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(54) **SEMICONDUCTOR APPARATUS AND METHOD OF MANUFACTURING THE SAME**

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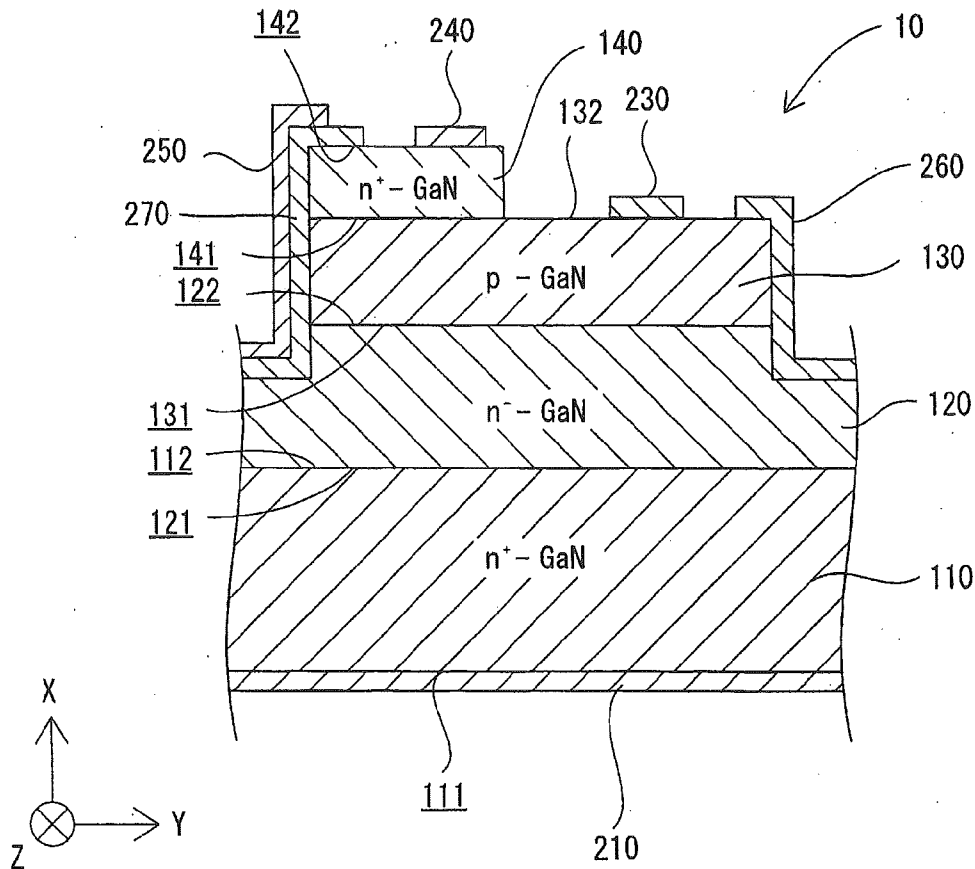(30) **Foreign Application Priority Data**

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(57) **ABSTRACT**

A semiconductor apparatus includes a semiconductor substrate that has a diameter of 2 inches or larger, and an N-type semiconductor layer that is stacked on the semiconductor substrate using a material including gallium nitride (GaN). A median of a plurality of measured values of the concentration of carbon (C) at a plurality of locations on a face of a region of the N-type semiconductor layer is equal to or lower than 1.0×10^{16} cm^{-3}. The maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

FIG. 1

FIG. 2

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        ┌─────────────────────────────┐
        │ METHOD OF MANUFACTURING A   │
        │ SEMICONDUCTOR APPARATUS     │
        └─────────────────────────────┘
                     │
                     ▼                        P122
        ┌─────────────────────────────┐
        │ ARRANGING A SUBSTRATE IN A  │
        │ REACTION CHAMBER OF A       │
        │ MOCVD APPARATUS             │
        └─────────────────────────────┘
                     │
                     ▼                        P124
        ┌─────────────────────────────┐
        │ FORMING A FIRST N-TYPE      │
        │ SEMICONDUCTOR LAYER         │
        └─────────────────────────────┘
                     │
                     ▼                        P126
        ┌─────────────────────────────┐
        │ FORMING A P-TYPE            │
        │ SEMICONDUCTOR LAYER         │
        └─────────────────────────────┘
                     │
                     ▼                        P128
        ┌─────────────────────────────┐
        │ FORMING A SECOND N-TYPE     │
        │ SEMICONDUCTOR LAYER         │
        └─────────────────────────────┘
                     │
                     ▼                        P130
        ┌─────────────────────────────┐
        │ FORMING ELECTRODES          │
        └─────────────────────────────┘
                     │
                     ▼
        ┌─────────────────────────────┐
        │        COMPLETION           │
        └─────────────────────────────┘
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FIG. 3

FIG. 4

FIG. 5

THE MAXIMUM CONCENTRATION DIFFERENCE
RELATIVE TO THE MIDDLE VALUE (CARBON)

