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GAS SENSOR AND METHOD FOR MANUFACTURING GAS SENSOR

Abstract

A gas sensor characterized by including an electrode portion which includes one or more electrode pairs each having a first electrode and a second electrode, the first electrode and the second electrode being opposed to each other in a first direction in the electrode pair, with a gap formed therebetween, a sensitive membrane disposed between the first electrode and the second electrode in the electrode pair, and a voltage application section which applies a voltage to the electrode portion such that the voltage is applied between the first electrode and the second electrode. The sensitive membrane is a dense body.

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure relates to a gas sensor and a method for manufacturing a gas sensor.

BACKGROUND ART

[0002] In a conventional chemical sensor using a MEMS, a pair of electrodes is provided, and the distance between the electrodes is several micrometers even when the distance is the shortest.

Although such a sensor exhibits sensitivity, its responsiveness is poor, and a long time is needed for concentration detection. Therefore, it was difficult to perform real-time measurement at intervals of several seconds to several tens of seconds. Meanwhile, as shown in Patent Literature 1, there has been reported a gas sensor which uses a nano-gap electrode having an inter-electrode distance of about several nm to 100 nm and which has improved responsiveness.

CITATION LIST

Patent Literature

[0003] Patent Literature 1: JP2021-32746A

SUMMARY OF INVENTION

Technical Problem

[0004] Although the sensor disclosed in Patent Literature 1 exhibited quick response when exposed to a gas to be detected, when the sensor was actually used, a long time was needed to recover its sensor characteristics. Also, since the mechanism of enhancing its responsiveness has not yet been elucidated, knowledge about a sensor configuration for obtaining quick response has been insufficient.

[0005] The present disclosure provides a gas sensor having enhanced responsiveness.

Solution to Problem

[0006] A gas sensor, which is a first aspect of the present disclosure, is characterized by comprising:

[0007] an electrode portion which includes one or more electrode pairs each having a first electrode and a second electrode, the first electrode and the second electrode being opposed to each other in a first direction in the electrode pair, with a gap formed therebetween;

[0008] a sensitive membrane disposed between the first electrode and the second electrode in the electrode pair; and

[0009] a voltage application section which applies a voltage to the electrode portion such that the voltage is applied between the first electrode and the second electrode, wherein the sensitive membrane is a dense body.

[0010] A gas sensor manufacturing method, which is a second aspect of the present disclosure, is a method for manufacturing the above-described gas sensor, wherein the sensitive membrane is formed by means of physical vapor deposition or chemical vapor deposition.

[0011] In the gas sensor manufacturing method, which is the second aspect of the present disclosure, heat treatment is performed for the sensitive membrane after being formed.

Advantageous Effect of Invention

[0012] The technique according to the present disclosure can enhance responsiveness.

Description

BRIEF DESCRIPTION OF DRAWINGS

[0013] FIG. 1 is a side sectional view schematically showing a gas sensor of a first embodiment.

[0014] FIG. 2 is a partial enlarged view of the gas sensor of FIG. 1.

[0015] FIG. 3 is a plan view SEM image of electrode pairs of the gas sensor.

[0016] FIG. 4 is a plan view SEM image of a sensitive membrane of the gas sensor.

[0017] FIG. 5 is a schematic view used for describing an electrode pair and its inter-electrode volume.

[0018] FIG. 6 is an explanatory view used for describing a method for measuring the width and height of a first electrode in its cut surface.

[0019] FIG. 7 is a process chart used for describing a process of manufacturing the gas sensor.

[0020] FIG. 8 is a process chart which is continued from FIG. 7 and is used for describing the process of manufacturing the gas sensor.

[0021] FIG. 9 is an explanatory view used for briefly describing a sensor evaluation device.

[0022] FIG. 10(A) is an explanatory graph showing changes with time in the output of a gas sensor of Comparative Example 2, and FIG. 10(B) is an explanatory graph showing changes with time in the output of a gas sensor of Experimental Example 4.

[0023] FIG. 11(A) is an explanatory view used for describing depletion layers of tin oxide before exposure of the gas sensor to a gas to be detected, and FIG. 11(B) is an explanatory view used for describing depletion layers of tin oxide after exposure of the gas sensor to the gas to be detected.

DESCRIPTION OF EMBODIMENTS

[0024] In the below, embodiments of the present disclosure will be listed and illustrated.

[0025] [1] A gas sensor of the present disclosure comprises: [0026] an electrode portion which includes one or more electrode pairs each having a first electrode and a second electrode, the first electrode and the second electrode being opposed to each other in a first direction in the electrode pair, with a gap formed therebetween; [0027] a sensitive membrane disposed between the first electrode and the second electrode in the electrode pair; and [0028] a voltage application section which applies a voltage to the electrode portion such that the voltage is applied between the first electrode and the second electrode, [0029] wherein the sensitive membrane is a dense body.

[0030] In the gas sensor described in the above paragraph [1], since the sensitive membrane is densified, movement of electrons in depletion layers becomes easy, whereby the response speed (rising and returning speeds) of an outputted electric signal can be increased.

[0031] [2] In the above-described gas sensor, at least some particles which constitute the sensitive membrane are electrically coupled with one another.

[0032] In the gas sensor described in the above paragraph [2], since the particles which constitute the sensitive membrane are coupled with one another so as to enable electrical conduction, the contact resistance between the particles can be reduced. Accordingly, conduction paths for electrons are easily formed, and movement of electrons in depletion layers becomes easy.

[0033] [3] A method for manufacturing the above-described gas sensor in which the sensitive membrane is formed by means of physical vapor deposition or chemical vapor deposition.

[0034] In the gas sensor described in the above paragraph [3], since a homogeneous sensitive membrane can be formed, stable output of the electric signal becomes possible.

[0035] [4] In the above-described gas sensor manufacturing method, heat treatment is performed for the sensitive membrane after being formed.

[0036] In the gas sensor described in the above paragraph [4], since the particles which constitute the sensitive membrane are easily coupled with one another, the contact resistance between the particles can be reduced, whereby movement of electrons in depletion layers becomes easy.

First Embodiment

1-1. Structure of Gas Sensor

[0037] A first embodiment in which the present disclosure is embodied will now be described with reference to FIGS. 1 to 11. A gas sensor 10 of the first embodiment shown in FIG. 1 is one example of the gas sensor of the present disclosure. In the following description, for convenience of explanation, the upper and lower directions appearing in FIGS. 1 and 2 will be defined as the upper and lower directions. However, the upper and lower directions are not required to coincide with the upper and lower directions in a state in which the gas sensor 10 is actually disposed.

