cavity, and a membrane. The membrane extends over at least a portion of the cavity, preferably over the entire cavity forming a substantially closed cell. The cavity is arranged in the substrate material and the membrane material is supported above the cavity by the substrate material.

[0020] The transducer has a relatively simple construction compared to prior art transducers, obviating deposition of a support layer for defining cavities and supporting the membrane. Mechanical and acoustic properties of the transducer are improved by reducing the number of structural elements of different materials thus reducing structural discontinuities causing possible weak points and boundary effects. The characteristics of the transducer such as its frequency response and collapse voltage of the transducer may be calculated and modelled more accurately

[0021] Although several substrate materials and membrane materials may be suitably applied, it is particularly useful that the substrate comprises silicon, e.g. being a silicon wafer, and that the membrane comprises silicon nitride, since it has been found these materials have excellent properties as a substrate material or membrane material, respectively, with respect to their mechanical (and thus acoustic) and electric properties.

[0022] Claim 13 defines a transducer with a particularly well suited and controllable membrane material. The composition of the stack of layers comprised in the membrane determine its mechanical, acoustic and electric properties.

[0023] The embodiment of claim 14 allows providing a membrane with a desired stress profile, in particular along an edge of the cavity at a support structure. A recessed membrane is further mechanically protected.

[0024] The bottom of the cavity is considered the side of the cavity opposite the membrane, generally oriented toward the bulk of the substrate material.

[0025] Another aspect of the invention is an electro-acoustic transducer array comprising a plurality of electro-acoustic transducers according to the above description, as transducer cells.

[0026] The invention will hereafter be explained in more detail with respect to the accompanying drawings. The drawings illustrate a presently preferred embodiment for fabricating a plurality of cMUT cells, which embodiment comprises the photolithographic definition and self-stopped etching of a silicon substrate with a thermally grown silicon dioxide layer to form cMUT cells, and consecutive steps of deposition of a sacrificial layer, lift-off, deposition of silicon nitride membranes, etching the sacrificial film and deposition and patterning of electrodes.

[0027] It should be noted that the drawings are not necessarily to scale and that details which are not necessary for understanding the present invention may have been omitted. Terms "upper", "lower", "above", and the like relate to the embodiments as oriented in the figures.

> Figs. 1A-1H are cross-sectional views illustrating several steps of the method of fabricating a plurality of electro-acoustic transducers;
> Figs. 2A and 2B show two different positions of membranes;
> Fig. 3 shows a simulated profile of the stress at the edges of the membrane as a function of the membrane position with respect to the overall device top surface.

[0028] Fig. 1A is a cross-sectional view of a silicon wafer 1 to be used as a substrate for the transducers. The wafer 1 is provided with a thermally grown silicon dioxide layer 2A, 2B, which generally forms on both surfaces of the substrate (Fig. 1B). The wafer may be doped to have a relatively high conductivity.

[0029] The oxide layer (2A) on one surface of the substrate 1 is lithographically patterned in a manner known as such. The patterned layer 2A' comprising the oxide layer 2A and possibly a remaining layer of photo-resist, acts as a resist layer for etching portions of wafer material, whereby the resist pattern is transferred to the substrate 1 and cavities 3 are created in the wafer material according to the resist pattern (Fig. 1C). The cavities 3 will lateron result in the cells of the transducer. The etching process parameters (e.g. etching rate and time) determine the volume (cross-sectional shape) of the cavities 3 in the substrate material.

[0030] A preferred etching method is reactive ion etching (RIE), which has been found to be self-stopping. Most etching processes may be controlled relatively accurately. Etching at least a portion of the cavities 3 in parallel allows providing a relatively large uniformity of the dimensions of the cavities 3.Next, sacrificial material is applied by deposition of a layer thereof on top of the structured substrate 1, with portions 4A of the sacrificial material being applied to the remaining portions of the resist layer 2A', and portions 4B of the sacrificial material filling at least a portion of the cavities 3 (Fig. 1D).