FIG. 6

FIG. 7

THE MAXIMUM CONCENTRATION DIFFERENCE
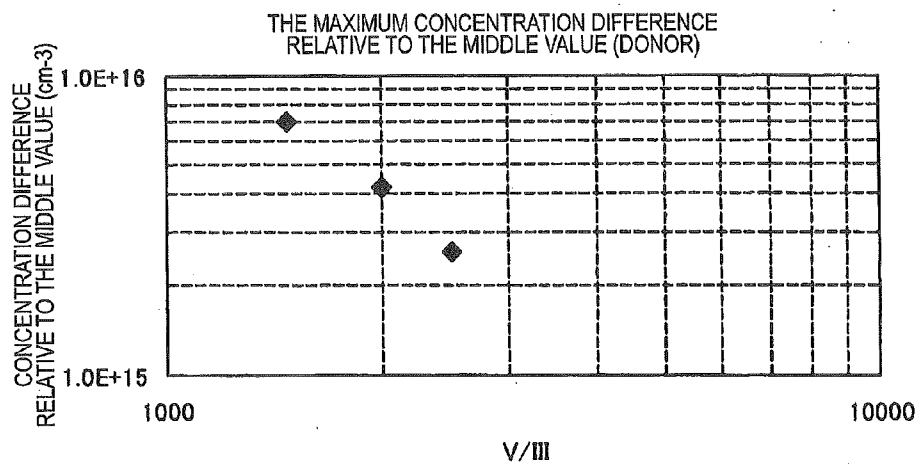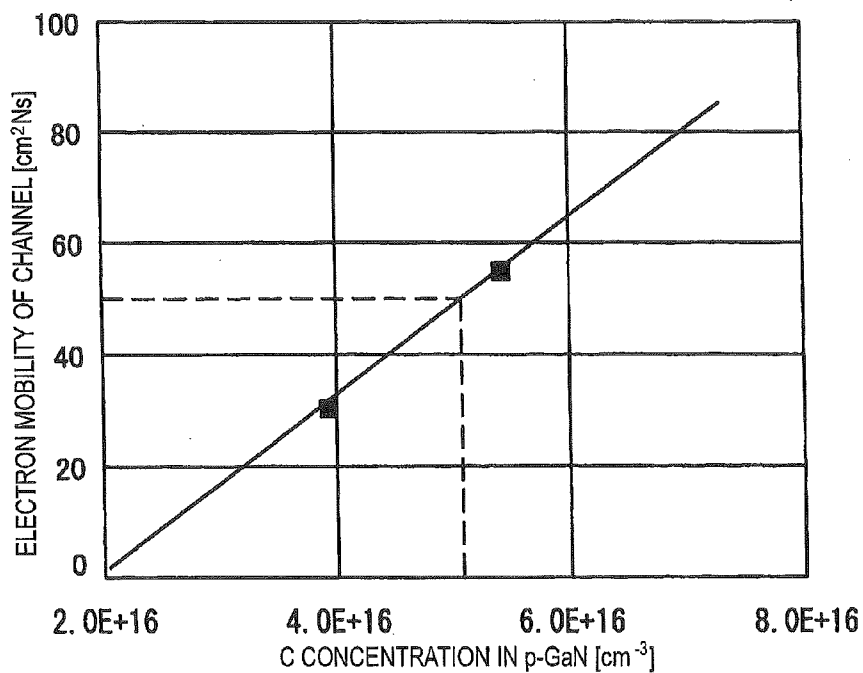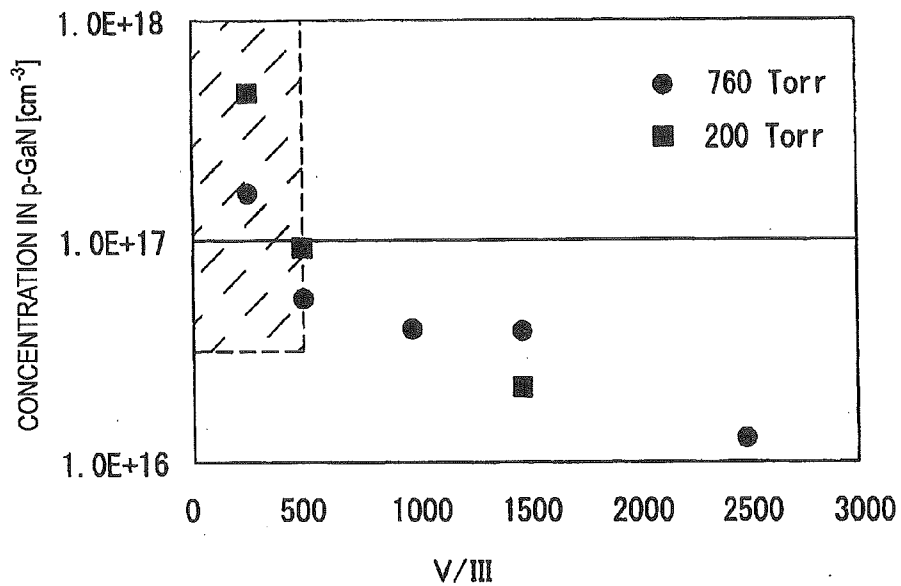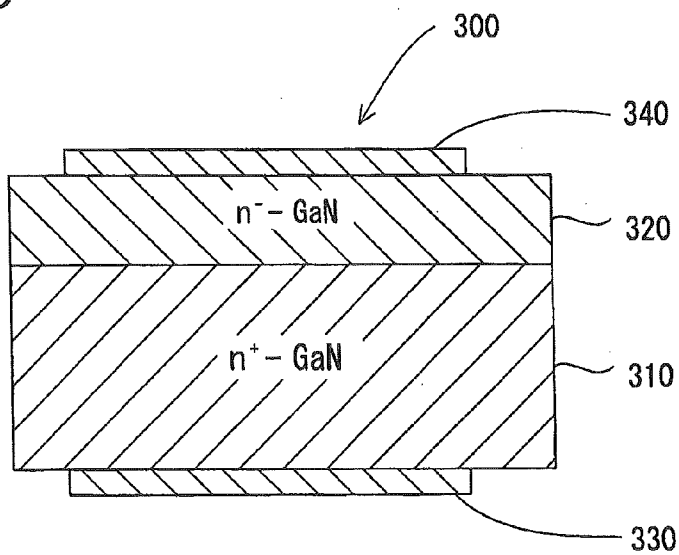RELATIVE TO THE MIDDLE VALUE (DONOR)

FIG. 8

FIG. 9

FIG. 10

SEMICONDUCTOR APPARATUS AND METHOD OF MANUFACTURING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of Japanese Patent Application No. 2013-048719 (filed on Mar. 12, 2013), the entire contents of which are hereby incorporated by reference.

