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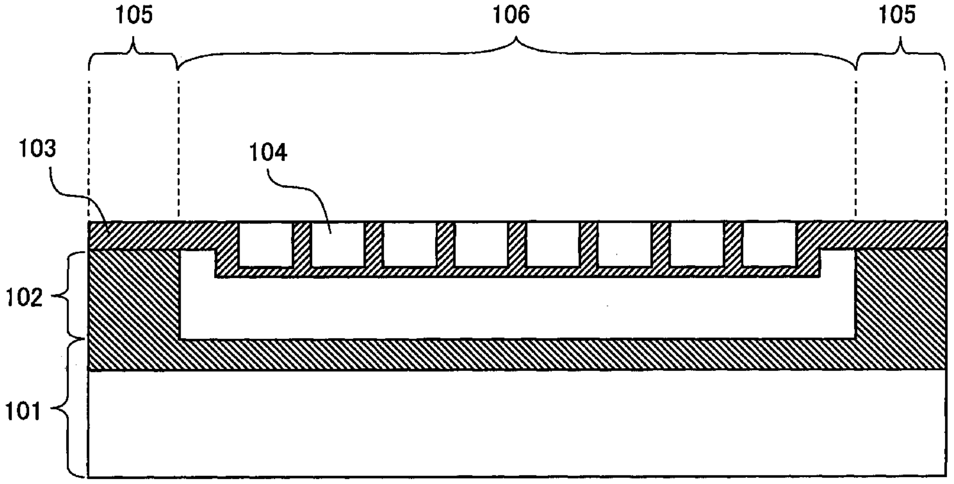
FIG. 1



(57) **Abstract:** An elastic wave transducer includes a substrate (101) having a lower electrode, a support member (102) formed on the substrate, and a membrane (103) that is held by the support member and has an upper electrode. The membrane has a first region (105) that is in contact with the support member, and a second region (106) that is out of contact with said support member and is deformed by receiving an elastic wave. The second region of the membrane has a region in which the bulk density of the second region becomes smaller in accordance with an increasing distance thereof from the first region of the membrane. In addition, the second region has a bulk density ratio that is larger than or equal to 0.1 and is less than or equal to 0.5.

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DESCRIPTION

ELASTIC WAVE TRANSDUCER, ELASTIC WAVE TRANSDUCER ARRAY, ULTRASONIC PROBE, AND ULTRASONIC IMAGING APPARATUS

Technical Field

[0001]

The present invention relates to a transducer for performing the transmission and reception of elastic waves, and in particular, it relates to a transducer having a membrane structure.

Background Art

[0002]

As a transducer for transmitting and receiving elastic waves, there has been one for performing the transmission and reception of ultrasonic waves. A transducer using a piezoelectric element is in general use as the transducer for performing the transmission and reception of ultrasonic waves. On the other hand, attention has been focused on a CMUT (Capacitive Micromachined Ultrasonic Transducer), a PMUT (Piezoelectric Micromachined Ultrasonic Transducer) and the like which are transducers that transmit and receive ultrasonic waves by the vibration of a membrane (also called a vibration membrane) structure. These transducers are formed or fabricated by using semiconductor manufacturing techniques, and have benefits and have benefits such as the possibility of an increase of the number of arrays, easiness of integration with circuits, and so on.

[0003]

Here, the operation of a general CMUT will be described. A CMUT is formed of a substrate having a lower electrode and a membrane structure having an upper electrode arranged in opposition thereto, and hence is of such a construction that a potential difference can be generated between the membrane and the substrate. When a direct current potential difference (DC bias) is applied between these membrane and substrate, the membrane is attracted to the substrate by means of an electrostatic attraction force. In this state, by further application of an alternating current potential difference, the membrane is caused to vibrate, whereby an ultrasonic wave can be generated. In addition, when an ultrasonic wave is incident on the CMUT, the ultrasonic wave can be detected by measuring a capacitance change generated between the substrate and the membrane.

[0004]

Thus, in the CMUT, the structure of the membrane and the substrate is important, and hence, various thoughts or contrivances have been made about such a thing. Published Japanese Translation No. 2004-503313 of a PCT International Publication discloses the control of charge distribution by forming a raised region on a substrate portion together with a technique for inputting a drive waveform in consideration of the nonlinearity of a CMUT. In addition, Japanese Laid-open Patent Publication No. 2006-319712 discloses a membrane structure in which electric flux is made perpendicular with respect to electrodes in a central portion of an element.

[0005]

Here, consideration is given to "the receiving sensitivity" and "the resonance frequency" as the performance of a CMUT. Because the CMUT is a transducer that detects capacitance, the receiving sensitivity thereof is defined as:

(the change of capacitance due to the input of an ultrasonic wave) / (the quantity of charge due to a DC bias) = $\Delta C/C \cdot Vdc$. In addition, it is required that the resonance frequency be a value equal to or higher than a certain level, for example a value from 3 MHz to 10 MHz or more.

[0006]

The following two methods are exemplified as an effective method for improving the receiving sensitivity. The first method is a method of increasing an electrostatic capacitance formed between the substrate and the membrane by decreasing a distance between the substrate and the membrane (a distance between an electrode formed on the substrate and an electrode formed on the membrane). According to this method, the change of capacitance ΔC upon displacement of the membrane becomes large by the increased electrostatic capacitance, so it is possible to obtain accordingly larger electric signal. The second method is a method of increasing the change of capacitance ΔC by increasing the displacement of the membrane due to the input of an ultrasonic wave (pressure applied to the membrane). Assuming that the membrane is a spring mass system having a mass and a restoring force, a large displacement of the membrane by a pressure is equivalent to the restoring force or the spring coefficient (or modulus) being small.

[0007]

The above-mentioned relation will be described by taking, as an example, a circular membrane with its periphery fixedly held. Assuming that the thickness of the membrane is h, the radius thereof is a, the young's modulus thereof is E, and the mean load on the membrane is p, then the deflection w of the membrane generated at its central portion is represented by the following expression 1.

[Expression 1]

$$w = 0.171\frac{pa^4}{Eh^3} \quad \cdots (1)$$

[0008]

If the membrane is approximately considered to be a spring which is deformed by the deflection w and an external force $p\pi a^2$, the spring coefficient k is represented by the following expression 2.

[Expression 2]

$$k = \frac{\pi}{0.171} \frac{Eh^3}{a^2} \quad \cdots (2)$$

[0009]

In addition, denoting the density of the membrane by ρ, the mass m of the membrane is represented by the following expression 3.

[Expression 3]

$$m = \pi \rho a^2 h \quad \cdots (3)$$

[0010]

If the membrane is considered to be a simple spring-mass system, the resonant frequency f thereof is represented by the following expression 4.

[Expression 4]

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{1}{2\pi} \sqrt{\frac{1}{0.171} \frac{Eh^2}{\rho a^4}} \quad \cdots (4)$$

[0011]

Here, the discussion is returned to the sensitivity and the resonance frequency as stated above. A high sensitivity means that the spring coefficient k is small. In order to decrease the spring coefficient k, it is desirable from expression 2 above that the thickness h of the membrane be thin, and the radius a of the membrane be large. On the other hand, in order to improve the resonance frequency, it is desirable from expression 4 above that the thickness h of the membrane is thick, and the radius a of the membrane is small. In other words, to hold the resonance frequency equal to or higher than a certain level and to increase the sensitivity demand opposite directionalities or requirements with respect to the thickness h of the membrane and the radius a of the membrane.

[0012]

Therefore, it is not easy to satisfy two directionalities or requirements of "holding the resonant frequency equal to or higher than a certain level" and "increasing the sensitivity" at the same time by changing the size of the radius and the thickness of a membrane having a flat-plate shape or the like, and hence a limitation has existed thereon.

[0013]

Thus, in the past, a CMUT having a satisfactory receiving sensitivity has not yet been developed.

Disclosure of Invention

[0014]

The present invention provides a technique that can improve receiving sensitivity while holding a resonance frequency in an elastic wave transducer having a membrane structure.

[0015]

In addition, the present invention provides a transducer, an elastic wave transducer array, an ultrasonic probe, and an ultrasonic imaging apparatus which have a resonant frequency equal to or higher than a certain level, as well as have high receiving sensitivity and high performance.

[0016]

An elastic wave transducer according to a first aspect of the present invention includes

a substrate having a lower electrode,

a support member formed on the substrate, and

a membrane that is held by the support member and has an upper electrode,

wherein the membrane has a first region that is in contact with the support member, and a second region that is out of contact with the support member and is deformed by receiving an elastic wave, and

wherein the second region of the membrane has a region in which the bulk density of the second region becomes smaller in accordance with the increasing distance thereof from the first region of the membrane.

[0017]

An elastic wave transducer according to a second aspect of the present invention includes

a substrate having a lower electrode,

a support member formed on the substrate, and a membrane that is held by the support member and has an upper electrode,

wherein the membrane has a first region that is in contact with the support member, and a second region that is out of contact with the support member and is deformed by receiving an elastic wave, and

wherein a bulk density ratio of the membrane at least in the second region is larger than or equal to 0.1 and is less than or equal to 0.5.

[0018]

An elastic wave transducer array according to a third aspect of the present invention has a plurality of elastic wave transducers each of the above-mentioned construction that are arranged in an array-like manner.

[0019]

An ultrasonic probe according to a fourth aspect of the present invention is provided with an elastic wave transducer array of the above-mentioned construction.

[0020]

An ultrasonic imaging apparatus according to a fifth aspect of the present invention is provided with an ultrasonic probe of the above-mentioned construction.

[0021]

According to the present invention, in an elastic wave transducer having a membrane structure, the receiving sensitivity thereof can be improved while holding a resonance frequency thereof. In addition, it is possible to provide an elastic wave transducer, an elastic wave transducer array, an ultrasonic probe, and an ultrasonic imaging apparatus that have a resonant frequency equal to or higher than a certain level, and have a high receiving sensitivity.