[0031] Preferably, the sacrificial material 4A, 4B is copper which may be deposited by physical vapour deposition in a high vacuum. This provides minimum sidewall coverage and leaves the sides of the patterned resist layer 2A' exposed to an anisotropic etchant. Next, the resist layer 2A' is removed by which the portions of sacrificial copper layer 4A are removed as well (lift-off; Fig. 1E). This removal can be done by etching, for example with hydrofluoric acid. The oxide layer 2B may be removed as well in this step. The remaining portions of sacrificial copper 4B and the substrate material 1 are substantially not affected by this step, as is preferred.

The thus processed substrate 1 does not require successive polishing prior to providing the membrane.

[0032] Next (Fig. 1F), a layer 5 of stacked silicon nitride forming the membrane material is provided over the patterned substrate 1 and the remaining portions of sacrificial material 4B by deposition. The silicon nitride may be deposited virtually stress-free.

[0033] Here, the silicon nitride is fabricated in three main steps. First, a first film is deposited of low stress silicon nitride using plasma enhanced chemical vapour deposition with two plasma frequencies, which material is also known as dual frequency silicon nitride. This first layer provides the main thickness of the membrane. The material provides reliable, crack-free sacrificial release of the membrane.

[0034] Next, a second layer is deposited of silicon oxide or silicon oxynitride (with considerable compressive stress), also using dual frequency PECVD. This layer increases the electrical insulation of the stack of layers forming the membrane.

[0035] Finally, a third layer is deposited, comprising high tensile stress silicon nitride. This third layer compensates for compressive stress of particularly the second layer in the membrane, making the membrane effectively stress-free or low tensile stressed.

[0036] Sacrificial etching openings are provided through the membrane layer 5, either during or after formation of the layer 5. Through these sacrificial etching openings the remaining portions of sacrificial copper 4B are removed by etching such that substantially open transducer cells 6 are formed by the material of the substrate 1 and the membrane 5 is suspended above the cavities 3 of the cells 6 by the substrate material (Fig. 1G). No support structures of other materials are required.

[0037] The use of copper as a sacrificial material allows using wet chemical etching with a relatively high etching selectivity. Sacrificial etching can e.g. be performed with standard chemical methods such as sodium persulphate, which shows excellent etching selectivity with respect to the structural materials silicon and silicon nitride which define the cavities. Preferably, the sacrificial etching openings are closed after the substantially complete removal of the sacrificial material 4B, e.g. by deposition of one or more additional layers of silicon nitride membrane material.

[0038] As an example, the first layer of the membrane 5 is provided with sacrificial etching openings. After deposition of the first layer, the sacrificial copper 4B is etched. Then second and third layers are deposited, by which process steps the sacrificial etching openings are sealed.

[0039] Next, one or more electrodes 7 are provided on the membrane 5 at the positions of the cells, and possibly a number of other conductors to provide an array of capacitive micromachined ultrasonic transducers 8 (Fig. 1H). The electrodes and conductors may be provided by vacuum deposition of a metal film and/or lithographic methods known per se, thus allowing grouping membrane cells to arrays of transducers 8 in a desired arrangement. The substrate 1 forms the other electrode for the transducer 8, here it forms a common electrode for all transducers 8. The substrate may also be divided for providing a plurality of transducer arrays.

[0040] The method of fabrication of the membrane 5 allows to fabricate membranes with different properties. Two exemplary embodiments are indicated in Figs. 2A and 2B, which each show a cross sectional view of a membrane 5 provided with isolines of stress intensity. Regions with low relative stress intensity are indicated with "L", regions with high relative stress intensity are indicated with "H". The regions with maximum stress intensity are indicated with "H_m".

[0041] In Figs. 2A and 2B the substrate 1 (partially shown) defining the cavity 3 and the bottom of the cavity (not indicated) is located below the membrane 5. The top surface of the membrane 5 facing away from the substrate 1, and therewith from (the bottom of) the cavity 6 is denoted with reference numeral 9, the bottom surface of the membrane 5 facing towards the substrate lies denoted with reference numeral 10. The membrane 5 has a thickness t indicated in the figures. Here, the membrane thickness t is substantially equal across the shown width of the membrane 5. For particular purposes a membrane 5 may be provided with a thickness which is different at different positions, affects the properties of the transducer cell such as frequency response, collapse voltage, etc.