[0038] The gas sensor 10 includes a substrate 20, insulating layers 31 to 35, heating elements 40, an electrode portion 50, a sensitive membrane 60, a voltage application section 80 (see FIG. 9), and an output section 90 (see FIG. 9). The electrode portion 50 includes one or more electrode pairs 70 each having a first electrode 71 and a second electrode 72. The electrode portion 50 preferably includes four or more electrode pairs 70, more preferably 100 or more electrode pairs 70.

[0039] FIG. 3 shows, as an example, the electrode portion 50 including a plurality of electrode pairs 70. As shown in FIG. 3, in each electrode pair 70, the first electrode 71 and the second electrode 72 are opposed to each other and separated from each other in a first direction, with a gap formed therebetween. The first direction is a direction which is parallel to an upper surface of the substrate 20 and in which the first electrode 71 and the second electrode 72 extend. The first direction is also a direction in which the first electrode 71 and the second electrode 72 are opposed to each other. The first direction is orthogonal to a direction in which the plurality of first electrodes 71 are arranged and is also orthogonal to a direction in which the plurality of second electrodes 72 are arranged.

[0040] The substrate 20 is composed of, for example, a silicon wafer. Although no particular limitation is imposed on the material of the substrate 20, the material is, for example, a semiconductor such as silicon. In the case where a ceramic substrate (e.g., a sapphire substrate, a zirconia substrate, an alumina substrate, or the like) is used for the substrate 20, formation of the insulating layers 31 to 34, which will be described later, can be omitted. No particular limitation is imposed on the planar shape of the substrate 20, and the planar shape of the substrate 20 may be, for example, rectangular or circular. No particular limitation is imposed on the size of the substrate 20, and the substrate 20 may be a rectangular substrate having a length of 0.1 mm to 10 mm measured along each side, or a circular substrate whose area is approximately the same as that of the rectangular substrate. No particular limitation is imposed on the thickness of the substrate 20, and the substrate 20 may have a thickness of, for example, 400 μm to 500 μm .

[0041] The substrate 20 may have a space portion 21 formed by removing a portion of the substrate 20. The space portion 21 is, for example, a cavity which penetrates the substrate 20 and is open to front and back surfaces thereof, a recess which is open to only one of the front and back surfaces of the substrate 20, or the like. Although no particular limitation is imposed on the shape of the opening 22 of the space portion 21, the sectional shape of the interior of the space portion 21, etc., in general, their shapes are simple shapes such as rectangular shape, circular shape, etc. No particular limitation is imposed on the size of the space portion 21. In the case where the space portion 21 is a cavity, the space portion 21 is preferably formed such that its opening at one of the front and back surfaces of the substrate 20 has a larger opening area as compared with its opening at the other of the front and back surfaces of the substrate 20. Although no particular limitation is imposed on their opening areas, the opening area of the larger opening is preferably set to 0.01 mm² to 4 mm², more preferably 0.25 mm² to 2 mm². In the case where the space portion 21 is a recess, its opening area may be set to the same range as the cavity.

[0042] The electrode portion 50, which will be described later, is insulated from the substrate 20 by the insulating layers 31 to 35 provided on the substrate 20. The insulating layers 31 to 35 may be formed on the entire surface of the substrate 20 or formed on only a portion of the substrate 20. The insulating layers 31, 33, and 35 are stacked on a surface (upper surface) of the substrate 20 on one side. The space portion 21 is provided in the substrate 20. In the case where the substrate 20 has the

space portion **21**, the insulating layers **31**, **33**, and **35** cover the opening **22** of the space portion **21** and are supported by the substrate **20**. The insulating layers **31**, **33**, and **35** may be formed to cover the entire opening **22** or may be formed to cover a portion of the opening **22** if the insulating layers **31**, **33**, and **35** can be supported by the substrate **20**. The insulating layers **32** and **34** are stacked on a surface (lower surface) of the substrate **20** on the other side. No particular limitation is imposed on the materials of the insulating layers **31** to **35** so long as they have sufficient insulating properties. Examples of the materials of the insulating layers **31** to **35** include silicon compounds such as SiO_2 , Si_3N_4 , and SiO_xN_y (x and y are arbitrary values). No particular limitation is imposed on the shapes and thicknesses of the insulating layers **31** to **35**. A monolayer insulating layer may be provided instead of the insulating layers **31**, **33**, and **35**. By forming a silicon oxide film on the substrate **20**, leak current between the electrodes of each electrode pair **70** can be prevented.

[0043] A plurality of heating elements **40** are provided in the gas sensor **10**. The heating elements **40** are provided on the insulating layer **33** and are covered with the insulating layer **35**. Lead portions (not shown) for supplying electric power from an external circuit are connected to the heating elements **40** via contact portions (not shown) for the heating elements (hereinafter referred to as “heating element contact portions”). Contact pads (not shown) are provided on the surfaces of the heating element contact portions. The heating elements **40** generate heat when a voltage is applied thereto. As a result, the temperature of the sensitive membrane **60** increases, whereby the sensitive membrane **60** is activated, and measurement of gas concentration becomes possible. No particular limitation is imposed on the positions where the heating elements **40** are disposed so long as they are located within the insulating layers **31**, **33**, and **35**. In the case where the space portion **21** is formed in the substrate **20**, the heating elements **40** are preferably disposed at positions corresponding to the space portion **21**. By disposing the heating elements **40** at positions corresponding to the space portion **21**, it is possible to suppress dissipation of heat from the heating elements **40** to the substrate **20**. Also, since heat can be efficiently transferred to the sensitive membrane **60**, the temperature of the sensitive membrane **60** can be controlled more accurately. Notably, the positions corresponding to the space portion **21** refer to a positional relation in which the heating elements **40** at least partially overlap with the space portion **21** in the thickness direction of the substrate **20**, and it is more preferred that the entire heating elements **40** overlap with the space portion **21**. The heating elements **40** have electrical conductivity, and no particular limitation is imposed on their material. For example, platinum, a platinum alloy, a nickel alloy, a chromium alloy, a nickel-chromium alloy, or the like may be used for the heating elements **40**. Of these materials, platinum or a nickel-chromium alloy, which have large temperature coefficients of resistance and whose resistances and temperature coefficients of resistance are less likely to change in repeated use over a long period of time, are preferably used for the heating elements **40**.