[0022]

Further features of the present invention will become apparent from the following description of exemplary embodiments with reference to the attached drawings.

Brief Description of Drawings

[0023]

Fig. 1 is a cross sectional view of a transducer of a first embodiment.

Fig. 2 is a plan view of the transducer of the first embodiment.

Fig. 3A through Fig. 3I are views illustrating a first example of a manufacturing process for the transducer of the first embodiment.

Fig. 4A through Fig. 4F are views illustrating a second example of the manufacturing process for the transducer of the first embodiment.

Fig. 5 is a cross sectional view of a transducer of a second embodiment.

Fig. 6A through Fig. 6F are views illustrating an example of a manufacturing process for the transducer of the second embodiment.

Fig. 7 is a cross sectional view of a transducer of a third embodiment.

Fig. 8 is a cross sectional view along line B-B' of Fig. 7.

Fig. 9 is a cross sectional view of a transducer of a fourth embodiment.

Fig. 10A through Fig. 10C are vertical cross sectional views and a transverse cross-sectional view of regions 803A through 803C of Fig. 9, respectively.

Fig. 11 is a cross sectional view of a transducer of a fifth embodiment.

Description of Embodiments

[0024]

In the following embodiments, an example of an ultrasonic wave transducer will be illustrated as one example of an elastic wave transducer of the present invention. An elastic wave transducer array can be constructed by arranging a plurality of elastic wave transducers according to the present invention in an array-like manner. Such an elastic wave transducer array is preferably applicable, for example, to an ultrasonic detecting element (probe) in an ultrasonic imaging apparatus (ultrasonic diagnostic apparatus). However, the present invention can also be applied to transducers of other elastic waves than ultrasonic waves.

[0025]

As stated above, in the CMUT thus far used, it is not easy to satisfy the two directionalities or requirements of "holding the resonance frequency equal to or higher than a certain level" and "increasing the sensitivity" at the same time, and a limitation thereon has existed.

[0026]

Accordingly, in order to break through this limitation, the inventors have noted the density ρ of the membrane included in the above-mentioned expression 4. By decreasing the density ρ of the membrane, the resonance frequency f thereof can be increased, and hence it becomes possible to accordingly increase the sensitivity by an increased amount of the resonant frequency. Specifically, it is possible to make the radius a larger and the thickness h thinner by an amount corresponding to the amount of decrease of the density ρ.

[0027]

In addition, the inventors have discovered that a similar effect can also be achieved by decreasing "the bulk density" of the membrane, instead of essentially decreasing the density thereof by changing the material of the membrane. Here, note that the bulk density is a density calculated from "the volume including voids" and "the mass", and is a term or expression used for the definition of the density of fine particles, etc. That is, "the bulk density" in this description is a value that is obtained by dividing the mass of the membrane by the entire volume thereof including openings, spaces or the like formed therein even if openings (recesses, concaves) are formed on a surface of the membrane, or if closed spaces (holes and pores) are formed in the interior of the membrane.

[0028]

<FIRST EMBODIMENT>

Hereinafter, a transducer according to a first embodiment of the present invention will be described. In the first embodiment, by forming openings (concaves or recessed portions) on a surface of a membrane, an improvement in sensitivity thereof is intended to be made while holding or maintaining a resonant frequency thereof.

[0029]

(Construction of a Transducer)

First of all, reference will be made to the shape of a transducer of this embodiment by using Fig. 1 and Fig. 2. Fig. 1 is a cross sectional view of the transducer of this embodiment, and Fig. 2 is a plan view of the transducer of this embodiment. Here, note that Fig. 1 illustrates a cross sectional view along line A-A' of Fig. 2.

[0030]

The transducer of this embodiment is composed of a substrate 101, a support member 102 and a membrane 103. The support member 102 is formed into an annular shape on the substrate 101, and serves to support a peripheral portion of the membrane 103 of a substantially disc shape. Typically, silicon (a part thereof being oxidized by a manufacturing process (see a hatched portion in Fig. 1)) is used for the substrate 101. In addition, silicon oxide is used for the support member 102, and a silicon thin film or a silicon nitride thin film is used for the membrane 103.

[0031]

As illustrated in Fig. 1, the membrane 103 is provided with a first region 105 that is in contact with the support member 102, and a second region 106 that is out of contact with the support member 102 and is deformed into a U-shape by receiving an elastic wave (ultrasonic wave). In this embodiment, the second region 106 is formed in a central portion of the membrane 103, and the first region 105 is formed around the second region 106 (i.e., in the peripheral portion of the membrane 103).

[0032]

The second region 106 of the membrane 103 is thicker than the first region 105, and a plurality of openings (concave portions) 104, which do not penetrate through the membrane 103, are formed on a surface of the second region 106 (i.e., a surface at an opposite side to the substrate 101). These openings 104 are a structure for decreasing the bulk density of the membrane 103. With such a structure, it is possible to ensure a sufficient thickness of the second region 106 which is a portion adapted to be caused to vibrate upon reception of an ultrasonic wave, so a desired resonance frequency can be kept. In addition, an improvement in the receiving sensitivity can be expected because the second region 106 is made lighter in weight due to the formation of the openings 104. Here, note that the bulk density is calculated by defining an upper surface of the membrane 103 as an interface.

[0033]

Here, as illustrated in Fig. 1, it is preferable that the second region 106 of the membrane 103 have a stepped portion formed on its substrate side, so that at least part of the second region is thicker than the first region 105. In particular, it is preferable that the second region 106 be formed thick in its central portion. With such a structure, the distance between an upper electrode and a lower electrode can be decreased, so that an electrostatic capacitance formed by the upper electrode and the lower electrode can be made greater. As a result, a large capacitance change can be obtained with respect to the input of a constant or fixed pressure. In other words, the sensitivity becomes much higher. In addition, in the thickened portion, the membrane is able to vibrate in a state where it is nearly a parallel flat plate arranged in parallel to the substrate, and hence it is possible to reduce the nonlinearity of the capacitance change.

[0034]

Here, if the membrane should be only thickened without formation of openings therein, the resonance frequency f will be decreased by an amount corresponding to an increased amount of the mass m of the membrane. In the present invention, however, the bulk density ρ of the membrane is decreased by the formation of the openings 104 or the like, so that the decrease of the bulk density acts in a direction to increase the resonance frequency. In other words, the sensitivity can be improved while keeping the resonance frequency at an appropriate level.

[0035]

On the other hand, there is a possibility that if the bulk density ρ of the membrane is simply decreased, the rigidity of the membrane will be reduced to decrease the spring constant of the membrane (i.e., Young's modulus becoming smaller), resulting in a decrease in the resonance frequency. However, in the construction of the present invention, by designing the thickness of the membrane to be thick, the membrane is able to keep or hold a constant or fixed rigidity as necessary even if the bulk density ρ thereof is small, thus making it possible to suppress the decrease of the resonance frequency in an efficient manner.

[0036]

Here, note that in case where a space (cavity) enclosed by the substrate 101, the support member 102 and the membrane 103 is kept in a vacuum, it is preferable that the openings 104 do not penetrate through the membrane. However, in case where it is not necessary to keep the space in vacuum, a through hole(s) can be formed through the membrane 103. For example, the membrane itself may be formed of a porous material. In this case, within the membrane 103, there can be formed a closed space(s) (closed pore(s)), or an open space(s) through which the cavity is in communication with outside air.

[0037]

Further, in this embodiment, as a preferred form, the openings 104 are formed so as to change the size and the number per unit area of the openings, as illustrated in Fig. 2, in such a manner that the bulk density decreases toward the center of the membrane 103. In other words, it is designed so that the bulk density of the second region 106 of the membrane 103 becomes smaller in accordance with the increasing distance from the first region 105. With this construction, the receiving sensitivity can be further improved. This is because an amount of displacement of the membrane upon reception of an ultrasonic wave becomes larger in accordance with the increasing distance from the first region 105 of the membrane 103, i.e., in a direction from the periphery toward the center of the membrane 103. By making that portion of the membrane of which the amount of displacement is large lighter in weight than the other, the sensitivity can be more improved in comparison with the case where openings are merely formed in the membrane.

[0038]

As to the manner in which the openings are formed, it is preferable from the viewpoint of the strength (rigidity) of the membrane that the area per opening be made greater in a direction toward the central portion of the second region 106, and that the direction of each beam (a wall between adjacent openings) be made in coincidence with a radial direction of the circle of the membrane, as illustrated in Fig. 2. By forming the openings in the membrane in this manner, the rigidity of the membrane can be kept at a predetermined level even if the mass of the entire membrane is made light.

[0039]

Here, "the distance L from the first region 105" at a certain point P in the second region 106 of the membrane 103 is defined as illustrated in Fig. 2. That is, on the membrane surface when a transducer element is seen from above, the shortest one among rectilinear distances from a boundary 107 between the first region 105 and the second region 106 to the point P is "the distance L from the first region 105". In the case of the membrane where the second region 106 is round, as illustrated in Fig. 2, the distance L can be grasped from a radius that passes through the point P from the center of the circle.

[0040]

In this embodiment, in the second region 106 of the membrane 103, the larger the distance from the first region 105, the smaller the bulk density becomes continuously or stepwise. However, in the present invention, such a region need only be included in a part of the second region 106. For example, it may be designed such that the bulk density decreases until halfway in the course of approaching the central portion, but the bulk density becomes unchanged partway and held constant. That is, the second region 106 need only have a region in which the larger the distance from the first region 105 of the membrane, the smaller the bulk density becomes.

[0041]

Although the side wall of each opening 104 is parallel to the thickness direction of the membrane in the figures, it may be a rounded side wall or a side wall having irregularities. The bottom surface of each opening 104 need not be in parallel to the membrane surface. In addition, the shape of each opening is not limited to such a shape as in this embodiment, but may be polygon. Moreover, the number and the arrangement of the openings may be set in any manner.