[0042] Fig. 2A illustrates a cell membrane, which extends above the surface of the substrate 1 to approximately 20% of the overall membrane thickness. In other words, the portion of the membrane 5 extending over the cavity 3 is raised along the edge of the cavity 3 with respect to an adjacent portion of the membrane 5 which is attached to a support structure.

[0043] Fig. 2B illustrates another case, wherein the membrane 5 is recessed into the cavity 3 to about 20% of its thickness being lower than the overall surface 9 of the membrane. In other words, the upper surface 9 of the portion of the membrane 5 which extends over the cavity 3 extends less from (the upper surface of) the substrate 1 than the top surface 9 of the portion of the membrane which is arranged on the supporting portion of the substrate 1 by a distance of about 20% of the thickness t of the portion of the membrane 5 which extends over the cavity 6. It should be noted that in the case of such a recessed membrane 5 the membrane layer thickness can be -and generally will be- substantially uniform across substantially the entire layer, in deviation from what is shown in Fig. 2B.

[0044] The general technical parameters of each cell, such as the collapse voltage and/or resonance frequency, may be the same for both cases of Figs. 2A, 2B, in case the membrane dimensions such as e.g. the membrane thickness, the top electrode (7) thickness, the size of the membrane e.g. the diameter, the distance between the cavity bottom and the top electrode bottom, and the material properties are the same.

[0045] However, positioning the membrane lower than the device surface level, generally determined by the upper surface 9 at a position where the membrane 5 is attached to and supported by the substrate 1, (Fig. 2B) lowers the stress intensity at the membrane edges, and this positively influences the mechanical durability of the membrane. E.g., in the regions H_m of maximum stress in the case of Fig. 2B the stress intensity is approximately 20% lower than in the case of Fig. 2A. Moreover, the regions of high stress are less concentrated in the case of Fig. 2B, reducing the risk of local fractures.

[0046] The profile of the stress P (in MPa) at the edges of the membrane is shown in Fig. 3 as a function of the position of the top surface 9 of the membrane (z) (in relative units with respect to the membrane thickness t of an unsupported portion of a membrane with a substantially uniform thickness) in respect to the overall device surface, which is generally determined by the average position of the upper surface 9 of the membrane at the positions where the membrane 5 is arranged on support structures, here the substrate 1.

[0047] The profile shown in Fig. 3 was calculated using a finite element method, simulating a silicon nitride membrane with a diameter of 30 micron and a thickness t of 1 micron, being deflected at the centre by a pressure difference of 100 kPa.

[0048] From Fig. 3 it may be appreciated that a lowered membrane, as in Fig. 2B, experiences a lower stress level than a raised membrane, as in Fig. 2A.

[0049] A further beneficial effect of having a lowered membrane (Fig. 2B) relative to a raised membrane (Fig. 2A) and to a membrane of which the top surface 9 is substantially even both over a cavity 6 and over a support structure 1 (Fig. 1H), is that the lowered membranes are better protected from the possible damage, when the transducer comes in contact with other objects, in particular solid objects. Typical sizes and shapes of electro-acoustic transducer cells fabricated according to the described method are substantially circular structures of several micrometers in diameter, several of which may be arranged to form transducer arrays of various designs. However, the use of known lithography techniques, e.g. for the patterning of the resist layer 2A, allow substantially free designing of transducer cells and structures for various purposes, e.g. having different electric and/or acoustic resonance frequencies.

[0050] The invention is not restricted to the above described embodiments which can be varied in a number of ways within the scope of the claims. For instance, the amount of sacrificial material 4B in one or more cavities 3 may be varied and/or be structured; this may result in local thickness variations of the membrane material which in turn affect at least its acoustic properties and thus those of the transducer.

[0051] Means for promoting adhesion of the substrate and the membrane material and/or for adapting the crystal structures may be provided for improving at least mechanical properties.