[0044] The electrode portion **50** (one or more electrode pairs **70**) is provided on the surface of the insulating layer **35**. One end of the first electrode **71** and one end of the second electrode **72** are disposed to face each other with a nano-gap formed therebetween. In the present first embodiment, the nano-gap means a gap of a distance of 100 nm or less between the one end of the first electrode **71** and the one end of the second electrode **72**.

[0045] Each of the first electrode **71** and the second electrode **72** is formed of a single type of metal or a plurality of types of metals. Examples of the metal used to form the first electrode **71** and the second electrode **72** include gold (Au) and platinum (Pt). The first electrode **71** and the second electrode **72** have, for example, a two-layer structure including a lower layer electrode and an upper layer electrode. For example, the lower layer electrode is formed of titanium (Ti), and the upper layer electrode is formed of platinum (Pt).

[0046] Lead portions (not shown) for supplying electric power from the external circuit are connected to the first electrode **71** and the second electrode **72** via contact portions (not shown) for the electrodes (hereinafter referred to as “electrode contact portions”). Contact pads (not shown)

are provided on the surfaces of the electrode contact portions.

[0047] The sensitive membrane **60** is provided on the upper surface of the first electrode **71**, the upper surface of the second electrode **72**, and the upper surface of the insulating layer **35**. The sensitive membrane **60** is disposed between the first electrode **71** and the second electrode **72** of each electrode pair **70**. The sensitive membrane **60** is preferably formed of a metal oxide. The sensitive membrane **60** is preferably formed of an oxide semiconductor. The oxide semiconductor is preferably an n-type semiconductor. Preferred examples of the n-type semiconductor include SnO₂, ZnO, In₂O₃, Fe₂O₃, ITO (tin-doped indium), and WO₃, whose resistances change easily.

[0048] The sensitive membrane **60** is preferably a dense body. The dense body is a body whose porosity is less than 10%. The surface of the sensitive membrane **60** is, for example, the surface of the dense body as shown in FIG. **4**. Since the sensitive membrane **60** is densified, electrons easily move in depletion layers, whereby the response speed (rising speed and returning speed) of an electric signal outputted from the output section **90** can be increased.

[0049] At least some particles which constitute the sensitive membrane **60** are electrically coupled (bound) with one another. The expression “particles are electrically coupled with one another” is defined as a state in which at least a half of the surface area of a certain particle, excluding end portions, is in contact with the surfaces of other particles, and a path through which electrons having propagated through the certain particle propagate is formed in at least a half of the surface area of the particle. The particles electrically coupled with one another create a state in which electricity flows between the particles (a state in which electrical conduction is enabled). Since the particles which constitute the sensitive membrane **60** are electrically coupled with one another, the contact resistance between the particles can be reduced, whereby movement of electrons in depletion layers becomes easy.

[0050] The voltage application section **80** applies a voltage to the electrode portion **50** such that the voltage is applied between the first electrode **71** and the second electrode **72**. The voltage application section **80** includes, for example, a voltage control circuit (a constant voltage circuit or the like) which performs an operation of applying a voltage to the electrode portion **50** on the basis of electric power supplied from a power source, and a control section (CPU or the like) which controls the voltage control circuit.

[0051] The output section **90** outputs an electric signal representing the gas concentration detected by using the electrode portion **50**. The output section **90** may include, for example, an amplifier which amplifies the electric signal, etc.

[0052] A gas detected by the gas sensor **10** is preferably flammable. The resistance of the gas sensor **10** can be changed by a flammable gas. Preferred examples of the flammable gas include ketones (e.g., acetone), alcohols (e.g., ethanol), carbon monoxide, nitrogen oxides (NO, N₂O), aldehydes (e.g., acetaldehyde), sulfide gases (e.g., hydrogen sulfide), and VOC gases (e.g., toluene).

[0053] The gas sensor **10** is preferably of a resistance measurement type or of an impedance measurement type.

1-2. Conditions of Electrical Index in Electrode Portion

[0054] An electrical index in the electrode portion **50** of the gas sensor **10** will be described. A division value obtained by dividing, by an inter-electrode volume, the voltage *V* applied to the electrode portion **50** by the voltage application section **80** is defined as an electrical index (hereinafter referred to simply as an index) *X* in the electrode portion **50**. The inter-electrode volume *B* is the product of an inter-electrode distance *D* and an electrode area *S*. Namely, the index *X* is represented by the following Expression (1).

[00001]
$$X = V / B = V / (D \times S) \quad \text{Expression(1)}$$

[0055] For example, in the case where the electrode pair **70** shown in FIG. **5** is provided singly, the

volume of a space SP between the first electrode **71** and the second electrode **72** corresponds to the inter-electrode volume B.

[0056] In the case where the electrode portion **50** is composed of a single electrode pair **70**, the inter-electrode distance D is the distance (shortest distance) in the first direction between the first electrode **71** and the second electrode **72** constituting that electrode pair **70**. Meanwhile, in the case where the electrode portion **50** is composed of a single electrode pair **70**, the inter-electrode distance D is the smallest one of the distances (shortest distances) in the first direction between the first electrodes **71** and the second electrodes **72** in all the electrode pairs **70**.

[0057] In the case where the electrode portion **50** is composed of a single electrode pair **70**, the electrode area S is the electrode area of one electrode (for example, the first electrode **71**) of that electrode pair **70**. Meanwhile, in the case where the electrode portion **50** is composed of a plurality of electrode pairs **70**, the electrode area S is the sum total of the electrode areas of electrodes on one side (for example, the first electrodes **71**) of all the electrode pair **70**.

[0058] A specific method for obtaining the electrode area in each electrode portion **50** will be described. First, one first electrode **71** is selected (in the case where the electrode portion **50** includes a single electrode pair **70**, the first electrode **71** of that electrode pair **70** is selected), and a cut surface is set. For example, the first electrode **71** of the electrode pair **70** for which the above-described inter-electrode distance D was determined is selected. For example, a plane which orthogonally intersects a plate face of the substrate **20** and passes through a position which is offset from a first end (an end portion on the second electrode **72** side) of the selected first electrode **71** toward a second end (an end portion located on the side opposite the second electrode **72**) by a distance (preferably, 25 nm) which falls within the range of 10 nm to 100 nm is defined as a cut surface of the electrode portion **50**. In the example of FIG. 3, an A-A cross section serves as the cut surface. The area of each first electrode **71** appearing in the cut surface is used as the electrode area. The electrode area S is the total area of the cross sections of all the first electrodes **71** in their cut surfaces obtained by cutting all the first electrodes **71** at a position offset in the first direction from their first ends by a distance in the range of 10 nm to 100 nm.