[0042]

(Operation of the Transducer)

Next, the operation of the transducer will be described. The substrate 101 is a low resistance substrate that has an unillustrated lower electrode, and it is electrically grounded. As the lower electrode, there are employed a silicon substrate itself of which the electric resistance is decreased by doping it with phosphorus, boron, etc., and an electric conductor such as Al, Au, or the like. Here, when a direct current voltage is applied to an unillustrated upper electrode formed on the membrane 103, the membrane 103 is caused to deform to the substrate 101 side under the action of an electrostatic attraction force. The membrane 103 is stopped at a position of balance between the electrostatic attraction force and its own restoring force. Under such a condition, when an alternating current voltage is applied to the electrodes, the membrane 103 is caused to vibrate about the position of balance so that an ultrasonic wave is thereby generated. On the other hand, when an ultrasonic wave is input to the membrane 103 which is at the position of balance, the membrane 103 ic caused to vibrate, whereby the capacitance between the substrate 101 and the membrane 103 is changed. Thus, the ultrasonic wave can be detected by measuring this change. Here, note that the upper electrode is formed on a surface of the membrane 103 at the substrate 102 side or a surface thereof at its opposite side. An electric conductor such as Al, Au or the like is used as the upper electrode.

[0043]

Next, the relation between the resonance frequency and the sensitivity will be described by using a dimensional example. For example, silicon nitride is used as a material for the membrane 103, and the size of the second region 106 of the membrane 103 is set to 40 μm in diameter. The voltage to be applied (hereinafter also referred to as an application voltage) is set to a value of 80 % of a voltage by which the membrane 103 is caused to collide with the substrate 101. An initial gap between the membrane 103 and the substrate 101 is set in such a manner that the gap therebetween when the application voltage is applied thereacross becomes 0.12 μm. For the thickness of the membrane, it is set to a value which satisfies a resonance frequency of 5 MHz. In this case, the plurality of openings 104 are formed in the second region 106 of the membrane 103 in such a manner that a bulk density ratio of the membrane 103 is adjusted to 0.467. In this description, "the bulk density ratio of the membrane" is a value which is the bulk density of the membrane 103 divided by a theoretical density of the membrane 103. Here, note that "the theoretical density" is a value which is the mass of the membrane 103 divided by the true or real volume of the membrane 103 (the volume of the membrane excluding the openings).

[0044]

In the above-mentioned condition, a comparison is made between the sensitivities of a membrane having the shape of this embodiment and a membrane of a planar or flat shape with no opening formed therein. Here, the magnitude of the capacitance change ΔC (unit: 1/V) with respect to the amount of charge under the condition that the above-mentioned voltage is applied to the membrane in case where a pressure of 1 kPa is applied to the entire membrane is used as a definition of sensitivity. Let us assume that the young's modulus of silicon nitride is 320 GPa, the density thereof is 3.27 g/cm^3, and the Poisson ratio thereof is 0.263. When the sensitivities are calculated by using the above-mentioned values, the sensitivity for the membrane having the shape of this embodiment is 1.06e-3, and the sensitivity for the membrane of the planar shape is 4.00e-4. Using the membrane having the shape of this embodiment, the sensitivity is improved by about 2.5 times.

[0045]

Another specific example will be described. Silicon nitride is used as a material for the membrane 103, and the size of the second region 106 is set to 40 μm in diameter. The application voltage is set to a value of 80 % of a voltage by which the membrane 103 is caused to collide with the substrate 101. An initial gap between the membrane 103 and the substrate 101 is set in such a manner that the gap therebetween when the application voltage is applied thereacross becomes 0.12 μm. For the thickness of the membrane, it is set to a value which satisfies a resonance frequency of 5 MHz. In this example, the bulk density ratio of the membrane 103 is set to 0.1.

[0046]

In the above-mentioned condition, a comparison is made between the sensitivities of a membrane having the shape of this embodiment and a membrane of a planar or flat shape with no opening formed therein. When the sensitivities are calculated by using the above-mentioned values, the sensitivity for the membrane having the shape of this embodiment is 2.25e-2, and is improved by about 56 times as compared with the sensitivity for the membrane of the planar shape.

[0047]

When the bulk density ratio of the membrane is less than 0.1, the strength of the membrane is decreased, and hence it becomes difficult to use the membrane as a transducer for ultrasonic waves. On the contrary, when the bulk density ratio of the membrane is larger than 0.5, the desired sensitivity can not be obtained, and it becomes difficult to apply the membrane to an ultrasonic diagnostic apparatus. Accordingly, a preferred range for the bulk density ratio of the membrane is more than or equal to 0.1 and less than or equal to 0.5.

[0048]

In this embodiment, the circular membrane has been described, but similar effects will be obtained even in the case of a membrane of a polygonal shape including a square and a rectangle. In addition, reference has been made to the case where the thickness of the membrane in its central portion is thicker as compared with its peripheral portion, but similar effects will be achieved even in the case where the thickness of a membrane is constant or uniform.

[0049]

(First Example of a Manufacturing Process of the Transducer)

A manufacturing process for the transducer of the first embodiment will be described while referring to Fig. 3A through Fig. 3I.

[0050]

A low resistance layer 211 is formed on a surface of a silicon substrate 210 by disposing the silicon substrate 210 in a diffusion furnace, introducing a PH_3 gas (10 % hydrogen dilution) into the furnace, and heat-diffusing phosphorus at a temperature of 1,050 degrees C (Fig. 3A). A silicon nitride layer 212 is then formed on the low resistance layer by means of a LPCVD (Fig. 3B). To form the silicon nitride layer 212, a mixture gas is used which contains a SiH_4 gas and a NH_3 gas mixed with each other at a mole ratio of 1 to 1. The silicon substrate 210 is disposed in an atmosphere heated to 700 through 800 degrees C, and the mixture gas is then introduced therein, whereby the silicon nitride layer 212 is formed with a thickness of about 50 nm.

[0051]

Then, an amorphous silicon layer 213 is deposited on the silicon nitride layer 212 by means of an RF plasma CVD method (Fig. 3C). A SiH_4 gas, which has been diluted to 10 % with a H_2 gas, is introduced into a plasma CVD apparatus at a substrate temperature of 350 degrees C, whereby the amorphous silicon layer 213 is deposited on the silicon nitride layer 212. By using a resist and a predetermined mask, a part 214 of the amorphous silicon layer 213 is etched and removed by means of a SF_6 gas. At that time, the layer thickness of the amorphous silicon layer is adjusted to 0.12 μm (Fig. 3D). Further, openings

215 for side walls of the membrane are formed in the amorphous silicon layer 213 by means of etching (Fig. 3E).

[0052]

Subsequently, a silicon nitride layer 216, which will become the membrane, is formed on the amorphous silicon layer (Fig. 3F). The silicon nitride layer 216 is formed by the use of an LPCVD method. To form the silicon nitride layer 216, a mixture gas is used which contains a SiH_4 gas and a NH_3 gas mixed with each other at a mole ratio of 1 to 1. The silicon substrate of Fig. 3E is disposed in an atmosphere heated to 700 through 800 degrees C, and the mixture gas is then introduced therein, whereby the silicon nitride layer 216 is formed with a thickness of about 1.15 μm. Etching openings 217 for etching the amorphous silicon layer are then formed. The etching openings 217 are formed by etching the silicon nitride layer 216 with a CF_4 gas by the use of a mask of a desired shape (Fig. 3G). The substrate of Fig. 3G is then soaked into a KOH aqueous solution which has been diluted to 10 %, whereby amorphous silicon layers 218 are removed to form spaces 220. Thereafter, a silicon nitride layer 219 is deposited on the openings 217, whereby the etching openings are closed (Fig. 3H).

[0053]

To control the bulk density of the silicon nitride layer 219 which acts as the membrane, a part (a central portion) of the silicon nitride layer 219 is etched by means of a CF_4 gas with the use of a mask pattern as illustrated in Fig. 1 and Fig. 2, whereby the openings 221 are formed (Fig. 3I). In this manner, the bulk density ratio of the membrane is controlled so as to become 0.467. An Al electrode is deposited on the membrane to provide an upper electrode.

[0054]

Here, note that if the thickness of the silicon nitride layer 216 is controlled to be about 0.5 μm in the step of Fig. 3F, a membrane having a bulk density ratio of 0.1 can be prepared.

[0055]

(Second Example of the Manufacturing Process of the Transducer)

Next, a process for producing the transducer using silicon for the membrane will be described while referring to Fig. 4A through Fig. 4F.

[0056]

A low resistance substrate 301 is prepared (Fig. 4A). An opening 302 is formed in the low resistance substrate 301 by means of dry etching (Fig. 4B). A silicon oxide layer 303 is formed by thermal oxidation (Fig. 4C). A separately prepared SOI (Silicon On Insulator) substrate 304 is joined or bonded to the silicon oxide layer 303. A convex portion 305 has been beforehand formed on a device layer of the SOI substrate 304 by means of etching (Fig. 4D). A handling layer and a BOX layer of the SOI substrate

304 are then removed (Fig. 4E). Openings 306 are formed on a surface of the SOI substrate, and an unillustrated electrode is formed on the surface (Fig. 4F). In this manner, the transducer of this embodiment can be obtained.

[0057]

Although in this process example, silicon oxide by thermal oxidation is used as an insulating layer, other forming techniques such as CVD, sputtering, or the like can be used, and silicon nitride can also be used as a material, and in addition, CVD or other deposition techniques can be adopted as a forming technique therefor. Also, when the convex portion 305 is formed, not only etching but also other deposition techniques including epitaxial growth can be used. Further, to remove the handling layer and the BOX layer, either of dry etching, wet etching, and mechanical working including grinding can be used, or they can be used in combination. Furthermore, in forming the openings 306, too, both of dry etching and wet etching can be made use of.

[0058]

<SECOND EMBODIMENT>

A transducer according to a second embodiment of the present invention will be described while referring to Fig. 5. The transducer of the second embodiment has a plurality of openings which are different in depth from each other.