BACKGROUND

[0002] 1. Technical Field
[0003] The present invention relates to a semiconductor apparatus and a method of manufacturing the same.
[0004] 2. Related Art
[0005] As semiconductor apparatuses (semiconductor devices and semiconductor elements) used for controlling electric power, a gallium nitride (GaN) based semiconductor apparatus is known, in which an N-type semiconductor layer is stacked on a semiconductor substrate. The N-type semiconductor layer contains gallium nitride (GaN) as a main material, and silicon (Si) as a donor (dopant or impurities). As such N-type semiconductor layers, one is known in which an n^--GaN layer has a low donor concentration of about 1×10^{16} cm^{-3} for the primary purpose of increasing withstanding voltage (e.g., see Patent Document 1).

[0006] In general, such N-type semiconductor layer is manufactured by a metal organic chemical vapor deposition (MOCVD) method. In MOCVD, trimethylgallium (TMGa: $(CH_3)_3Ga$) is used as a source of gallium (Ga). As a source of nitrogen, ammonia (NH_3) is used. Hydrogen is used as a carrier gas. Silane is used as an N-type dopant source.

[0007] [Patent Document 1] JP-A-2011-35066 A
[0008] When the N-type semiconductor layer has a low donor concentration of about 1×10^{16} cm^{-3}, the N-type semiconductor layer can be easily affected by other impurities to cause a non-uniform distribution of the concentration of donor, so that it is difficult to achieve uniform electric properties on the substrate. Such variation in the concentration of donor affects withstanding voltage in interfaces with other semiconductor layers and electrodes. In particular, when the N-type semiconductor layer is formed on a semiconductor substrate having a large diameter of more than 2 inches by vapor deposition, the N-type semiconductor layer is easily affected by impurities, such as carbon. Therefore, there is a problem in that, when a plurality of chips are cut out from the semiconductor wafer, variation in product quality is prone to be caused in each chip.

[0009] The present invention is directed to solve the above problems, and accordingly, can be embodied in the following forms.

[0010] (1) According to an aspect of the invention, a semiconductor apparatus includes a semiconductor substrate that has a diameter of 2 inches or larger and an N-type semiconductor layer that is stacked on the semiconductor substrate using a material including gallium nitride (GaN). A median of a plurality of measured values of the concentration of carbon (C) at a plurality of locations on a face of a region of the N-type semiconductor layer is equal to or lower than 1.0×10^{16} cm^{-3}, and the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

[0011] Carbon (C) of the N-type semiconductor layer has an action of compensating and reducing a donor of the N-type semiconductor layer. According to the semiconductor apparatus of the above form, because the median of a plurality of measured values of the concentration of carbon (C) is equal to or lower than 1.0×10^{16} cm^{-3} and the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}, the concentration of carbon (C) allows a concentration of donor in the region of the N-type semiconductor layer to be uniform, without non-uniformly compensating the donor by carbon (C). Therefore, when a plurality of chips are cut out from a substrate of more than 2 inches to form semiconductor apparatuses, the function of the donor in each of the obtained semiconductor apparatuses can be stable and uniform.

[0012] (2) In the configuration of (2), the N-type semiconductor layer contains silicon as a donor, a median of a plurality of measured values of the concentration of the donor at a plurality of locations on the face of the region of the N-type semiconductor layer is equal to or lower than 1.4×10^{16} cm^{-3}, and the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

[0013] If the concentration of donor is lower as in the above form, the donor can be easily affected by variation in the concentration of carbon (C). In the present form, because the concentration of carbon (C) is reduced, variation in action of the donor can be reduced.

[0014] (3) In the semiconductor apparatus of (1) or (2), electrodes are respectively connected to the substrate and the N-type semiconductor layer.

[0015] (4) In the semiconductor apparatus of (1) or (2) further includes a P-type semiconductor layer that is stacked on the N-type semiconductor layer, and an additional N-type semiconductor layer that is stacked on the P-type semiconductor layer. A drain electrode is connected to the substrate, a source electrode is connected the additional N-type semiconductor layer, and a gate electrode is connected to an insulation layer on the P-type semiconductor layer.

[0016] As aspects of the semiconductor apparatus, various configurations can be employed.

[0017] (5) According to another aspect of the invention, a method of manufacturing the semiconductor apparatus according to any one of (1) to (4) includes forming the N-type semiconductor layer by crystal growth using a group III raw material including trimethylgallium (TMGa) and a group V raw material including ammonia (NH_3). V/III, a mole ratio of the group V raw material to the group III raw material, is a range of 2100 to 4000.

[0018] With the configuration of (5), the N-type semiconductor layer is formed by crystal growth using the group III raw material including trimethylgallium (TMGa) and the group V raw material including ammonia (NH_3). By using such V/III, the concentration of carbon (C) can be set in the range as described above. Meanwhile, in the following description, the V/III means a mole ratio of the group V raw material to the group III raw material.

[0019] According to another aspect of the invention, a method of manufacturing a semiconductor apparatus having an N-type semiconductor layer stacked on a semiconductor substrate using a material including gallium nitride (GaN) includes a first step of arranging a plurality of the substrates in a region of more than 2 inches in diameter, and a second step of forming the N-type semiconductor layer by crystal growth, using a group III raw material including trimethylgallium

(TMGa) and a group V raw material including ammonia (NH$_3$). The second step is adjusted so that a V/III, a mole ratio of the group V raw material to the group III raw material, is within a range of 2100 to 4000, and also so that a median of a plurality of measured values of the concentration of carbon (C) at a plurality of locations on a face of a region of the N-type semiconductor layer is equal to or lower than $1.0 \times^{16}$ cm^{-3} and the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

[0020]   (7) In the configuration of (6), the second step is adjusted so that silicon (Si) is contained as a donor, and also so that a median of a plurality of measured values of the concentration of the donor at a plurality of locations on the face of the region of the N-type semiconductor layer is equal to or lower than 1.4×10^{16} cm^{-3}, and the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

[0021]   With the configuration of (7), a plurality of the substrates are arranged in the region of more than 2 inches and in this state, the N-type semiconductor layer is formed thereon by crystal growth. In this form, the N-type semiconductor layer can be concurrently formed on a plurality of the substrates in the region of more than 2 inches.