[0059] One example of a method for measuring the electrode area appearing in the cut surface will be described. In the cut surface of the first electrode **71**, the width W of the first electrode **71** is defined by the length of the shortest overlap between the cut surface and a straight line which intersects the side surfaces of the first electrode **71** and is parallel to the plate face of the substrate **20**. Here, the side surfaces are surfaces located on the left and right sides of the cut surface and each including a portion having an inclination of 45° or less in relation to a straight line orthogonally intersecting the plate face of the substrate **20** (also referred to as an orthogonal line) and a portion located below that portion. In the case where the left and right sides of the cut surface are curved, each side surface is a portion where a tangent line to a curved portion has an inclination of 45° or less in relation to the orthogonal line. Also, in the cut surface of the first electrode **71**, the height H of the first electrode **71** is defined by the length of the shortest overlap between the cut surface and an orthogonal line intersecting the upper surface of the first electrode **71**. The product of the width W and the height H of the first electrode **71** is defined as the electrode area appearing in the cut surface of the first electrode **71**. Here, the upper surface refers to a surface portion which is located at a center of the cut surface in the left and right direction and is other than the side surfaces.

[0060] For example, in the cut surface of the first electrode **71** as shown in FIG. 6 (A), a straight line L1 parallel to the plate face of the substrate **20** overlaps with the cut surface with a shortest overlap, and its overlapping length W1 is the width. Also, a straight line L2 orthogonally intersecting the plate face of the substrate **20** overlaps with the cut surface with a shortest overlap, and its overlapping length H1 is the height. Similarly, in the cut surface of the first electrode **71** as shown in FIG. 6 (B), a straight line L3 parallel to the plate face of the substrate **20** overlaps with the cut surface with a shortest overlap, and its overlapping length W2 is the width. Also, a straight

line L4 orthogonally intersecting the plate face of the substrate 20 overlaps with the cut surface with a shortest overlap, and its overlapping length H2 is the height. Similarly, in the cut surface of the first electrode 71 as shown in FIG. 6 (C), a straight line L5 parallel to the plate face of the substrate 20 overlaps with the cut surface with a shortest overlap, and its overlapping length W3 is the width. Also, a straight line L6 orthogonally intersecting the plate face of the substrate 20 overlaps with the cut surface with a shortest overlap, and its overlapping length H3 is the height. [0061] Notably, the electrode area S may be obtained by selecting a predetermined number of first electrodes 71 (for example, 100 first electrodes 71) from the plurality of first electrodes 71, calculating the average of cross sectional areas of the selected first electrodes 71, and multiplying the obtained average by the number of the first electrodes 71 contained in the electrode portion 50. [0062] The index in the electrode portion 50 (the index X represented by Expression (1)) is greater than 4.2×10^{16} V/m.³ and not greater than 2.0×10^{25} V/m.³, preferably not less than 6.0×10^{19} V/m.³ and not greater than 2.0×10^{25} V/m.³, more preferably not less than 6.0×10^{20} V/m.³ and not greater than 2.0×10^{25} V/m.³. By virtue of such a configuration, the response speed (rising and returning speeds) of the electric signal outputted by the output section 90 can be increased.

1-3. Conditions of the Electrode Area

[0063] The above-described electrode area S is not less than 2.5×10^{-15} m.² and not greater than 2.1×10^{-11} m.², preferably not less than 2.1×10^{-14} m.² and not greater than 2.1×10^{-12} m.². Notably, in the case where the electrode portion 50 is composed of a single electrode pair 70, the electrode area S is the electrode area of the first electrode 71 of that electrode pair 70, and, in the case where the electrode portion 50 is composed of a plurality of electrode pairs 70, the electrode area S is the sum total of the electrode areas of the first electrodes 71 of all the electrode pairs 70. By virtue of such a configuration, the response speed (rising and returning speeds) of the electric signal outputted by the output section 90 can be increased.

1-4. Conditions of the Inter-Electrode Distance

[0064] The shortest inter-electrode distance among all the electrode pairs 70 in the electrode portion 50 is preferably not less than 5 nm and not greater than 100 nm. By virtue of such a configuration, a tunnel current effect is obtained between the electrodes, whereby the response speed (rising and returning speeds) of the electric signal outputted by the output section 90 can be further increased.

1-5. Conditions of the Total of the Widths of the First Electrodes

[0065] The total of the widths W of the first electrodes 71 of all the electrode pairs 70 in the electrode portion 50 (in the case where the electrode portion 50 includes a single electrode pair 70, the width W of the single first electrode 71) is preferably 20 nm or greater. By virtue of such a configuration, it is possible to reduce the resistance to electron movement, thereby increasing the response speed (rising and returning speeds) of the outputted electric signal.

1-6. Method for Manufacturing the Gas Sensor

[0066] A method for manufacturing the gas sensor 10 in which the present disclosure is embodied will be described with reference to FIGS. 7 and 8.

[0067] The method for manufacturing the gas sensor 10 includes a step of forming the electrode portion 50 on the substrate 20 by a lift-off method and a step of forming the sensitive membrane 60 in a gap portion of the electrode portion 50.

[0068] First, insulating layers 31, 33, and 35 and heating elements 40 are formed on a cleaned substrate 20 (silicon wafer). The cleaned substrate 20 is placed in a heat treatment furnace, and a silicon oxide film (see FIG. 7(A)) which becomes the insulating layer 31 (first insulating layer) is formed over the entire surface of the substrate 20 by means of thermal oxidation treatment. Notably, in FIGS. 7(A) to (C) and FIGS. 8(A) to (D), only the structure on the upper surface side of the substrate 20 is shown, and description regarding formation of the insulating layers 32 and 34 is

omitted. Subsequently, as shown in FIG. 7(A), a silicon nitride film is formed on the insulating layer **31** by means of plasma CVD performed by using, for example, SiH.sub.4 and NH.sub.3 as source gases. The formed silicon nitride film serves as the insulating layer **33** (lower insulating layer). Subsequently, as shown in FIG. 7(B), the heating elements **40** are formed on the surface of the insulating layer **33** by, for example, a sputtering method. For example, each heating element **40** is composed of a Ti layer and a Pt layer located thereabove. Next, patterning of resist is performed by means of photolithography, and the pattern of the heating elements **40** is formed by means of etching treatment.