[0059]

The transducer of this embodiment has a cross-sectional structure as illustrated in Fig. 5, and is composed of a substrate 401, a support member 402 and a membrane 403. An unillustrated lower electrode is formed on the substrate 401, and an unillustrated upper electrode is formed on the membrane 403.

[0060]

A plurality of openings 404 are formed on a vibrating portion (a second region) of the membrane 403. The depths of the openings 404 are large or deep in the center of the membrane 403, and become smaller or shallower in a direction to approach a peripheral portion (a first region) of the membrane 403. By the provision of such openings 404, the bulk density in the vibrating portion of the membrane 403 can be made smaller in the direction toward the center (i.e., in accordance with the increasing distance from the peripheral portion). With the membrane of such a construction, the sensitivity can be increased while keeping or holding the resonance frequency thereof. Here, note that the shape of each opening is not limited to that which is illustrated in this embodiment, but a bottom surface thereof may be or may not be in parallel to the membrane, and in addition, even a rounded bottom surface or side wall may be employed. In addition, the number and the arrangement of the openings can also be altered as necessary.

[0061]

A process for producing the transducer of this embodiment will be described while using Fig. 6A through

Fig. 6F.

[0062]

A low resistance substrate 501 is prepared (Fig. 6A). An opening 502 is formed in the low resistance substrate 501 by means of dry etching (Fig. 6B). A silicon oxide layer 503 is formed by thermal oxidation (Fig. 6C). A separately prepared SOI substrate 504 is joined or bonded to the silicon oxide layer 503 (Fig. 6D). After removing a handling layer of the SOI substrate 504, a BOX layer 505 is patterned. On the BOX layer, there is formed a resist layer 506, the thickness of which is varied by changing an amount of exposure (Fig. 6E). By etching the SOI substrate 504 including this resist layer 506, a plurality of openings 507 of varying or different depths are formed on a surface of the membrane. Thereafter, an unillustrated electrode is formed on the surface of the membrane (Fig. 6F). In this manner, the transducer of this embodiment can be obtained.

[0063]

Although in this process example, silicon oxide by thermal oxidation is used as an insulating layer, other forming techniques such as CVD, sputtering, or the like can be used, and silicon nitride can also be used as a material, and in addition, CVD or other deposition techniques can be adopted as a forming technique therefor. Also, to remove the handling layer, either of dry etching, wet etching, and mechanical working including grinding can be used, or they can be used in combination. Although the openings 507 of different depths are formed by varying the thickness of the resist, patterning and etching can be repeated each for openings of the same depth. Alternatively, by making use of the fact that the etching rate varies depending on the size or area of each opening, the depth of each opening can be controlled by varying the size or area of the opening (specifically, by increasing the opening size or area in accordance with the decreasing distance to the center of the membrane). Here, note that in forming the openings 507, too, both of dry etching and wet etching can be made use of.

[0064]

<THIRD EMBODIMENT>

A transducer according to a third embodiment of the present invention will be described while referring to Fig. 7 and Fig. 8. The transducer of the third embodiment has a plurality of closed spaces in the interior of a membrane.

[0065]

The transducer of this embodiment has a cross-sectional structure as illustrated in Fig. 7, and a spatial structure as illustrated in Fig. 8. Fig. 8 illustrates a cross section on line B-B' of Fig. 7, and Fig. 7 illustrates a cross section on line C-C' of Fig. 8. The transducer of this embodiment is composed of a substrate 601, a support member 602 and a membrane 603. An unillustrated lower electrode is formed on the substrate 601, and an unillustrated upper electrode is formed on the membrane 603.

[0066]

A plurality of closed spaces 604 of varying or different sizes are formed in the interior of a vibrating portion (a second region) of the membrane 603. The sizes (volumes) of the closed spaces 604 are large in the center of the membrane 603, and become smaller in a direction to approach a peripheral portion (a first region) of the membrane 603. By the provision of such closed spaces 604, the bulk density in the vibrating portion of the membrane 603 can be made smaller in the direction toward the center (i.e., in accordance with the increasing distance from the peripheral portion).

[0067]

In the construction of this embodiment, too, similar to the above-mentioned first and second embodiments, the sensitivity can be increased while keeping or holding the resonance frequency thereof. In addition, the transducer of this embodiment has a flat surface, so the formation of the electrode on the membrane surface can be carried out in an easy manner.

[0068]

Here, note that the circular column-shaped spaces are illustrated in this embodiment, but the present invention is not limited to this. The shape of each closed space can be spherical or polyhedral including triangular pyramidal, etc. In addition, the number and the arrangement of the closed spaces can be set as appropriate. The transducer of this embodiment can also be produced by combining conventional well-known semiconductor manufacturing techniques in an appropriate manner.

[0069]

<FOURTH EMBODIMENT>

A transducer according to a fourth embodiment of the present invention will be described while referring to Fig. 9 and Fig. 10A through Fig. 10C. The transducer of the fourth embodiment has a plurality of closed spaces in the interior of a membrane. In the third embodiment, the bulk density is controlled by changing the sizes of the closed spaces, but in the fourth embodiment, the bulk density is controlled by changing the number of closed spaces per unit volume.

[0070]

The transducer of this embodiment has a cross-sectional structure as illustrated in Fig. 9, and is composed of a substrate 801, a support member 802 and a membrane 803. An unillustrated lower electrode is formed on the substrate 801, and an unillustrated upper electrode is formed on the membrane 803. Fig. 10A illustrates a vertical cross sectional view (upper row) of a region 803A of the membrane 803, and a transverse cross sectional view (lower row) on line D-D' of the vertical cross sectional view. Fig. 10B illustrates a vertical cross sectional view and a transverse cross sectional view of a region 803B of the membrane 803, and Fig. 10C illustrates a vertical cross sectional view and a transverse cross sectional view of a region 803C. Here, note that the region 803A is a central region of the membrane 803, and the region 803B and the region 803C are sequentially and increasingly distant from the center in this order.

[0071]

As illustrated in Fig. 10A through Fig. 10C, a plurality of closed spaces 901 of the same size are formed in the interior of a vibrating portion (a second region) of the membrane 803. The number of closed spaces 901 per unit volume is the most in the central region 803A of the membrane 803, and decreases in a direction toward a peripheral portion (a first region) of the membrane 803. By the provision of such closed spaces 901, the bulk density in the vibrating portion of the membrane 803 can be made smaller in the direction toward the center (i.e., in accordance with the increasing distance from the peripheral portion). In the construction of this embodiment, too, similar to the above-mentioned first through third embodiments, the sensitivity can be increased while keeping or holding the resonance frequency thereof.

[0072]

Here, note that in this embodiment, the membrane is composed of a total of four kinds of regions comprising three kinds of regions containing therein closed spaces and one kind of region containing therein no closed spaces, but the present invention is not limited to this construction.

The total number of regions can be three or five or more. In addition, the number of closed spaces per unit area can be continuously changed. If doing so, the bulk density of the membrane changes continuously, and hence, it is easy to suppress the anisotropy of the mechanical characteristics of the membrane.

[0073]

<FIFTH EMBODIMENT>

A transducer according to a fifth embodiment of the present invention will be described while referring to Fig. 11. The transducer of this embodiment operates in collapse mode where at least part of a vibrating portion (a second region) of a membrane is in contact with a substrate.

[0074]

First of all, the collapse mode will be explained in a concise manner. The collapse mode is a mode in which transmission and reception are carried out with the membrane being in contact with the lower substrate disposed therebelow. First, the contact between the membrane and the lower substrate will be described. As a direct current initial potential difference to be applied to the transducer is increased, an electrostatic attraction force is increased so that the membrane is thereby attracted to the lower substrate. This attracted position is decided by the balance between the electrostatic attraction force and a restoring force of the membrane. In addition, when the electrostatic attraction force is increased by making the initial potential difference larger, the electrostatic attraction force exceeds the restoring force of the membrane, whereby the membrane is placed into contact with the lower substrate. This operation is called pull-in, and the potential difference at this time is called a pull-in voltage Vp. However, hysteresis exists in the initial potential difference and the position of the membrane, and hence, in order to make the membrane out of contact with the lower electrode thereby to separate the membrane and the lower substrate from each other, the potential difference has to be decreased below the pull-in voltage. The potential difference at this time is called a snap-back voltage Vs.

[0075]

By performing transmission and reception with the potential difference equal to or larger than Vs after once increasing the initial potential difference of the transducer to Vp thereby to place the membrane and the lower substrate into contact with each other, it becomes possible to perform the driving of the membrane in the collapse mode in which transmission and reception are carried out while keeping or holding the membrane and the lower substrate in contact with each other.

[0076]

The electromechanical transduction (conversion) efficiency of the transducer can be improved by performing the driving in the collapse mode. (Reference: Baris Bayram et al., IEEE UFFC Vol. 50, No. 9, pp1184 -1190, Sep. 2003)

[0077]

In the collapse mode as referred to above, the distance between the membrane and the lower substrate is very small in the vicinity of a region in which the membrane is in contact with the lower substrate, so a change in electrostatic capacitance due to minute vibration of the membrane becomes large. In other words, the vicinity of the region in which the membrane and the lower substrate are in contact with each other contributes greatly to the improvement of the electromechanical transduction efficiency.

[0078]

The transducers of either structures of the above-mentioned first through fourth embodiments can be driven to operate in the collapse mode. Hereinbelow, the operation of a transducer in the collapse mode will be described while taking as an example the transducer of the fourth embodiment.

[0079]

Fig. 11 illustrates a cross sectional shape of the transducer when operating in the collapse mode. By increasing the initial potential difference, the membrane 803 is placed in contact with the lower substrate 801. In general, the greatest deflected portion in the membrane is first placed into contact with the lower substrate, so in this embodiment, a part of the region 803A of the membrane

803 comes in contact with the lower substrate 801. By performing transmission and reception while keeping or holding such a contact state, it becomes possible to carry out the operation in the collapse mode.