[0052] The use of copper as a sacrificial material and the protruding or recessed arrangement of the membrane of an electro-acoustic transducer are not limited to the specific combinations in which they are presented here and either aspect may also be used to advantage in other situations and methods.

[0053] The present invention allows providing cMUTs with high repeatability since the technology allows relatively easy reproducibility with significantly reduced risks of having uncontrolled changes in device parameters.

Claims

1. Method of fabrication of an electro-acoustic transducer (8), comprising the steps of
   providing a substrate (1) having a surface;
   providing a cavity (3) in the surface of the substrate;
   providing a layer (5) of membrane material on the surface of the substrate to form a membrane over at least a portion of the cavity.

2. Method of claim 1, comprising the steps of
   filling at least a portion of the cavity (3) with a sacrificial material (4B);
   providing the layer of membrane material on at least a portion of the sacrificial material in the cavity; and
   removing the sacrificial material and thus forming the membrane (5) supported over at least a portion of the cavity.

3. Method of claim 1 or 2, wherein the step of providing the cavity (3) comprises
   providing a resist layer (2A') with a defined pattern on at least a portion of the surface of the substrate (1); and
   removing substrate material according to the pattern of the resist layer.

4. Method of claim 2 and claim 3, wherein the sacrificial material (4A, 4B) is applied on at least a portion of the substrate (1) and the resist layer (2A') and wherein a portion (4A) of the sacrificial material is removed with a lift-off technique.

5. Method of any one of the preceding claims wherein the substrate (1) comprises silicon.

6. Method of claim 3, 4 or 5, wherein the resist layer (2A') comprises at least one of an oxide layer and a photo-resist layer and the removal of substrate material is performed by reactive ion etching (RIE).

7. Method of any one of the preceding claims wherein the membrane material comprises silicon nitride.

8. Method of claim 7, wherein the membrane (5) is fabricated according to a method comprising the steps

of:

deposition of a first layer comprising silicon nitride;
deposition of a second layer comprising at least one of silicon oxide and silicon oxynitride;
deposition of a third layer comprising silicon nitride.

9. Method of any one of the preceding claims wherein the sacrificial material (4A, 4B) comprises copper.

10. Electro-acoustic transducer (8) comprising a substrate (1) of a substrate material, a cavity (3) and a membrane (5) extending over at least a portion of the cavity,
wherein the cavity is arranged in the substrate material and the membrane is supported above the cavity by the substrate material.

11. Electro-acoustic transducer (8) according to claim 10, wherein the substrate material (1) comprises silicon.

12. Electro-acoustic transducer (8) according to claim 10 or 11, wherein the membrane (5) comprises silicon nitride.

13. Electro-acoustic transducer (8) according to claim 12, wherein the membrane (5) comprises a first layer, a second layer and a third layer,
wherein the first layer comprises silicon nitride,
wherein the second layer comprises at least one of silicon oxide and silicon oxynitride, and
wherein the third layer comprises silicon nitride.

14. Electro-acoustic transducer (8) according to any one of claims 10-13, wherein the membrane (5) comprises a first surface (9), a first membrane portion and a second membranes portions,
wherein the first surface faces away from the substrate (1),
wherein the first membrane portion is arranged on a first portion of the substrate (1) adjacent a cavity (3), the first membrane portion being attached to and supported by the first substrate portion, and
wherein the second membrane portion is arranged adjacent the first substrate portion and extending over at least a portion of the cavity,
wherein at least the first surface of the second membrane portion extends a different distance from the substrate than the first surface of the first membrane portion.

15. Electro-acoustic transducer array comprising a plurality of electro-acoustic transducers (8) according to any one of the claims 10-14.