[0069] No particular limitation is imposed on the method for forming the heating elements **40**. For example, a component which becomes the heating element **40** is caused to adhere to and deposit on the surface of the insulating layer **33**, and then, unnecessary portions are removed by various types of etching methods, which are similar to the method described as an example in the description of the method for forming the space portion **21**. Subsequently, as shown in FIG. 7(C), the insulating layer **35**, which is formed of, for example, a silicon nitride film, is formed on the surface of the insulating layer **33** (the insulating layer **35** serves as an upper insulating layer). In this manner, the insulating layers **33** and **35** (second insulating layer) and the heating elements **40** disposed in the insulating layers **33** and **35** (second insulating layer) are formed. Notably, components which become the insulating layers **31** to **35** may be caused to adhere to and deposit on the surface of the substrate **20**, thereby forming these layers, or these layers may be formed by bonding previously formed insulating layers to the surface of the substrate.

[0070] Subsequently, as shown in FIG. 8(A), a photoresist composition is applied onto the insulating layer **35** by means of spin coating and is dried, whereby a resist film **37** is formed. Notably, in FIGS. 8(A) to (D), the structure of a portion below the insulating layer **35** and the heating elements **40** is not shown. The resist film **37** is formed to a thickness of, for example, 20 nm to 40 nm. The resist film **37** is formed by using a photoresist composition for electron beam exposure. A mask pattern is formed by exposing the resist film **37** by means of electron beam lithography and performing development. The mask pattern is formed such that the gap length of each electrode pair **70** becomes, for example, 20 nm.

[0071] Subsequently, as shown in FIG. 8(B), a metal film **70A** is formed to cover almost the entire surfaces of the insulating layer **35** and the resist film **37**. The metal film **70A** is formed by using gold (Au) or platinum (Pt). The metal film **70A** preferably has a thickness of 5 nm to 20 nm and is formed to have a thickness of, for example, 15 nm. Such metal film **70A** is formed by means of, for example, electron beam deposition. The mask pattern is peeled off, and, simultaneously, portions of the metal film **70A** overlapping that portion are removed. As a result, as shown in FIG. 8(C), an electrode portion **50** (a plurality of electrode pairs **70**) in which the metal film **70A** is stacked is formed. For example, the inter-electrode distance (nano-gap length) in each electrode pair **70** is, for example, 20 nm. Each electrode pair **70** is formed such that the width of the first electrode **71** becomes, for example, 15 nm. Instead of using the above-described electron beam lithography, formation of the electrode pairs **70** may be performed by using nanoimprint lithography in which a mold (metal die) serving as an original plate is pressed against a resist film, thereby transferring a pattern to the resist film. Notably, after formation of the electrodes, annealing (for example, heat treatment at 360° C.) may be performed in vacuum.

[0072] In the case where, as shown in FIG. 1, the space portion **21** is provided in the substrate **20**, the space portion **21** can be formed by, for example, removing a portion of the substrate **20** by means of etching. No particular limitation is imposed on the etching method, and wet etching or dry etching may be used. Also, the etching may be anisotropic etching or isotropic etching. Notably, in the case where a cavity is formed in the substrate **20**, a wet etching method using an anisotropic etchant is preferred.

[0073] Subsequently, as shown in FIG. 8(D), a sensitive membrane **60** is formed on the upper surfaces of the first electrodes **71**, the upper surfaces of the second electrodes **72**, and the upper

surface of the insulating layer 35. Preferably, the sensitive membrane 60 is formed by a physical vapor deposition method (PVD method) or a chemical vapor deposition method (CVD method). An example of the physical vapor deposition method (PVD method) is a sputtering method. The sensitive membrane 60 is formed by an RF sputtering device in which, for example, a tin oxide (SnO.sub.2) target for sputtering is used.

[0074] Heat treatment may be performed for the sensitive membrane 60 after being formed. As a result, particles contained in the sensitive membrane 60 are bonded together, whereby the sensitive membrane 60 becomes dense. The heat treatment is performed by using the heater (heating element 40) provided in the gas sensor, and the temperature is changed by supplying electricity to the heater. As a result, the particles constituting the sensitive membrane 60 are easily bonded together, whereby the contact resistance between the particles can be reduced, and movement of electrons in depletion layers becomes easy.

1-7. Effects of the First Embodiment

[0075] The following description relates to an example of the effect of the present configuration.

[0076] In the gas sensor 10 of the first embodiment, the sensitive membrane 60 is a dense body. Therefore, movement of electrons in depletion layers becomes easy, and the response speed (rising and returning speeds) of an outputted electric signal can be increased.

[0077] In the gas sensor 10 of the first embodiment, at least some particles which constitute the sensitive membrane 60 are electrically coupled with one another. Since the particles which constitute the sensitive membrane 60 are coupled with one another so as to enable electrical conduction, the contact resistance between the particles can be reduced, and, thus, movement of electrons in depletion layers becomes easy.

[0078] In the method for manufacturing the gas sensor 10 of the first embodiment, the sensitive membrane 60 is formed by means of physical vapor deposition or chemical vapor deposition. Therefore, the sensitive membrane 60 can be homogeneously formed, and, thus, stable output of an electric signal becomes possible.

[0079] In the method for manufacturing the gas sensor 10 of the first embodiment, heat treatment is performed for the sensitive membrane 60 after being formed. As a result, the particles which constitute the sensitive membrane 60 are easily coupled with one another, and the contact resistance between the particles can be reduced. Therefore, conduction paths for electrons are easily formed, and, thus, movement of electrons in depletion layers becomes easy.

EXAMPLES

[0080] The present disclosure will now be described further specifically by means of examples.

1. Manufacture of Gas Sensors

[0081] Gas sensors of Experimental Examples 1 to 6 and Comparative Examples 1 and 2 shown in Table 1 were manufactured by the steps which will be described below. Experimental Examples 1 to 6 correspond to examples.