[0080]

In the collapse mode, as described above, the behavior of the membrane in the vicinity of the contacting region contributes greatly to the improvement of the electromechanical transduction efficiency. In this embodiment, the bulk density in the vicinity of the contacting region (i.e., a peripheral region which is adjacent to the contacting region and functions as the membrane) becomes the smallest. As a result, it is possible to further increase the degree of the improvement of the electromechanical transduction efficiency due to the collapse mode, thus making it possible to obtain the further increased effects of the present invention.

[0081]

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

[0082]

This application claims the benefit of Japanese

Patent Application No. 2008-21332, filed on January 31, 2008, which is hereby incorporated by reference herein in its entirety.

CLAIMS

1. An elastic wave transducer comprising:

a substrate having a lower electrode;

a support member formed on said substrate; and

a membrane that is held by said support member and has an upper electrode,

wherein said membrane has a first region that is in contact with said support member, and a second region that is out of contact with said support member and is deformed by receiving an elastic wave, and

wherein the second region of said membrane has a region in which the bulk density of said second region becomes smaller in accordance with an increasing distance thereof from the first region of said membrane.

2. An elastic wave transducer comprising:

a substrate having a lower electrode;

a support member formed on said substrate; and

a membrane that is held by said support member and has an upper electrode,

wherein said membrane has a first region that is in contact with said support member, and a second region that is out of contact with said support member and is deformed by receiving an elastic wave, and

wherein at least the second region of said membrane has a bulk density ratio that is larger than or equal to

0.1 and is less than or equal to 0.5.

3. The elastic wave transducer as set forth in claim 1 or 2, wherein an opening for decreasing the bulk density is formed in the second region of said membrane.

4. The elastic wave transducer as set forth in claim 3, wherein said opening does not penetrate through said membrane.

5. The elastic wave transducer as set forth in claim 1 or 2, wherein a closed space for decreasing the bulk density is formed in an interior of the second region of said membrane.

6. The elastic wave transducer as set forth in claim 1 or 2, wherein at least part of the second region of said membrane is thicker than the thickness of the first region of said membrane.

7. The elastic wave transducer as set forth in claim 1 or 2, wherein said membrane operates in collapse mode in which at least part of the second region of said membrane is in contact with said substrate.

8. An elastic wave transducer array wherein a plurality of elastic wave transducers each as set forth in

claim 1 or 2 are arranged in an array-like manner.