Fig. 1A

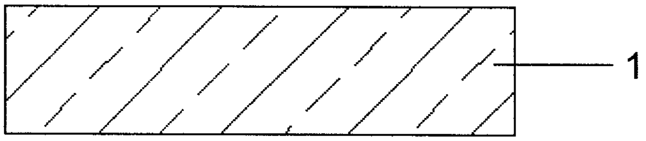


Fig. 1B

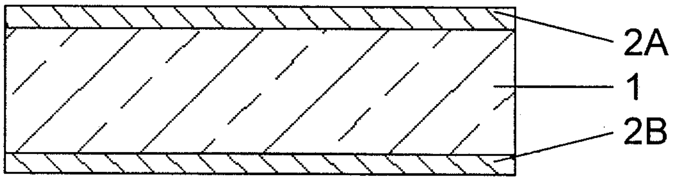


Fig. 1C

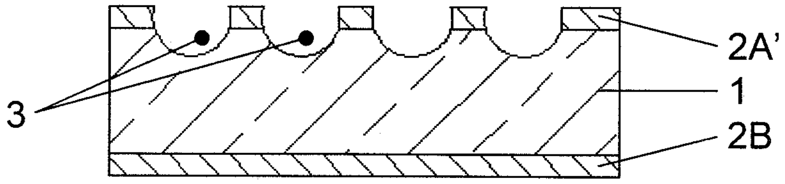


Fig. 1D

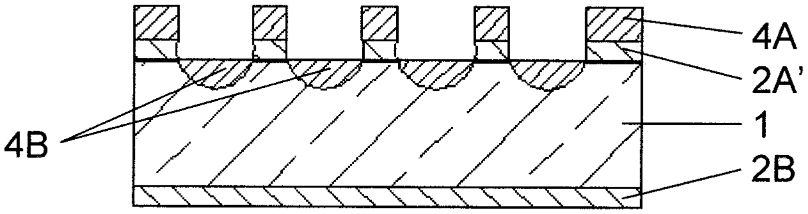


Fig. 1E

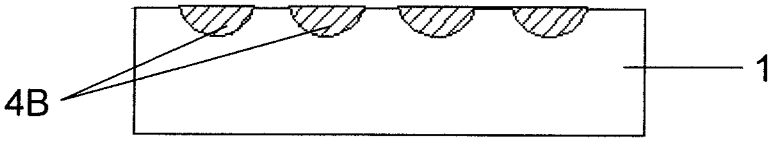


Fig. 1F

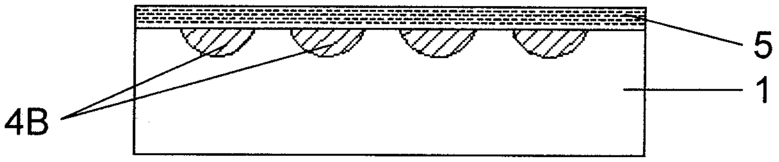


Fig. 1G

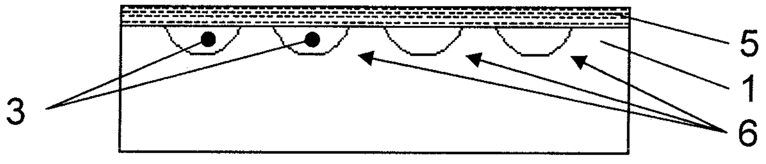
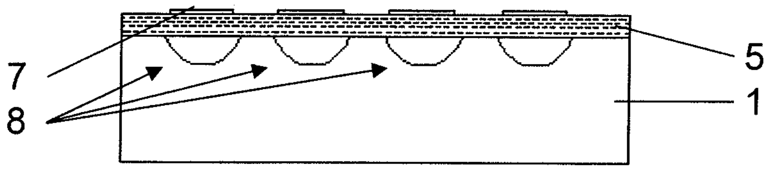