[0082] A silicon substrate (hereinafter also referred to simply as a substrate) of 3 mm×5 mm was used for the gas sensors of Experimental Examples 1 to 6 and Comparative Examples 1 and 2. An insulating layer was formed on the front and back surfaces of the substrate. The insulating layer is composed of a first insulating layer formed of silicon oxide (SiO.sub.2) and a second insulating layer stacked on the surface of the first insulating layer and formed of silicon nitride (Si.sub.3N.sub.4).

TABLE-US-00001

TABLE 1	Thickness	Inter-	Sum total of	sensitive	Application
electrode	Number of	Aceton	Rising	membrane	voltage
responsiveness	(nm)	(V)	(shortest)	(m.sup.2)	pairs (V/m.sup.3)
2.5	20	2.1 × 10 ⁻¹³	580	6.0 × 10 ⁻²⁰	0.17
20	20	2.1 × 10 ⁻¹³	580	6.0 × 10 ⁻¹⁹	0.40
20	20	2.1 × 10 ⁻¹³	580	6.0 × 10 ⁻¹⁸	0.53
20	20	2.1 × 10 ⁻¹³	580	6.0 × 10 ⁻²⁰	0.17

Index X sensitivity

Example 1	Experimental	20	0.25
Example 2	Experimental	20	0.025
Example 3	Experimental	200	2.5
Example 4	Experimental	200	0.25

@100 ppm (T90)

Example 1	Experimental	20	0.25
Example 2	Experimental	20	0.025
Example 3	Experimental	200	2.5
Example 4	Experimental	200	0.25

4 seconds

$10.\text{sup.}-13\ 580\ 6.0 \times 10.\text{sup.}19\ 0.40\ 5\ \text{seconds}$ Example 5 Experimental 200 0.025 20 nm $2.1 \times 10.\text{sup.}-13\ 580\ 6.0 \times 10.\text{sup.}18\ 0.48\ 4\ \text{seconds}$ Example 6 Comparative 20 2.5 20 μm $3 \times 10.\text{sup.}-12\ 1\ 4.2 \times 10.\text{sup.}16\ 0.58\ 5\ \text{seconds}$ Example 1 Comparative 200 2.5 20 μm $3 \times 10.\text{sup.}-12\ 1\ 4.2 \times 10.\text{sup.}16\ 0.87\ 5\ \text{seconds}$ Example 2 Returning responsiveness (T90) Evaluation
 Experimental 30 seconds A Example 1 Experimental 150 seconds A Example 2 Experimental 300 seconds B Example 3 Experimental 15 seconds A Example 4 Experimental 150 seconds A Example 5 Experimental 300 seconds B Example 6 Comparative Did not C Example 1 return for 600 seconds or more Comparative Did not C Example 2 return for 600 seconds or more

[0083] A space portion was formed in the substrate in such a manner that the space portion is open to the surface on the side where the insulating layer was formed. The area of the opening of the space portion was 1 mm.^{sup.2}. Heating elements are formed in the insulating layer at positions corresponding to the space portion. Heating element lead portions (not shown) for supplying electric power are connected to the heating elements. The heating element lead portions have contact portions for connection to an external circuit. The heating elements and the heating element lead portions have a two-layer structure composed of a Pt layer and a Ti layer.

[0084] One pair or plural pairs of electrodes are formed on the surface of the insulating layer at positions corresponding to the heating elements. A sensitive membrane is formed on the surface of the insulating layer at a position corresponding to the heating elements. The sensitive membrane is formed on the surface of the insulating layer in such a manner that the sensitive membrane comes into contact with the upper surfaces of the electrodes. Electrode lead portions are connected to the electrodes. The electrode lead portions have electrode contact portions for connection to the external circuit.

[0085] Each of the electrodes of Experimental Examples 1 to 6 has a lower layer electrode formed on the surface of the insulating layer and an upper layer electrode formed on the upper surface of the lower layer electrode. The lower layer electrode is formed of Ti. The upper layer electrode is formed of Pt. The thickness of the lower layer electrode is 3 nm. The thickness of the upper layer electrode is 10 nm.

[0086] Each of the electrodes of Comparative Examples 1 and 2 has a lower layer electrode formed on the surface of the insulating layer and an upper layer electrode formed on the upper surface of the lower layer electrode. The lower layer electrode is formed of Ti. The upper layer electrode is formed of Pt. The thickness of the lower layer electrode is 20 nm. The thickness of the upper layer electrode is 40 nm.

(1) Cleaning of Substrate

[0087] A silicon substrate having a thickness of 400 μm was immersed in a cleaning solution and cleaning was performed.

(2) Formation of Insulating Layer

[0088] The cleaned silicon substrate was placed in a heat treatment furnace, and a silicon oxide film having a thickness of 100 nm, which would become an insulating layer (first insulating layer), was formed on the entire surface of the substrate by means of thermal oxidation treatment.

(3) Formation of Insulating Layer and Heating Elements (Including Heating Element Lead Portions)

[0089] A silicon nitride film was formed on the first insulating layer of the substrate by means of plasma CVD in which SiH₄ and NH₃ were used as source gases. A silicon nitride film having a thickness of 400 nm was formed on the surface (upper surface) of the substrate on one side and used as an insulating layer (lower insulating layer). A silicon nitride film having a thickness of 200 nm was formed on the surface (lower surface) of the substrate on the other side and used as an insulating layer (lower insulating layer). After that, heating elements were formed on the surface of the second insulating layer by using a DC sputtering device. Specifically, a Ti layer having a thickness of 25 nm was formed on the surface of the second insulating layer, and a Pt layer having a thickness of 250 nm was further formed on the surface of this Ti layer, whereby

the heating elements were formed. Next, patterning of resist was performed by means of photolithography, and the pattern of the heating elements was formed by means of etching. After that, a silicon nitride film having a thickness of 400 nm, which would become the upper insulating layer of the second insulating layer, was formed in the same manner as in the case of the lower insulating layer. In this manner, the second insulating layer and the heating elements disposed in the second insulating layer were formed.

(4) Formation of Heating Element Contact Portions

[0090] The insulating layers were etched by means of dry etching so as to remove portions corresponding to the heating element contact portions, thereby exposing portions (portions of the heating elements) which would become the heating element contact portions. After that, by using a DC sputtering device, a Ti layer having a thickness of 20 nm was formed, and a Pt layer having a thickness of 40 nm was then formed. After sputtering, patterning of resist was performed by means of photolithography, whereby the heating element contact portions were formed.