[0022]   In a configuration in which an N-type semiconductor layer added with a donor of a low concentration is stacked, the present invention allows the concentration of the donor to be uniform over a broad range on the face of the N-type semiconductor layer, even on large semiconductor substrates of more than 2 inches.

[0023]   FIG. 1 is a sectional view schematically showing a configuration of a semiconductor apparatus.

[0024]   FIG. 2 is a flow chart showing a method of manufacturing the semiconductor apparatus.

[0025]   FIG. 3 is an explanatory view explaining a state where a plurality of substrates are arranged in a reaction chamber.

[0026]   FIG. 4 is a graph explaining a relationship of a concentration of carbon (C) on a face of a first N-type semiconductor layer and a V/III.

[0027]   FIG. 5 is an explanatory view explaining a relationship of a concentration difference between a median and the other measured values in the concentration of carbon (C) and the V/III.

[0028]   FIG. 6 is a graph explaining a relationship of a concentration of donor on the face of the first N-type semiconductor layer and the V/III.

[0029]   FIG. 7 is an explanatory view explaining a relationship of a concentration difference between a median and the other measured values in the concentration of donor and the V/III.

[0030]   FIG. 8 is a graph explaining a relationship of a channel mobility µ and a concentration of carbon (C) of a P-type semiconductor layer.

[0031]   FIG. 9 is a graph explaining a relationship of a concentration of carbon (C) and the V/III.

[0032]   FIG. 10 is a sectional view showing a semiconductor apparatus according to another embodiment.

A. EMBODIMENTS

[0033]   (1) Schematic Configuration of a Semiconductor Apparatus 10

[0034]   FIG. 1 is a sectional view schematically showing a configuration of the semiconductor apparatus 10. The semi-

conductor apparatus 10 is a GaN-based semiconductor apparatus formed using gallium nitride. The semiconductor apparatus mentioned herein is equivalent to one which includes a semiconductor wafer according to embodiments and the peripheral components. In addition, FIG. 1 is a view illustrated to easily understand technical features of the semiconductor apparatus 10, not intended to exactly depict dimensions of each part thereof. In the present embodiment, the semiconductor apparatus 10 is used for controlling electric power and thus, is referred to as a power device, also so-called a vertical MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor).

[0035]   The semiconductor apparatus 10 is a NPN-type semiconductor apparatus including a substrate 110, a first N-type semiconductor layer 120, a P-type semiconductor layer 130 and a second N-type semiconductor layer 140, and has a structure in which the first N-type semiconductor layer 120, the P-type semiconductor layer 130 and the second N-type semiconductor 140 are stacked in this order on a substrate 110 by crystal growth using a metal organic chemical vapor deposition (MOCVD) method.

[0036]   In FIG. 1, XYZ axes perpendicular to each other are shown. The X-axis of XYZ axes in FIG. 1 is an axis along a stacking direction, in which the first N-type semiconductor layer 120 is stacked on the substrate 110. A +X-axis direction of the X-axis direction along the X-axis is a direction directing from the substrate 110 to the first N-type semiconductor layer 120, and a –X-axis direction is a direction opposite to the +X-axis direction. The Y-axis and Z-axis of XYZ axes in FIG. 1 are axes perpendicular to the X-axis and also to each other. A +Y-axis direction of the Y-axis direction along the Y-axis is a direction directing from left to right in the paper plane of FIG. 1, and a –Y-axis direction is a direction opposite to the +Y-axis direction. A –Z-axis direction of the Z-axis direction along the Z-axis is a direction directing from the back side to the front side with respect to the paper plane of FIG. 1, and a +Z-axis direction is a direction opposite to the +Z-axis direction.

[0037]   (2) Configuration of Each Part of the Semiconductor Apparatus 10

[0038]   (2)-1 Substrate 110

[0039]   The substrate 110 has a plate shape extending along a plane parallel to the Y-axis and Z-axis. In the present embodiment, the substrate 110 consists essentially of gallium nitride (GaN) and also contains silicon (Si) as a donor at a concentration higher than that in the first N-type semiconductor layer 120. In the present embodiment, the average concentration of silicon (Si) over the entire region of the substrate 110 is equal to or higher than 1.0×10^{18} cm^{-3}. The substrate 110 may be a part configured to fix and support each semiconductor layer of the semiconductor apparatus 10, and in other embodiments, may also be a part consisting essentially of, for example, silicon (Si).

[0040]   The substrate 10 has an interface 111 and an interface 112. The interface 111 of the substrate 110 is a surface parallel to the Y-axis and the Z-axis and orienting to the –X-axis direction. The interface 112 of the substrate 110 is a surface parallel to the Y-axis and the Z-axis and orienting to the +X-axis direction, and is opposed to the interface 111. The interface 112 is adjacent to the first N-type semiconductor layer 120.

[0041]   A thickness of the substrate 110 is a distance between the interface 111 and the interface 112 in the X-axis direction, and in the present embodiment, is 320 µm (mi-

crometer). In other embodiments, the thickness of the substrate **110** may be any value selected from a range of 100 μm to 1 mm (millimeter).

[0042] In the present embodiment, an electrode **210**, also referred as to a drain electrode, is formed on the interface **111** of the substrate **110**. In the embodiment, the electrode **210** is an electrode having a structure, in which a layer formed of aluminum (Al) is stacked on a layer formed of titanium (Ti). In other embodiments, the electrode **210** may be an electrode formed of at least one of conductive materials, such as, platinum (Pt), Co (cobalt), palladium (Pd), nickel (Ni), and gold (Au), other than Ti and Al.