9. An ultrasonic probe comprising the elastic wave transducer array as set forth in claim 8.

10. An ultrasonic imaging apparatus comprising the ultrasonic probe as set forth in claim 9.

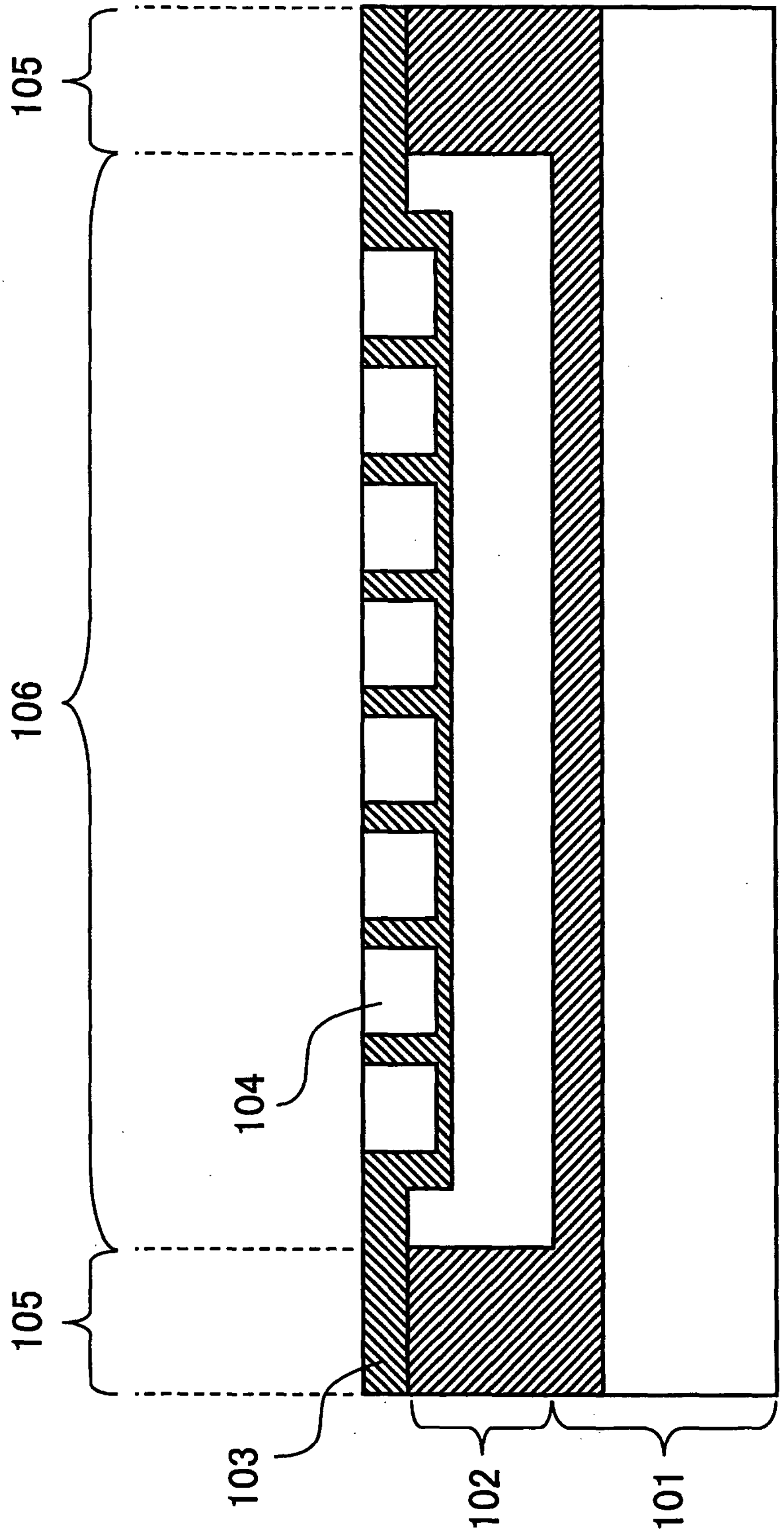

FIG. 1

FIG. 2

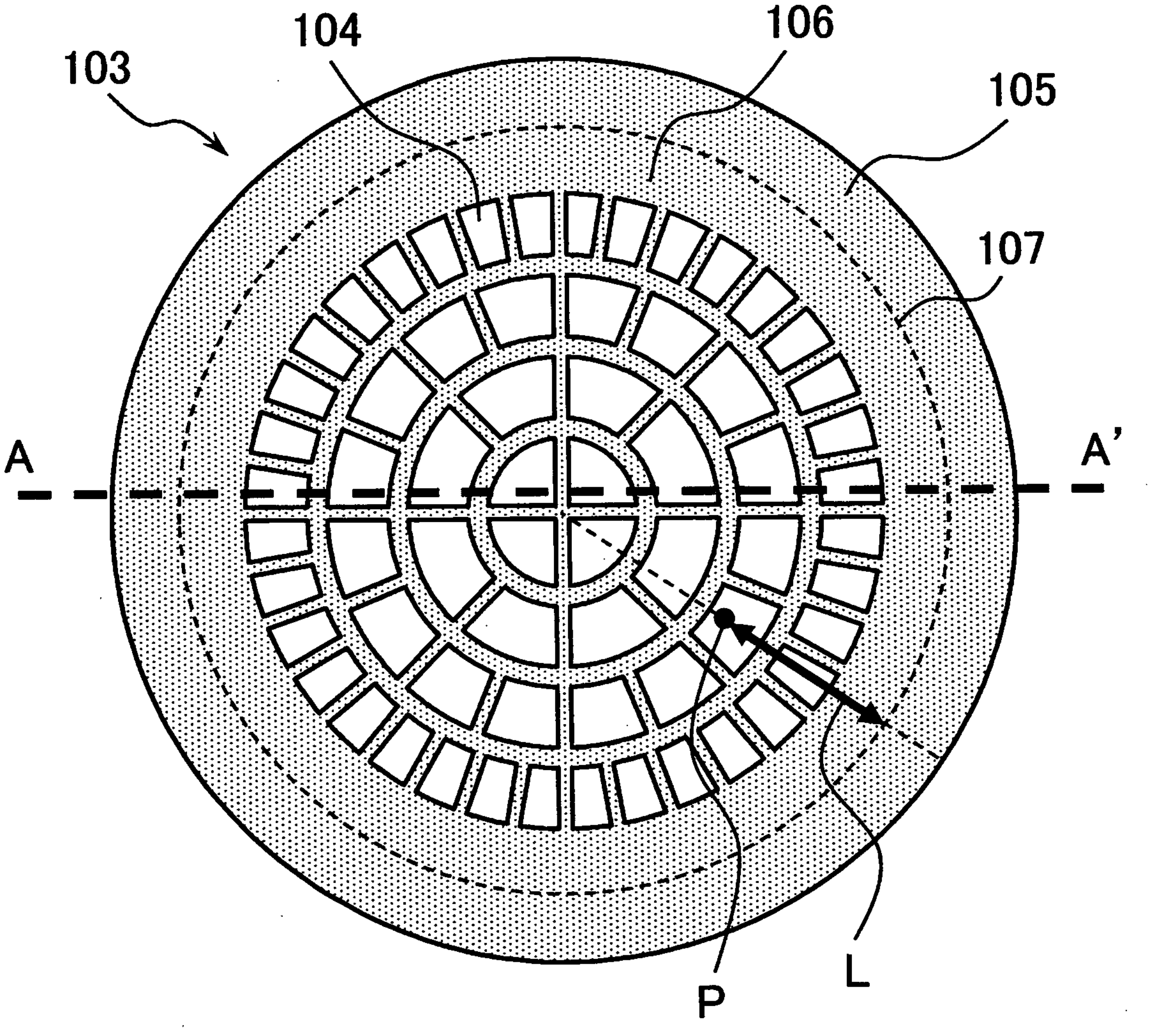

FIG. 3A

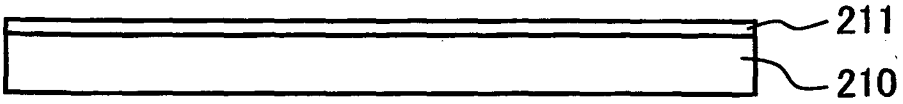

FIG. 3B

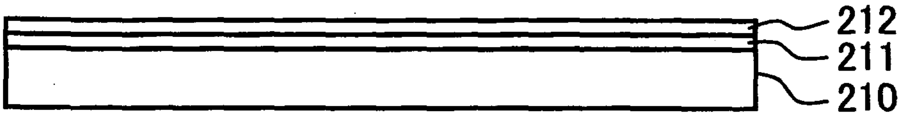

FIG. 3C

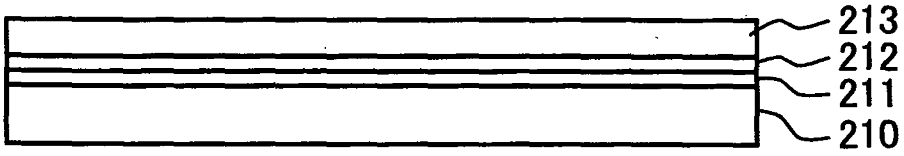

FIG. 3D

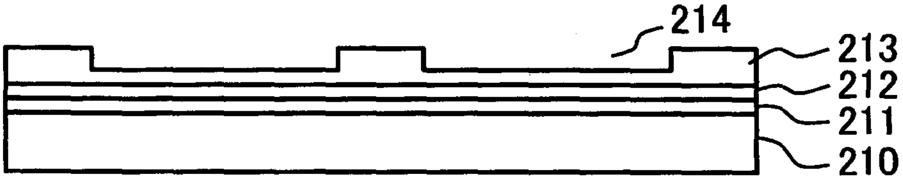

FIG. 3E

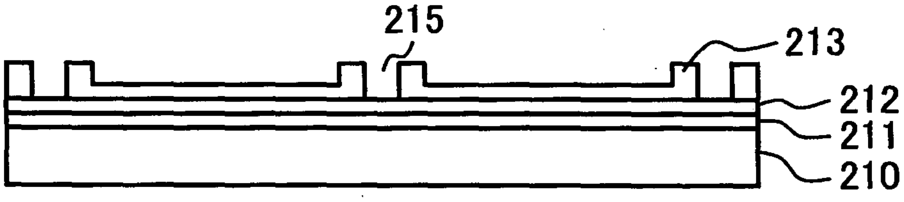

FIG. 3F

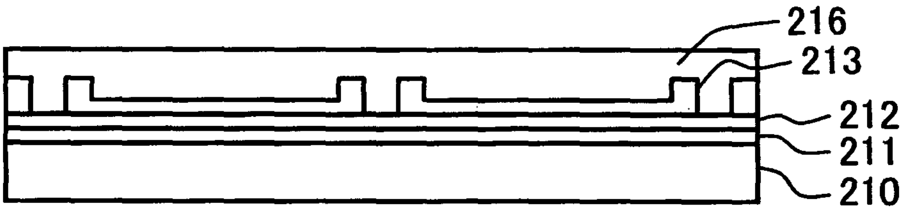