(5) Formation of Contact Pads

[0091] By using a DC sputtering device, a Cr layer having a thickness of 50 nm was formed on the substrate, and an Au layer having a thickness of 1 μm was formed on its surface. After that, patterning of resist was performed by means of photolithography, and, by means of etching, respective contact pads were formed on the surfaces of the electrode contact portions and the heating element contact portions.

(6) Formation of Space Portion

[0092] The substrate was immersed into a TMAH (tetramethylammonium hydroxide) solution, and anisotropic etching of silicon was performed so as to form a space portion at a position corresponding to the heating elements. The space portion was formed such that an opening was formed in the surface on which the insulating layers were formed.

(7) Formation of Sensitive Membrane

[0093] Tin oxide (SnO_2) was used as nanoparticles of a metal oxide provided at nanogap portions of the nanogap electrodes. A membrane was formed by using an RF sputtering device in which a tin oxide target for sputtering was used. The substrate was heated to 280° C., and tin oxide was sputtered, while sputtering to regions other than a region where a sensitive membrane was to be formed was prevented by a mask, whereby a sensitive membrane was formed. At that time, a membrane having a thickness of 20 nm or 200 nm was formed. FIG. 4 shows an SEM (scanning electron microscope) image obtained by observing the formed sensitive membrane. From FIG. 4, it is understood that the sensitive membrane is a dense film in which particles are bonded together and whose porosity is 10% or less. The particles of the sensitive membrane are electrically coupled (bonded) with one another.

[0094] Notably, a bonding treating (heat treatment) may be further performed so as to produce a more dense sensitive membrane. The heat treatment at that time was performed by using the heater (the heating elements 40) provided in the gas sensor. Specifically, by applying electricity to the heater, the temperature was elevated, and, in clean air, the gas sensor was heated at 300° C. to 600° C. for 10 minutes to 5 hours. Notably, it is sufficient that oxygen coexists so as to prevent reduction of tin oxide, and, therefore, the atmosphere may be a simulated gas produced from a gas cylinder or the like.

2. Gas Sensor Evaluation Method

[0095] Table 1 shows the results of evaluation performed for the manufactured gas sensors by using a gas sensor evaluation device 100 shown in FIG. 9. The gas sensor evaluation device 100 includes a sensor evaluation section 101 and mass flow controllers 102 and 103. For example, an electric signal outputted from the output section 90 of each gas sensor 10 is inputted to the sensor evaluation section 101, and evaluation is performed. In Experimental Examples 1 to 6, gas sensors having 580 electrode pairs were used so as to prevent the electric field strength from becoming excessively high. In the gas sensors of Experimental Example 1 to 6, the inter-electrode distance

(shortest inter-electrode distance) was 20 nm, the height of the first electrode was 13 nm, and the width of the first electrode was 27.5 nm. As will be described later, the height and the width of the first electrode described here were averaged values (averaged first electrode height and width) of 100 electrode pairs randomly selected from the 580 electrode pairs. The height of the upper layer electrode (Pt layer) was 10 nm, and the height of the lower layer electrode (Ti layer) was 3 nm. As will be described later, the height of the Pt layer and the height of the Ti layer were averaged values (averaged Pt layer height and Ti layer height) of 100 electrode pairs randomly selected from the 580 electrode pairs. In the gas sensors of Comparative Examples 1 and 2, the inter-electrode distance was 20 μm , the height of the first electrode was 60 nm, and the width of the first electrode was 50 μm . The height of the upper layer electrode (Pt layer) was 40 nm, and the height of the lower layer electrode (Ti layer) was 20 nm.

[0096] Notably, the inter-electrode distance (shortest inter-electrode distance) was measured through planar observation performed, by using an SEM (scanning electron microscope), in a state in which the electrode portion was formed. In Experimental Examples 1 to 6, the width and the height of the first electrode in its cut surface were averaged values (averaged first electrode height and width) of 100 electrode pairs randomly selected from the 580 electrode pairs. The cut surface was mirror-polished and was observed under an SEM (scanning electron microscope) for measurement.

[0097] Acetone was used as a gas to be detected. Measurement was performed by using purified air as a base gas and using acetone supplied from a 2000 ppm/N.sub.2 balance cylinder (product of TAKACHIHO CHEMICAL INDUSTRIAL CO., LTD.) Acetone was mixed with purified air by using the mass flow controllers **102** and **103** such that the concentration of acetone became a predetermined concentration (here 4, 10, or 100 ppm). The measurement flow rate was 200 sccm. The measurement atmosphere was controlled by using the heater (heating elements) disposed in each gas sensor. Specifically, electric power supplied to the heater was controlled such that the temperature of the gas sensor became 250° C. The heater temperature was controlled by using the previously calculated correlation between the heater temperature and the heater resistance; i.e., by supplying electric power to the heater in accordance with the heater resistance. FIG. **10** shows the results of measurement of responsiveness when acetone was added. The base resistance varies among elements. The base resistance and sensitivity were normalized such that the value of the base resistance became 1. In Experimental Examples 1 and 4 and Comparative Examples 1 and 2, measurement was performed by applying a voltage of 2.5 V between the electrodes.

[0098] FIG. **10(A)** is an explanatory graph showing changes in output with time in the gas sensor of Comparative Example 2, and FIG. **10(B)** is an explanatory graph showing changes in output with time in the gas sensor of Experimental Example 4. These graphs show that, as compared with the gas sensor of Comparative Example 2, the gas sensor of Experimental Example 4 has higher responsiveness. Namely, when acetone was added, the sensor resistance of the gas sensor of Experimental Example 4 decreased with good responsiveness, and, when the gas supplied to the gas sensor of Experimental Example 4 became the atmosphere, the gas sensor of Experimental Example 4 exhibited good responsiveness. The atmosphere, acetone (4 ppm), the atmosphere, acetone (10 ppm), the atmosphere, acetone (100 ppm) were supplied to the gas sensor in this order. The output voltage of the gas sensor changes in accordance with the concentration. A change in the sensor resistance can be converted to voltage by using a measurement circuit, and the measurement circuit can output a voltage corresponding to the resistance. In FIG. **10**, V_a represents the normalized base resistance, and V_g represents a change from the base resistance when the gas sensor exhibited sensitivity.