[0043] (2)-2 First N-Type Semiconductor Layer **120**

[0044] The first N-type semiconductor layer **120** is formed on the substrate **110** in a stacked state, and thus forms a layer extending on a plane parallel to the Y-axis and the Z-axis. The first N-type semiconductor layer **120** consists essentially of gallium nitride (GaN), and contains silicon (Si) as a donor at a concentration lower than that in the second N-type semiconductor layer **140**. A range of the concentration of silicon (Si) will be described below. The first N-type semiconductor layer **120** is also referred as to 'n⁻-GaN'.

[0045] The first N-type semiconductor layer **120** has an interface **121** and an interface **122**. The interface **121** of the first N-type semiconductor layer **120** is a surface parallel to the Y-axis and the Z-axis and orienting to the –X-axis direction. The interface **121** is adjacent to the substrate **110**. The interface **122** of the first N-type semiconductor layer **120** is a surface parallel to the Y-axis and the Z-axis and orienting to the +X-axis direction, and is opposed to the interface **121**. The interface **122** is adjacent to the P-type semiconductor layer **130**.

[0046] A thickness of the first N-type semiconductor layer **120** is a distance between the interface **121** and the interface **122** in the X-axis direction, and in the present embodiment, is 10 μm. In other embodiments, the thickness of the first N-type semiconductor layer **120** may be any value selected from a range of 5 to 15 μm.

[0047] (2)-3 P-Type Semiconductor Layer **130**

[0048] The P-type semiconductor layer **130** is formed on the first N-type semiconductor layer **120** in a stacked state, and thus forms a layer extending on a plane parallel to the Y-axis and the Z-axis. The P-type semiconductor layer **130** consists essentially of gallium nitride (GaN), and contains magnesium (Mg) as an acceptor. In the present embodiment, the average concentration of Mg over the entire region of the P-type semiconductor layer **130** is equal to or higher than 1.0×10^{18} cm⁻³ and equal to or lower 1.0×10^{20} cm⁻³. The P-type semiconductor layer **130** is also referred as to 'p-GaN'.

[0049] The P-type semiconductor layer **130** has an interface **131** and an interface **132**. The interface **131** of the P-type semiconductor layer **130** is a surface parallel to the Y-axis and the Z-axis and orienting to the –X-axis direction. The interface **131** is adjacent to the first N-type semiconductor layer **120**. The interface **132** of the P-type semiconductor layer **130** is a surface parallel to the Y-axis and the Z-axis and orienting to the +X-axis direction, and is opposed to the interface **131**. The interface **132** is adjacent to the second N-type semiconductor layer **140** and an electrode **230**.

[0050] A thickness of the P-type semiconductor layer **130** is a distance between the interface **131** and the interface **132** in the X-axis direction, and in the present embodiment, is 1

μm. In other embodiments, the thickness of the P-type semiconductor layer **130** may be any value selected from a range of 0.3 to 2 μm.

[0051] (2)-4 Second N-Type Semiconductor Layer **140**

[0052] The second N-type semiconductor layer **140** is formed on the P-type semiconductor layer **130** in a stacked state, and thus forms a layer extending on a plane parallel to the Y-axis and the Z-axis. The second N-type semiconductor layer **140** consists essentially of gallium nitride (GaN), and contains silicon (Si) as a donor at a concentration higher than that in the first N-type semiconductor layer **120**. In the present embodiment, the average concentration of silicon (Si) over the entire region of the second N-type semiconductor layer **140** is equal to or lower than 1.0×10^{19} cm⁻³. The second N-type semiconductor layer **140** is also referred as to 'n⁺-GaN'.

[0053] The second N-type semiconductor layer **140** has an interface **141** and an interface **142**. The interface **141** of the second N-type semiconductor layer **140** is a surface parallel to the Y-axis and the Z-axis and orienting to the –X-axis direction. The interface **141** is adjacent to the P-type semiconductor layer **130**. The interface **142** of the second N-type semiconductor layer **140** is a surface parallel to the Y-axis and the Z-axis and orienting to the +X-axis direction, and is opposed to the interface **141**. The interface **142** is adjacent to an electrode **240**.

[0054] A thickness of the second N-type semiconductor layer **140** is a distance between the interface **141** and the interface **142** in the X-axis direction, and in the present embodiment, is 0.2 μm. In other embodiments, the thickness of the second N-type semiconductor layer **140** may be any value selected from a range of 0.1 to 0.5 μm.

[0055] (2)-5 Electrodes and Insulation Layers

[0056] Electrodes are formed on the substrate and each layer. Namely, the electrode **230**, also referred to as a P body electrode, is formed on the interface **132** of the P-type semiconductor layer **130**. The electrode **230** reduces electrons and positive holes generated in the P-type semiconductor layer **130**, thereby enhancing withstanding voltage. The electrode **240**, also referred to as a source electrode, is formed on the interface **142** of the second N-type semiconductor layer **140**. An insulation layer **260** is formed to extend from an upper surface of the first N-type semiconductor layer **120** to a side surface (the right side in the figure) of the P-type semiconductor layer **130**, and an insulation layer **270** is formed to extend from the upper surface of the first N-type semiconductor layer **120** to a side surface (the left side in the figure) of the second N-type semiconductor layer **140** by way of a side surface of the P-type semiconductor layer **130**. The insulation layers **260** and **270** are layers formed of aluminum oxide (Al₂O₃), silicon dioxide (SiO₂), or the like. On the insulation layer **270**, an electrode **250**, also referred to as a gate electrode, is formed.

[0057] (3) Method of Manufacturing the Semiconductor Apparatus **10**

[0058] FIG. **2** is a flow chart showing the method of manufacturing the semiconductor apparatus **10**. Upon manufacturing of the semiconductor apparatus **10**, a manufacturer firstly prepare a MOCVD apparatus for implementing the metal organic chemical vapor deposition (MOCVD) method and then arrange a plurality of substrates **110** in a reaction chamber of the MOCVD apparatus (step P**122**). Preferably, substrates having a diameter of more than 2 inches are used as the substrates **110**. In this step, the substrates **110** having a diam-

eter of 2 inches or less may be arranged in a closely-packed state using a plurality of substrates thereof (e.g., seven substrates). The substrates 110 have a thickness of 300 μm to 500 μm and are doped with silicon (Si). The concentration thereof is 1.0×10^{18} cm^{-3}.