FIG. 3G

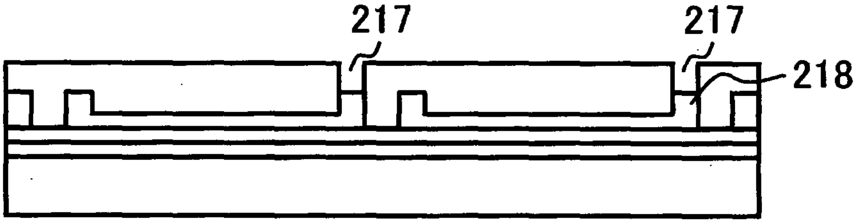

FIG. 3H

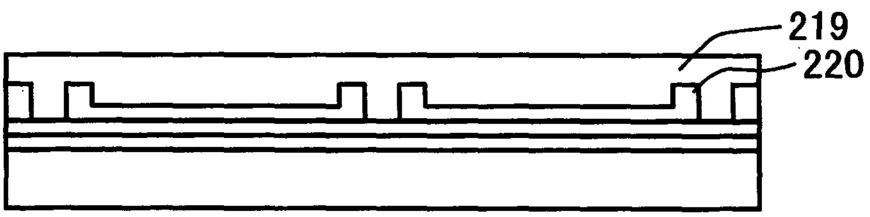

FIG. 3I

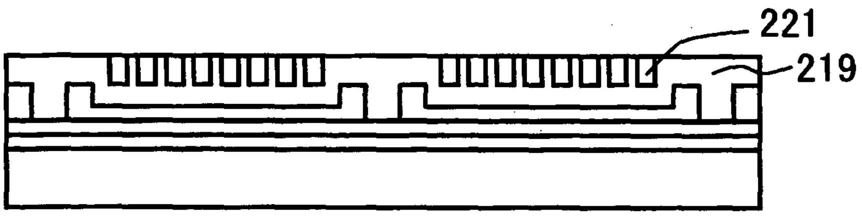

FIG. 4A

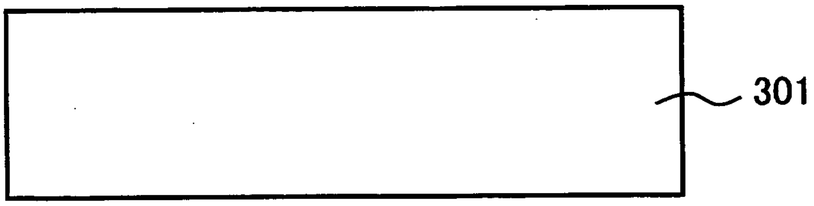

FIG. 4B

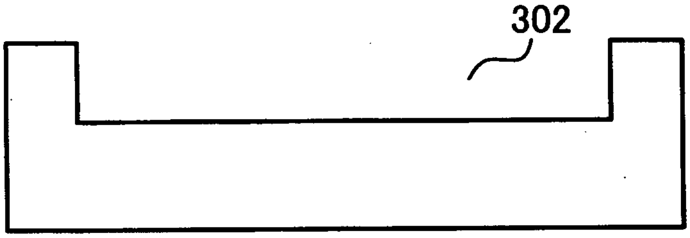

FIG. 4C

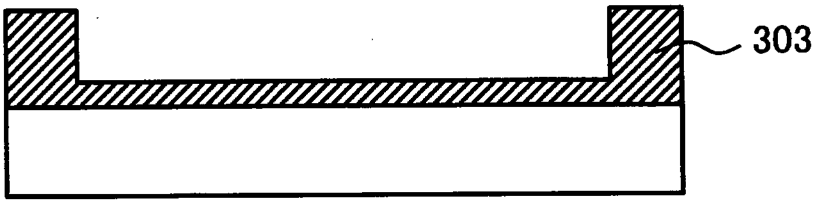

FIG. 4D

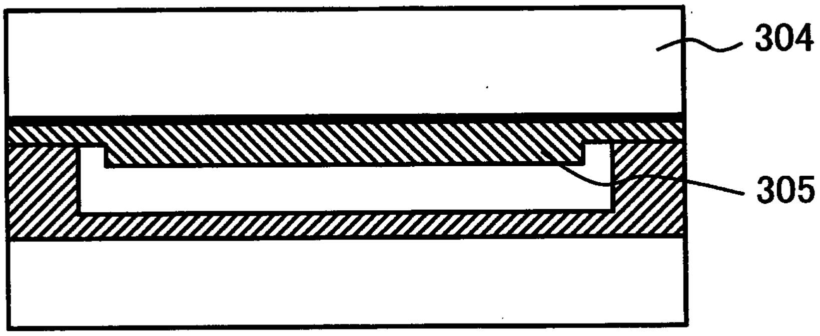

FIG. 4E

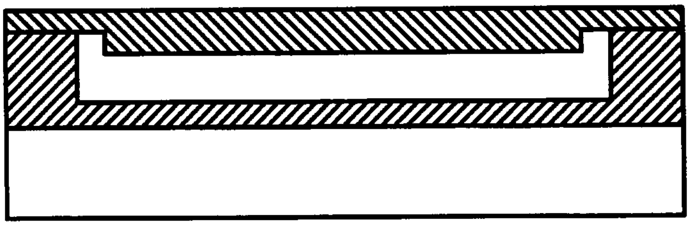

FIG. 4F

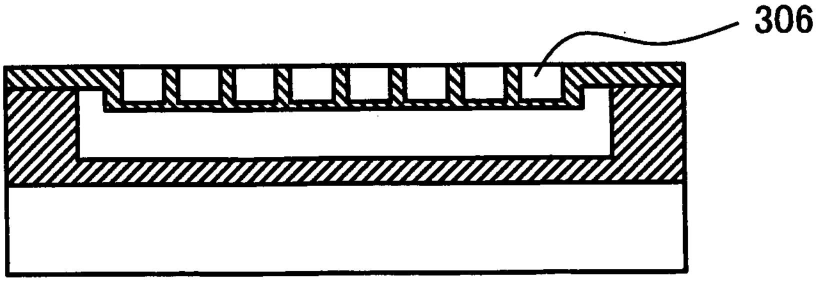

FIG. 5

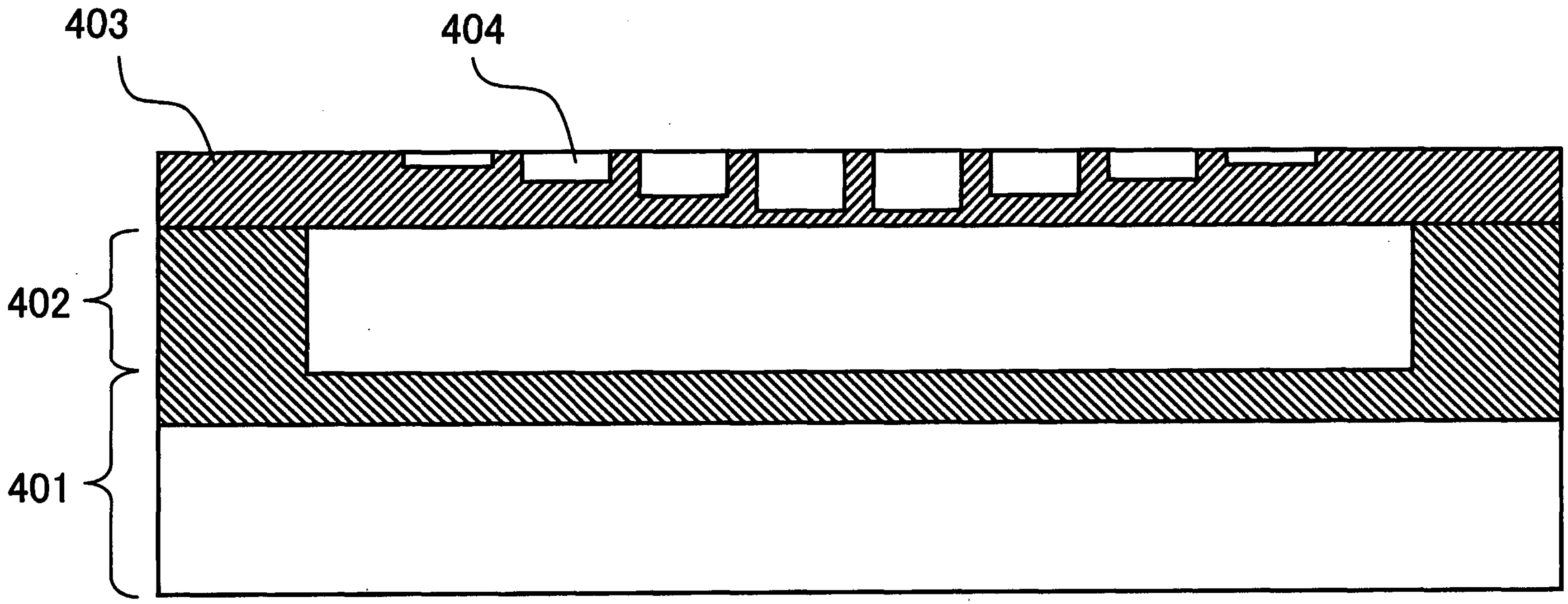

FIG. 6A

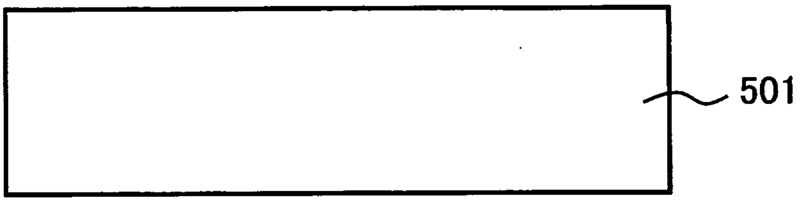