[0099] As to rising time and returning time, T_{90} represents a time needed to reach 90% of an initial value (a value at the time when sensitivity saturates), which is considered as 100%. Similarly, T_{50} represents a time needed to reach 50% of the initial value (a value at the time when sensitivity saturates), which is considered as 100%. In Experimental Example 4, the rising responsiveness

(T90 response speed) at the time of exhibition of sensitivity was 5 seconds or less, and the output returned to the original value within 15 seconds in a recovery period. A conceivable reason of this is that the inter-electrode electric field strength is high. In Experimental Example 4, since the voltage applied to the electrode portion is 2.5 V, the electric field strength becomes 6.0×10^{20} V/m.³. Meanwhile, in the case of Comparative Examples 1 and 2, in which the inter-electrode distance is 20 μm , the rising responsiveness (T90 response speed) was 30 seconds, which is relatively quick, but the output did not return to a value corresponding the base resistance (V_a) within the measurement time; i.e., T50 was 300 seconds or longer, which shows that the recovery properties are very poor. A conceivable reason of this is that, in Comparative Examples 1 and 2, the electric field strength is low unlike Experimental Examples 1 to 6. In Comparative Examples 1 and 2, since the height of the first electrode is 60 nm and the width of the first electrode is 50 μm , the electric field strength becomes 4.2×10^{16} V/m.³. The thickness of the SnO₂ layer was 200 nm.

[0100] In Experimental Examples 2 and 5, the voltage applied to the electrode portion was 0.25 V, and in Experimental Examples 3 and 6, the voltage applied to the electrode portion was 0.025 V. As shown in Table 1, when the applied voltage is lowered to 0.025 V, the returning responsiveness (returning of the output) becomes slightly bad. Namely, this test revealed that it is preferred that the electric field strength is 6.0×10^{18} V/m.³ or higher.

[0101] The dependency of current on gas concentration measured in Experimental Examples 1 to 6 shows that the concentration of oxygen vacancies of tin oxide changes with gas. Namely, a conceivable reason of this is that, when the gas sensor is exposed to the gas to be detected and the oxygen partial pressure becomes low, which is shown as a change from FIG. 11(A) to FIG. (B), the width of depletion layers of tin oxide decreases from L1 to L2, whereby movement of electrons becomes easy, and, thus, resistance decreases.

OTHER EMBODIMENTS

[0102] The present invention is not limited to the embodiment described by the above description with reference to the drawings, and, for example, embodiments which will be described below are contained in the technical scope of the present invention. Also, various features of the above-described embodiments and the embodiments which will be described below may be combined in any manner so long as a conflict does not occur.

[0103] In the above-described first embodiment, as the method for measuring the area of the cut surface of the first electrode 71, a method for measuring the width W and the height H of the cut surface have been shown as an example. However, other methods may be used. For example, the area of the cut surface may be measured by using, for example, an analysis software program or the like.

[0104] In the above-described first embodiment, the inter-electrode distance of an electrode pair whose inter-electrode distance (shortest distance) is the smallest among the plurality of electrode pairs is employed as the inter-electrode distance D. However, the average of the inter-electrode distances (shortest distances) of all of the plurality of electrode pairs or the average of inter-electrode distances (shortest distances) of a predetermined number of electrode pairs selected from the plurality of electrode pairs may be used.

[0105] In the above-described first embodiment, the plane which passes through a position which is offset from the first end (an end portion on the second electrode 72 side) of the first electrode 71 by a distance which falls within the range of 10 nm to 100 nm is defined as a cut surface, and the conditions of the index X and the electrode area are defined for that cut surface. However, there may be employed a configuration which satisfies the conditions of the above-described index X and the above-described the electrode area in any cut surface which passes through any position which is offset from the first end by a distance of 10 nm to 100 nm.

[0106] In the above-described first embodiment, the electrode area S is obtained by calculating the average value of the sectional areas of a predetermined number (for example, 100) of first

electrodes **71** among the plurality of first electrodes **71**, and multiplying the average value by the number of the first electrodes **71**. However, the electrode area *S* may be obtained by adding together the sectional areas of the all the first electrodes **71**, without calculating the average value. [0107] In the above-described first embodiment, gold (Au), platinum (Pt), and titanium (Ti) are shown as examples of the materials of the first electrode **71** and the second electrode **72**. However, the materials may be elements which are high in catalytic activity such as palladium (Pd), ruthenium (Ru), rhodium (Rh), and iridium (Ir).

[0108] In the above-described first embodiment, the heating elements **40** and the electrode portion **50** are formed on the insulating layer **33** and the insulating layer **35**, respectively. However, they may be formed on an insulating film such as a silicon oxide (SiO₂) film or an alumina (Al₂O₃) film.

[0109] Notably, the embodiments disclosed this time should be considered to be illustrative and not to be restrictive in all aspects. The scope of the present invention is not limited to the embodiments disclosed this time, and it is intended that the present invention encompasses all modifications within the range shown by the claims and the range of equivalents of the claims.

REFERENCE SIGNS LIST

[0110] **10**: gas sensor [0111] **20**: substrate [0112] **21**: space portion [0113] **22**: opening [0114] **31** to **35**: insulating layer [0115] **37**: resist film [0116] **40**: heating element [0117] **50**: electrode portion [0118] **60**: sensitive membrane [0119] **70**: electrode pair [0120] **70A**: metal film [0121] **71**: first electrode [0122] **72**: second electrode [0123] **80**: voltage application section [0124] **90**: output section [0125] **100**: gas sensor evaluation device [0126] **101**: sensor evaluation section [0127] **102**, **103**: mass flow controller

Claims

1. A gas sensor characterized by comprising: an electrode portion which includes one or more electrode pairs each having a first electrode and a second electrode, the first electrode and the second electrode being opposed to each other in a first direction in the electrode pair, with a gap formed therebetween; a sensitive membrane disposed between the first electrode and the second electrode in the electrode pair; and a voltage application section which applies a voltage to the electrode portion such that the voltage is applied between the first electrode and the second electrode, wherein the sensitive membrane is a dense body.
 2. A gas sensor according to claim 1, wherein at least some particles which constitute the sensitive membrane are electrically coupled with one another.
 3. A gas sensor manufacturing method for manufacturing the gas sensor according to claim 1, the method being characterized in that the sensitive membrane is formed by means of physical vapor deposition or chemical vapor deposition.
 4. A gas sensor manufacturing method according to claim 3, wherein heat treatment is performed for the sensitive membrane after being formed.
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