[0059] In a subsequent step P124, the MOCVD apparatus forms the first N-type semiconductor layer 120 on the substrate 110 by crystal growth using silane as a dopant source, based on operations of the manufacturer. Trimethylgallium (TMGa) as a group III raw material, ammonia (NH$_3$) as a group V raw material, and silane as an N-type dopant source are supplied to the reaction chamber through a piping of the MOCVD apparatus, using hydrogen (H$_2$) as a carrier gas. In this case, the first N-type semiconductor 120 is formed to have, for example, a thickness of 5 to 15 μm. Meanwhile, V/III of the sources, a growth pressure, a concentration of silicon (Si) and the like will be described below.

[0060] Then, in a step P126, the MOCVD apparatus forms the P-type semiconductor layer 130 on the first N-type semiconductor layer 120 by crystal growth using CP2Mg (bis (cyclopentadienyl)magnesium) as a dopant source, based on operations of the manufacturer.

[0061] In a subsequent step P128, the MOCVD apparatus forms the second N-type semiconductor layer 140 on the P-type semiconductor layer 130 by crystal growth using silane as a dopant source, based on operations of the manufacturer. The concentration of silicon (Si) in the second N-type semiconductor layer 140 is higher than that in the first N-type semiconductor layer 120. As conditions of the step P128, the same conditions as those in the step P124 with respect to sources, pressure and the like, except for the concentration of silicon (Si), can be employed.

[0062] Next, in a step P130, the manufacturer takes an intermediate product of the semiconductor apparatus 10 out of the MOCVD apparatus, and forms the electrodes 210, 230, 240 and 250 and the insulation layers 260 and 270, respectively, on the intermediate product. Thereby, the semiconductor apparatus 10 is completed.

[0063] (4) Operations/Effects of the Embodiment

[0064] (4)-1 A concentration of carbon (C) and a concentration of donor in the step (P124) of forming the first N-type semiconductor layer 120 will be described.

[0065] FIG. 3 is an explanatory view explaining a state where a plurality of substrates 110 are arranged in the reaction chamber. In FIG. 3, ones having a diameter of 2 inches were used as the substrates 110, and seven substrates 110 were arrange within an area of 6 inches to be arranged in a closely packed state. Namely, six substrates are arranged to surround one substrate 110. This is intended to equate placing seven GaN substrates of 2 inches with using a substrate of 6 inches in a pseudo manner, instead of using substrates of 2 inches or greater (e.g., 6 inches). Then, the first N-type semiconductor layer 120 was grown and stacked on the plurality of substrates 110 and subsequently, the concentrations of carbon (C) and donor on a face of the first N-type semiconductor layer 120 was investigated.

[0066] FIG. 4 is a graph explaining a relationship of the concentration of carbon (C) on the face of the first N-type semiconductor layer 120 and the V/III, in which variation in the concentration of carbon (C) of the first N-type semiconductor layer 120 grown on the substrates 110 while varying the V/III is illustrated. The V/III means a mole ratio of the group V raw material to the group III raw material. Specifically, to obtain the graph in FIG. 4, the present inventors used

trimethylgallium (TMGa) as the group III raw material and also used ammonia (NH$_3$) as the group V raw material. Three kinds of V/III, i.e., 1473 (first group), 2000 (second group), and 2506 (third group), were used. Then, a plurality of samples (seven substrates), in which an N-type semiconductor layer was formed on each of substrates of 2 inches, were manufactured and the concentrations of carbon (C) thereof were measured. The concentrations of carbon (C) were measured using a secondary ion-microprobe mass spectrometer (SIMS). In this case, each of the measured values was obtained by sampling the concentration of carbon (C) on the face of each of the seven substrates. FIG. 5 is an explanatory view explaining a relationship of concentration differences between a median and other measured values in the concentrations of carbon (C) and the V/III. As shown in FIG. 5, the concentrations of carbon (C) were studied using differences between the median and the other values in the measured values.

[0067] As shown in FIGS. 4 and 5, the median of the concentration of carbon (C) in the first group (V/III: 1473) is 1.4×10^{16} cm^{-3}, and the maximum value in difference between the median and the other measured values is 9.3×10^{15} cm^{-3}. The median of the concentration of carbon (C) in the second group (V/III: 2000) is 8.7×10^{15} cm^{-3}, and the maximum value in difference between the median and the other measured values is 5.0×10^{15} cm^{-3}. The median of the concentration of carbon (C) in the third group (V/III: 2506) is 7.4×10^{15} cm^{-3}, and the maximum value in difference between the median and the other measured values is 2.6×10^{15} cm^{-3}. If comparing the first to third groups, it can be found that, as the V/III is increased, the median of the concentration of carbon (C) is decreased from 1.4×10^{16} cm^{-3} to 7.4×10^{15} cm^{-3} and also the maximum value in difference between the median and the other measured values is narrowed from 9.3×10^{15} cm^{-3} to 2.6×10^{15} cm^{-3}, and thereby variation in concentration is reduced.

[0068] FIG. 6 is a graph explaining a relationship of a concentration of a donor on the face of the first N-type semiconductor layer 120 and the V/III. Correspondingly to FIG. 4, the concentrations of donor with respect to the V/III (the first to third groups) were measured on the seven substrates. The concentrations of donor were obtained by a C-V measurement. In this case, the measured values were obtained by sampling the concentration of donor on the face of each of the seven substrates, similarly to the concentration of carbon (C) in FIG. 4. FIG. 7 is an explanatory view explaining a relationship of concentration differences between a median and other measured values in the concentrations of donor and the V/III. As shown in FIG. 7, the concentrations of donor were studied using differences between the median and the other values in the measured values.