FIG. 6B

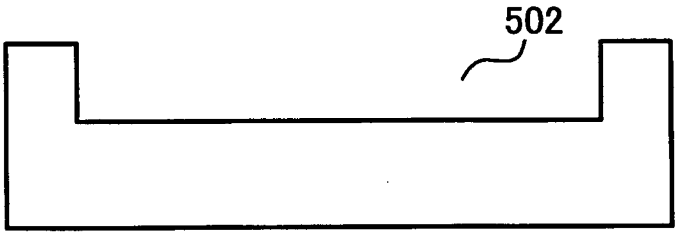

FIG. 6C

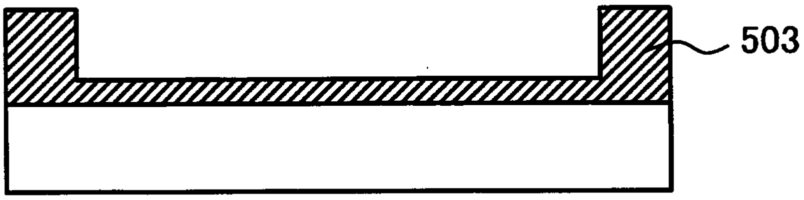

FIG. 6D

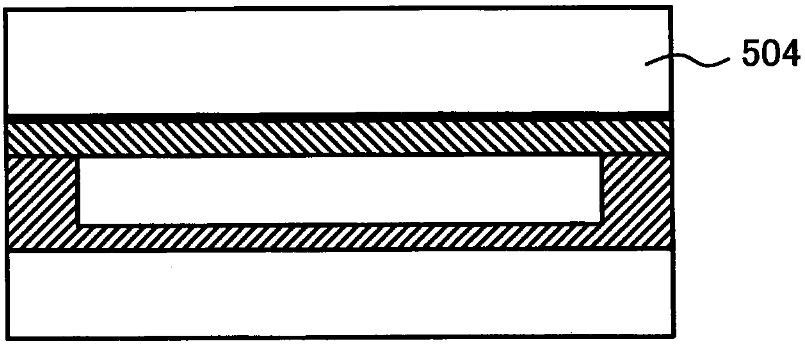

FIG. 6E

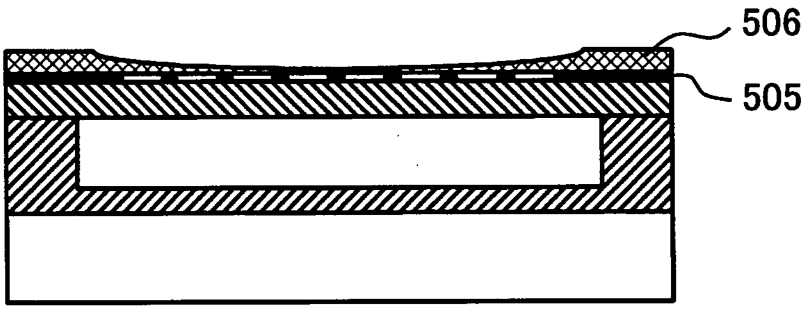

FIG. 6F

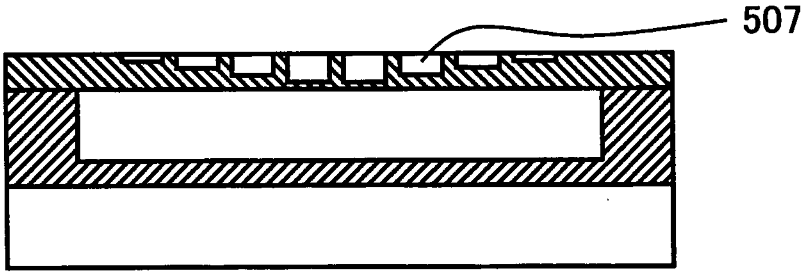

FIG. 7

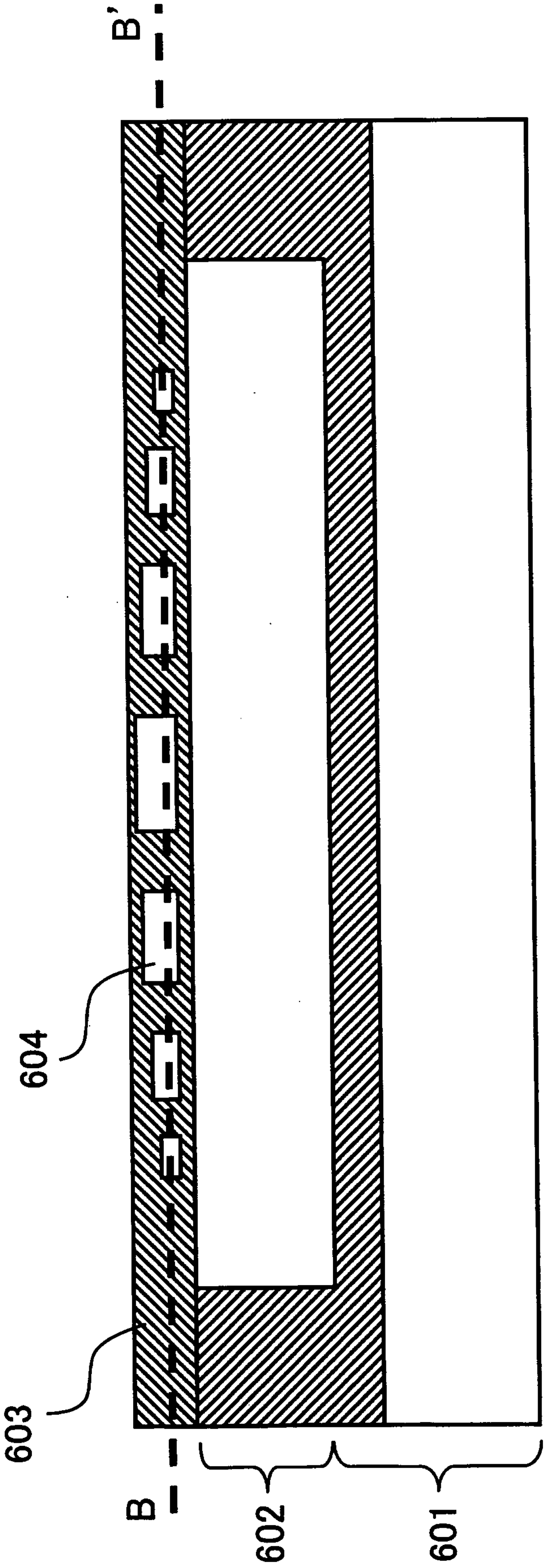

FIG. 8

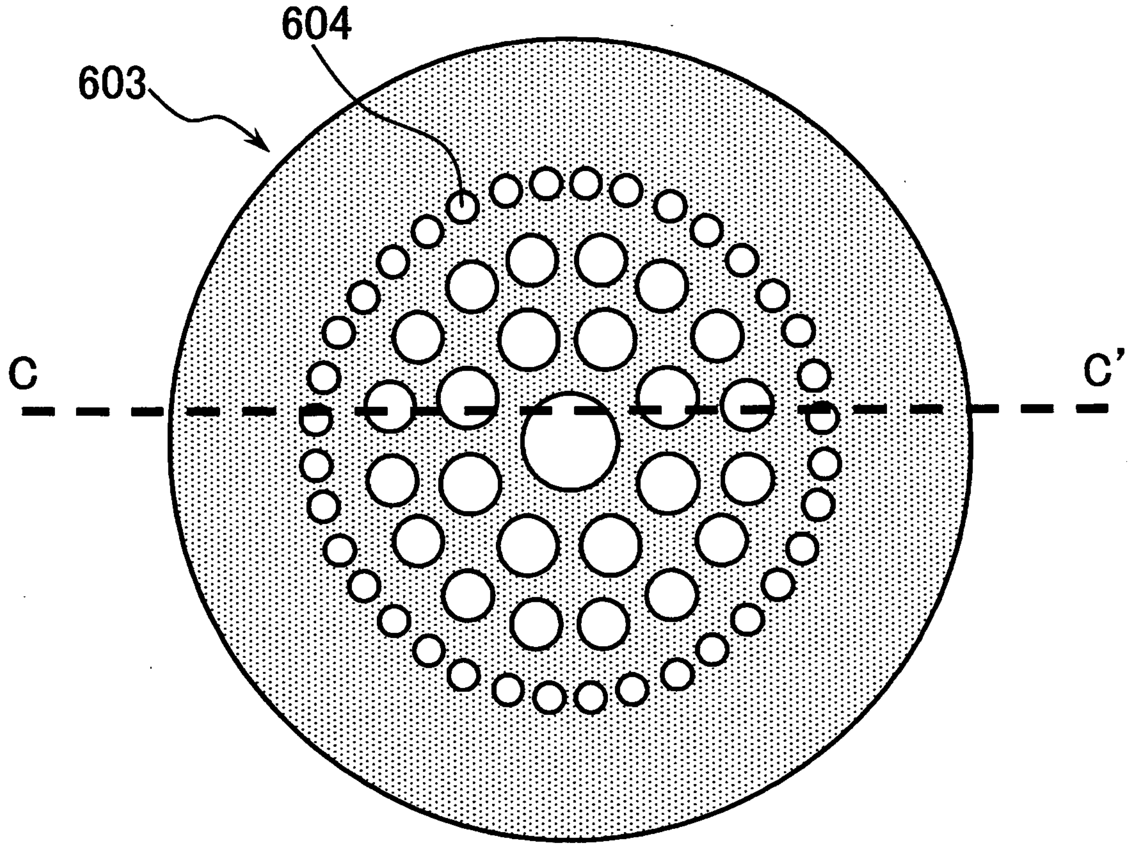

FIG. 9

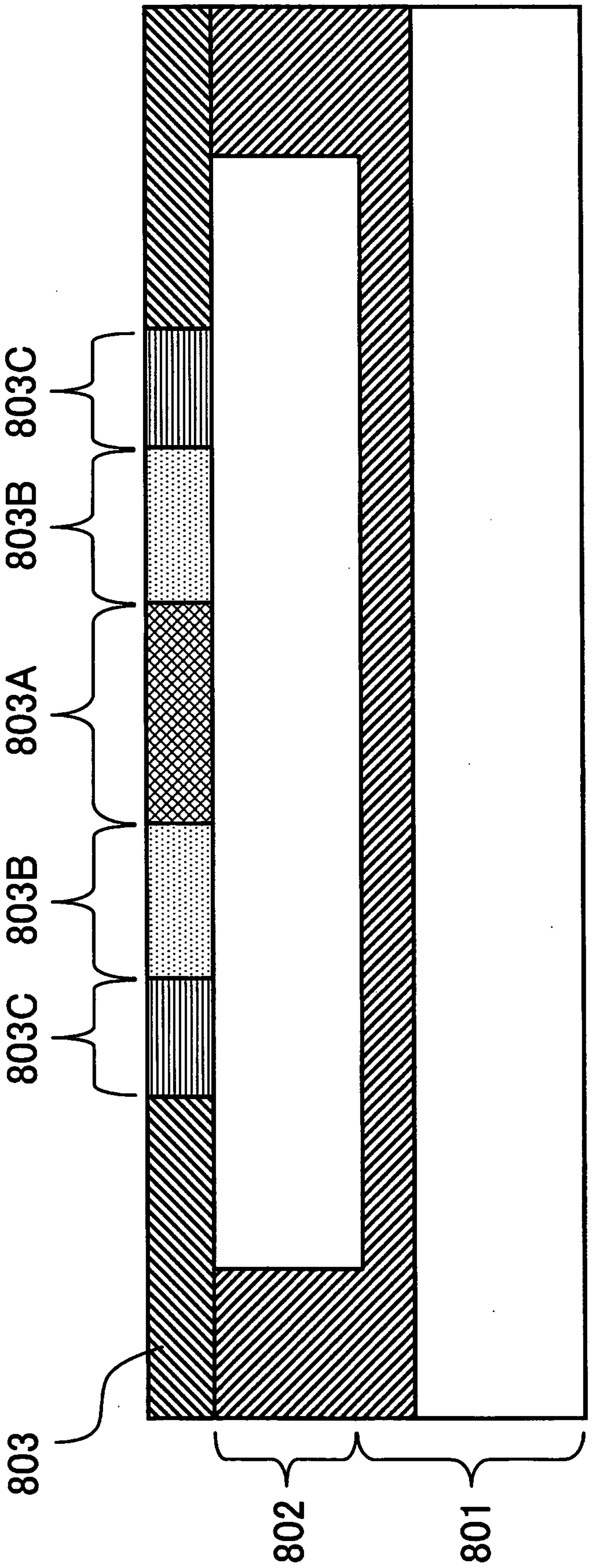

FIG. 10A

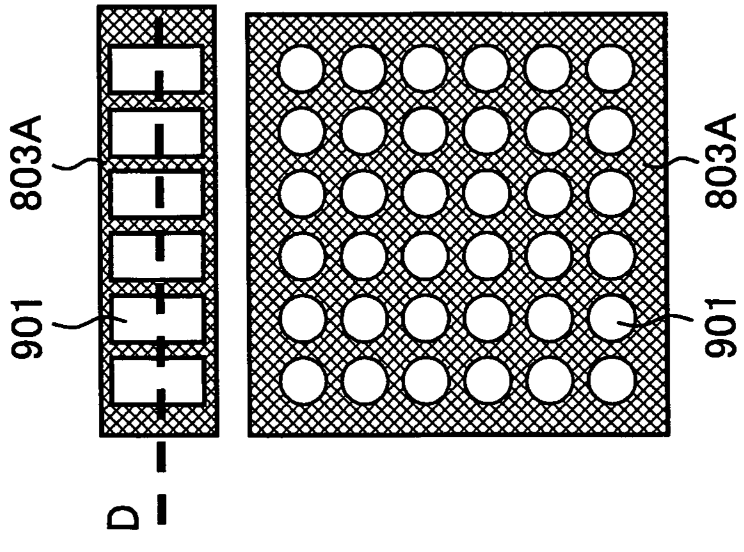

FIG. 10B

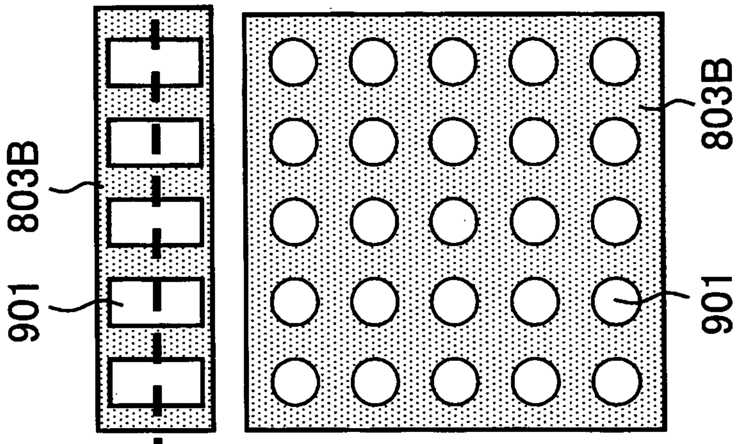

FIG. 10C

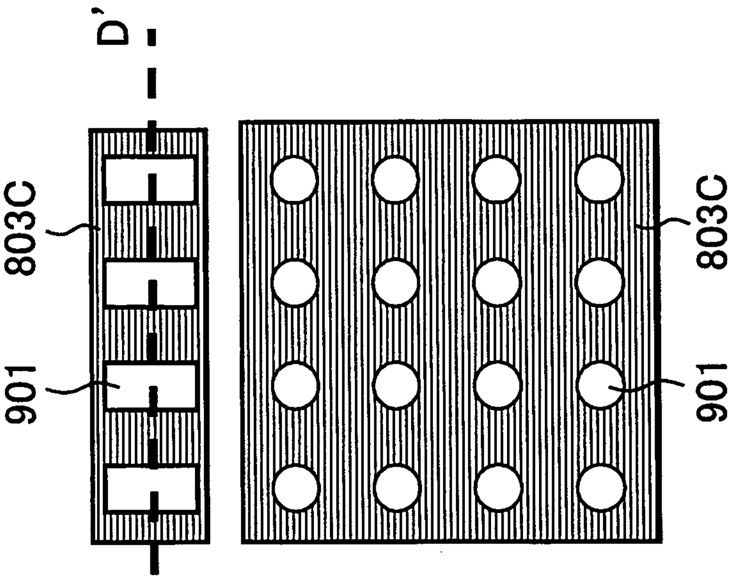

FIG. 11