Fig. 1H



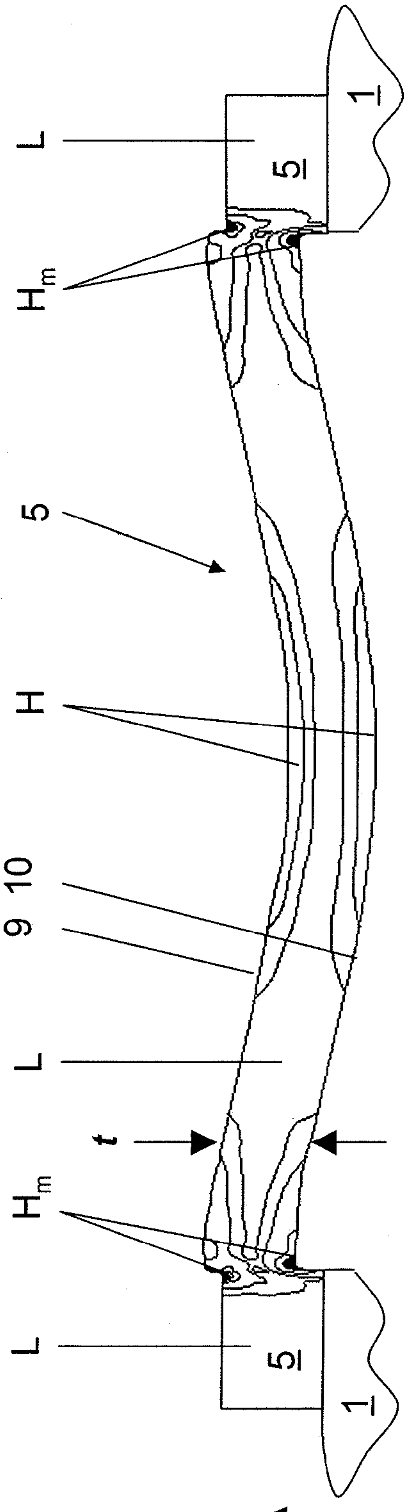


Fig. 2A

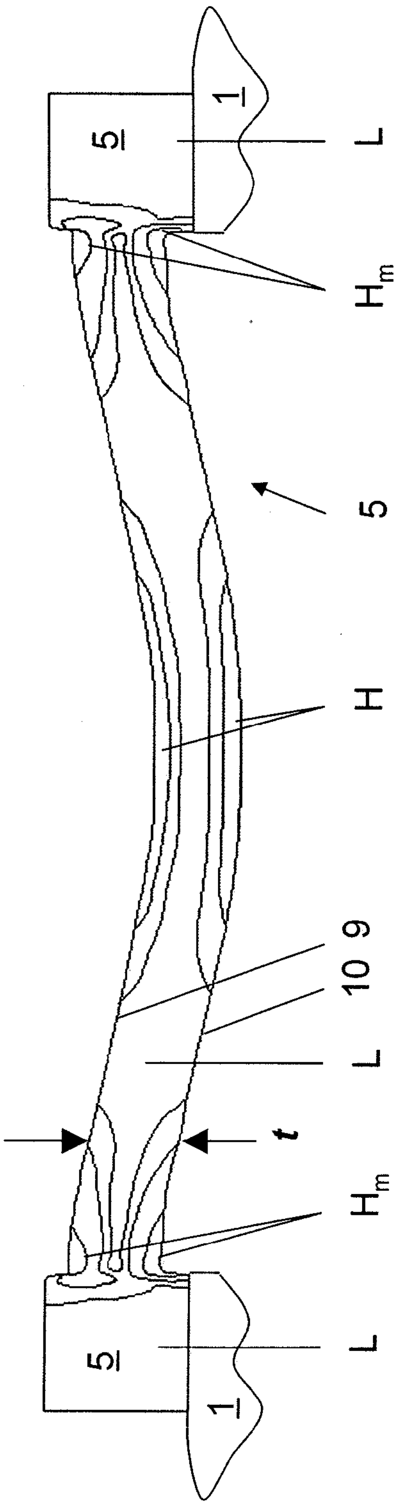


Fig. 2B

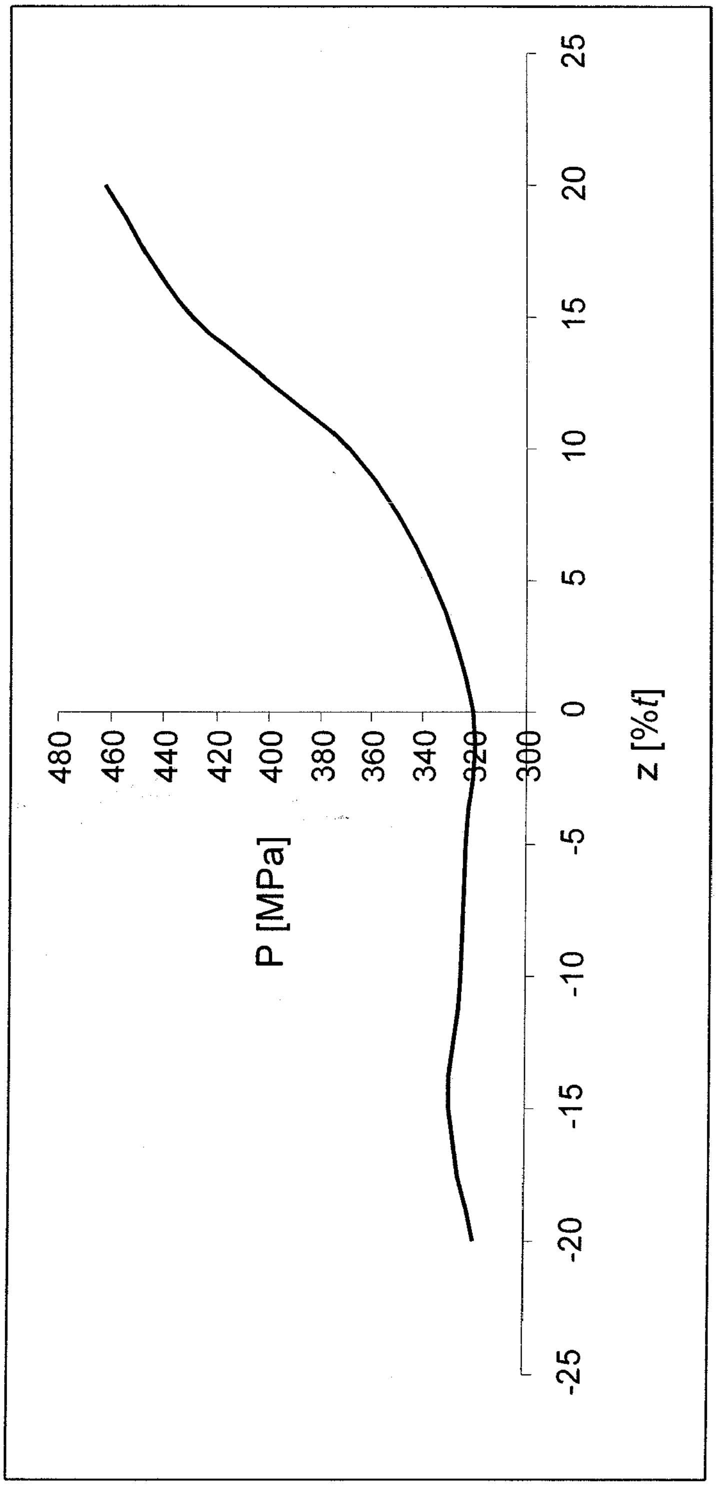

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Fig. 3

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EUROPEAN SEARCH REPORT

Application Number
EP 08 16 0405

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 1 722 595 A (MATSUSHITA ELECTRIC IND CO LTD [JP]) 15 November 2006 (2006-11-15) * paragraphs [0011], [0019], [0020]; figure 3 *	1,7,8, 10,12-14	INV. B06B1/02
Y		2,4,9	
X	CALIANO ET AL: "A silicon microfabricated electrostatic transducer: 1 MHz transmission in air and in water" MICROELECTRONIC ENGINEERING, ELSEVIER PUBLISHERS BV., AMSTERDAM, NL, vol. 53, no. 1-4, 1 June 2000 (2000-06-01), pages 573-576, XP022553248 ISSN: 0167-9317 * pages 573-574 *	1,3,5,6, 10,15	
X	FR 2 897 051 A (GEN ELECTRIC [US]) 10 August 2007 (2007-08-10) * page 6, line 24 - page 8, line 29; figure 1 *	1,5,7, 10,15	
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	9 December 2008	Trique, Michael

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 08 16 0405

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
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