[0069] As shown in FIGS. 6 and 7, the median of the concentration of donor in the first group (V/III: 1473) is 3.0×10^{16} cm^{-3}, and the maximum value in difference between the median and the other measured values is 7.0×10^{15} cm^3. The median of the concentration of donor in the second group (V/III: 2000) is 2.0×10^{16} cm^{-3}, and the maximum value in difference between the median and the other measured values is 4.2×10^{15} cm^{-3}. The median of the concentration of donor in the third group (V/III: 2506) is 7.3×10^{15} cm^{-3}, and the maximum value in difference between the median and the other measured values is 2.6×10^{15} cm^{-3}. If comparing the first to third groups, as the V/III is increased, the median of the concentration of donor is decreased from 3.0×10^{16} cm^{-3} to

7.3×10^{15} cm^{-3} and also the maximum value in difference between the median and the other measured values is narrowed from 7.0×10^{15} cm^{-3} to 2.6×10^{15} cm^{-3}. Thus, it can be found that the concentrations of donor exhibit the same tendency as those in the concentrations of carbon (C). Namely, it can be found that the concentrations of silicon (Si) exhibit the same tendency as those in the concentrations of carbon (C). From this, it is conceived that the donor and the carbon have a relationship as described below.

[0070] Carbon (C) of the first N-type semiconductor layer 120 compensates the donor of the first N-type semiconductor layer 120, thereby reducing action of the donor. Accordingly, variation in concentration of the donor can be reduced by lowering the concentration of carbon (C) and also decreasing variation in concentration of carbon (C). By reducing variation in concentration of the donor, it is possible that, when a plurality of chips are cut out from the substrate 110 of more than 2 inches to form semiconductor apparatuses, the action of the donor in each of the obtained semiconductor apparatuses is stable and uniform.

[0071] The lower the variation in concentration of the donor, the more preferable it is, but for example, when a specification, in which, as a range in which products are less affected, the value of the concentration of donor is equal to or less than 1.4×10^{16} cm^{-3} and variation thereof with respect to the median is more than 5.0×10^{15} cm^{-3}, is required, the concentration of donor is regulated below such values due to a limitation in an adjusting range of the concentration of carbon (C) in the first N-type semiconductor layer 120.

[0072] The first N-type semiconductor layer 120 is formed by crystal growth using the group III raw material including trimethylgallium (TMGa) and the group V raw material including ammonia (NH$_3$). Accordingly, carbon (C) in trimethylgallium (TMGa) is entrained into the first N-type semiconductor layer 120. Therefore, when the V/III is increased, the concentration of carbon (C) in the N-type semiconductor layer can be decreased, but if the V/III is higher than 4000, the crystal growth rate is reduced, thereby decreasing productivity. On the other hand, if the V/III is lower than 2100, the concentration of carbon (C) is increased, thereby increasing variation in the concentration of donor. Therefore, the V/III of the group V raw material to the group III raw material adjusted to a range of 2100 to 4000 is preferably used.

[0073] Also, the range of the V/III is more preferably from 2500 to 3500, further more preferably, from 2500 to 3000. By using such V/III, the concentration of carbon (C) can be reduced, thereby decreasing variation in the concentration of donor.

[0074] (4)-2 The reason that the concentration of carbon (C) in the step (P126) of forming the P-type semiconductor layer 130 is set to be equal to or higher than 5.0×10^{16} cm^{-3} is described.

[0075] If the concentrations of carbon in the first and second N-type semiconductor layers 120 and 140 are equal to or lower than 1.0×10^{16} cm^{-3}, the P-type semiconductor 130 becomes a rate-limiting factor in an electron mobility of the semiconductor apparatus 10. Therefore, to improve an ON resistance and the like of the semiconductor apparatus, it is requested that a channel mobility between the P-type semiconductor layer 130 and the insulation layer 270, i.e., a sheet conductivity σ[S] is higher, for example, that the sheet conductivity σ[S] of the channel is 40 μS or higher. Herein, the sheet conductivity a is expressed by the following equation (1).

$$\sigma = \mu \cdot \in \cdot Em/2 \qquad (1)$$

[0076] μ: channel mobility [cm^2/Vs]

[0077] ∈: dielective constant of the insulation layer [F/cm]

[0078] Em: breakdown voltage [V/cm]

[0079] Because ∈ and Em are determined by material properties, for example, if substituting ∈=3×10^{-13} and Em=5× 10^6, the channel mobility μ has to be equal to or higher than 50 cm^2/Vs.

[0080] FIG. 8 is a graph explaining a relationship of the channel mobility μ and the concentration of carbon (C). A vertical axis represents the channel mobility μ and a horizontal axis represents the concentration of carbon (C) of the P-type semiconductor layer. In FIG. 8, it can be found that, as the concentration of carbon (C) in the P-type semiconductor layer 130 is increased, the electron mobility of the channel is increased. Here, it can be found that, when the channel mobility μ is set to be equal to or higher than 50 cm^2/Vs, the concentration of carbon (C) in the P-type semiconductor layer 130 set to be equal to or higher than 5.0×10^{16} cm^{-3} is preferable.

[0081] FIG. 9 is a graph explaining a relationship of the concentration of carbon (C) and the V/III. To set the concentration of carbon (C) to be equal to or higher than t than 5.0×10^{16} cm^{-3}, the following method can be employed in the step P126 of FIG. 2. Specifically, to obtain the graph in FIG. 9, the inventors used trimethylgallium (TMGa) as the group III raw material and also used ammonia (NH$_3$) as the group V raw material, and also used as a doping source magnesium (Mg) of 1.0×10^{18} cm^{-3} to 1.0×10^{20} cm^{-3}. Cases where the V/III was varied between 250 and 2500 and the pressure is set to 760 Torr and 200 Torr are investigated. A plurality of samples, in each of which a P-type semiconductor layer was formed, were manufactured and the concentrations of carbon (C) thereof were measured. The concentrations of carbon (C) were measured using a secondary ion-microprobe mass spectrometer (SIMS).

[0082] From FIG. 9, it was found that the concentration of carbon (C) of the P-typed semiconductor layer 130 is increased as the V/III is deceased. To set the concentration of carbon (C) to be equal to or higher than 5.0×10^{16} cm^{-3}, the V/III has to be within a range represented by oblique lines in FIG. 9, i.e., 500 or lower. In addition, the V/III has to be 1 or higher to achieve a vapor deposition.

[0083] Also, although the pressure supplying the source gases was investigated with respect to cases of 200 to 760 Torr, carbon (C) can be increased in a case of 200 Torr. Herein, the pressure is preferably a range of 300 to 500 Torr, particularly preferably, 400 to 450 Torr.

[0084] Such concentration of carbon (C) can be easily set by adjusting the V/III and pressures of supplying the sources gases.

[0085] The concentration of carbon (C) of the P-type semiconductor layer 130 is preferably equal to or more than 5.0× 10^{16} cm^{-3}, but if considering influences of electric properties, such as withstanding voltage, of the semiconductor apparatus 10, preferably 1×10^{18} cm^{-3} or lower. In addition, the concentration of carbon (C) of the P-type semiconductor layer 130 is preferably five or more times larger than the concentrations of carbon (C) of the first and second N-type semiconductor layers 120 and 140, thereby enhancing the electron mobility. Particularly preferably, the concentration of carbon (C) of the P-type semiconductor layer 130 is seven or more times.

B. OTHER EMBODIMENTS

[0086] The present invention is not limited to the foregoing embodiments, examples or variants thereof, but can be embodied in various configurations without departing from the scope and sprits of the invention. For example, technical features in the embodiments, examples, and variants thereof corresponding to technical features in each of the forms described in the section "Summary of the Invention" can be appropriately modified and combined to solve some or all of the technical problems as described above, or to achieve some or all of the effects as described above. In addition, the technical features can be appropriately omitted, unless it is mentioned herein that the technical features are essential.

[0087] FIG. 10 is a sectional view showing a semiconductor apparatus according to another embodiment. The present embodiment is an example applied to a Schottky barrier diode. A semiconductor apparatus 300 is constituted by arranging an N-type semiconductor layer 320 of a GaN substrate 310, connecting an ohmic electrode 330 to an outer surface of the substrate 310, and then connecting a Schottky electrode 340 to an outer surface of the N-type semiconductor layer 320. As such, various configurations, in which an N-type semiconductor layer is formed on a substrate, can be employed as a semiconductor apparatus, to which the present invention can be applied.

[0088] In addition to the semiconductor wafer on which a concentration of carbon (C) or donor in semiconductor layers is adjusted, the semiconductor apparatus according to the present invention includes various components, such as electrodes, as the peripheral components of the semiconductor wafer. For example, the present invention can be embodied in aspects, such as an electric device having a semiconductor apparatus of the foregoing type or an apparatus for manufacturing a semiconductor apparatus of the foregoing type.

What is claimed is:

1. A semiconductor apparatus comprising:
   a semiconductor substrate that has a diameter of 2 inches or larger; and
   an N-type semiconductor layer that is stacked on the semiconductor substrate using a material including gallium nitride (GaN),
   wherein a median of a plurality of measured values of the concentration of carbon (C) at a plurality of locations on a face of a region of the N-type semiconductor layer is equal to or lower than 1.0×10^{16} cm^{-3}, and
   the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

2. The semiconductor apparatus according to claim 1, wherein the N-type semiconductor layer contains silicon as a donor,
   a median of a plurality of measured values of the concentration of the donor at a plurality of locations on the face of the region of the N-type semiconductor layer is equal to or lower than 1.4×10^{16} cm^{-3}, and
   the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

3. The semiconductor apparatus according to claim 1, wherein electrodes are respectively connected to the substrate and the N-type semiconductor layer.

4. The semiconductor apparatus according to claim 1, further comprising:
   a P-type semiconductor layer that is stacked on the N-type semiconductor layer; and
   an additional N-type semiconductor layer that is stacked on the P-type semiconductor layer;
   wherein a drain electrode is connected to the substrate,
   a source electrode is connected the additional N-type semiconductor layer, and
   a gate electrode is connected to an insulation layer on the P-type semiconductor layer.

5. A method of manufacturing the semiconductor apparatus according to claim 1, comprising:
   forming the N-type semiconductor layer by crystal growth using a group III raw material including trimethylgallium (TMGa) and a group V raw material including ammonia (NH$_3$), and
   wherein V/III, a mole ratio of the group V raw material to the group III raw material, is a range of 2100 to 4000.

6. A method of manufacturing a semiconductor apparatus having an N-type semiconductor layer stacked on a semiconductor substrate using a material including gallium nitride (GaN) comprising:
   a first step of arranging a plurality of the substrates in a region of more than 2 inches in diameter; and
   a second step of forming the N-type semiconductor layer by crystal growth, using a group III raw material including trimethylgallium (TMGa) and a group V raw material including ammonia (NH$_3$),
   wherein, the second step is adjusted so that a V/III, a mole ratio of the group V raw material to the group III raw material, is within a range of 2100 to 4000, and also so that a median of a plurality of measured values of the concentration of carbon (C) at a plurality of locations on a face of a region of the N-type semiconductor layer is equal to or lower than 1.0×10^{16} cm^{-3} and the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

7. The method according to claim 6, wherein, the second step is adjusted so that silicon (Si) is contained as a donor, and also so that a median of a plurality of measured values of the concentration of the donor at a plurality of locations on the face of the region of the N-type semiconductor layer is equal to or lower than 1.4×10^{16} cm^{-3}, and the maximum value in difference between the median and the other measured values is lower than 5×10^{15} cm^{-3}.

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