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(45) **Date of Patent:** Aug. 12, 2025

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## OTHER PUBLICATIONS

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Search Report by Registered Search Organization issued Mar. 28, 2025 in corresponding Japanese patent application No. 2021-114156 (33 pages; with English machine translation).

\* cited by examiner

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(57) **ABSTRACT**

The present disclosure provides a nitride semiconductor device. The nitride semiconductor device includes: an electron transport layer, made of a nitride semiconductor; an electron supply layer, disposed on the electron transport layer and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer; a first protective layer, disposed on the electron supply layer and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer; a second protective layer, disposed on a portion of the first protective layer and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer; and a gate layer, disposed on the second protective layer.

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## ABSTRACT

The present disclosure provides a nitride semiconductor device. The nitride semiconductor device includes: an electron transport layer, made of a nitride semiconductor; an electron supply layer, disposed on the electron transport layer and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer; a first protective layer, disposed on the electron supply layer and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer; a second protective layer, disposed on a portion of the first protective layer and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer; and a gate layer, disposed on the second protective layer.

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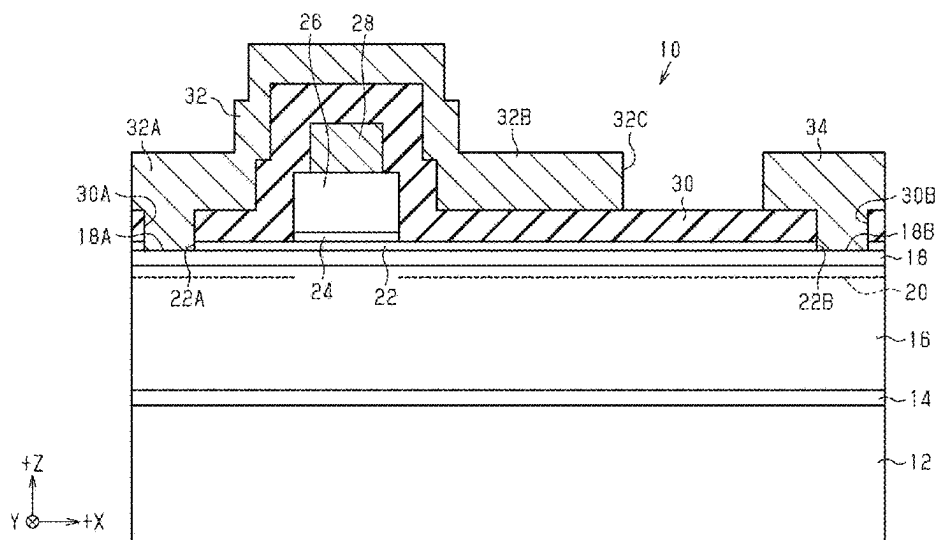
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**16 Claims, 13 Drawing Sheets**



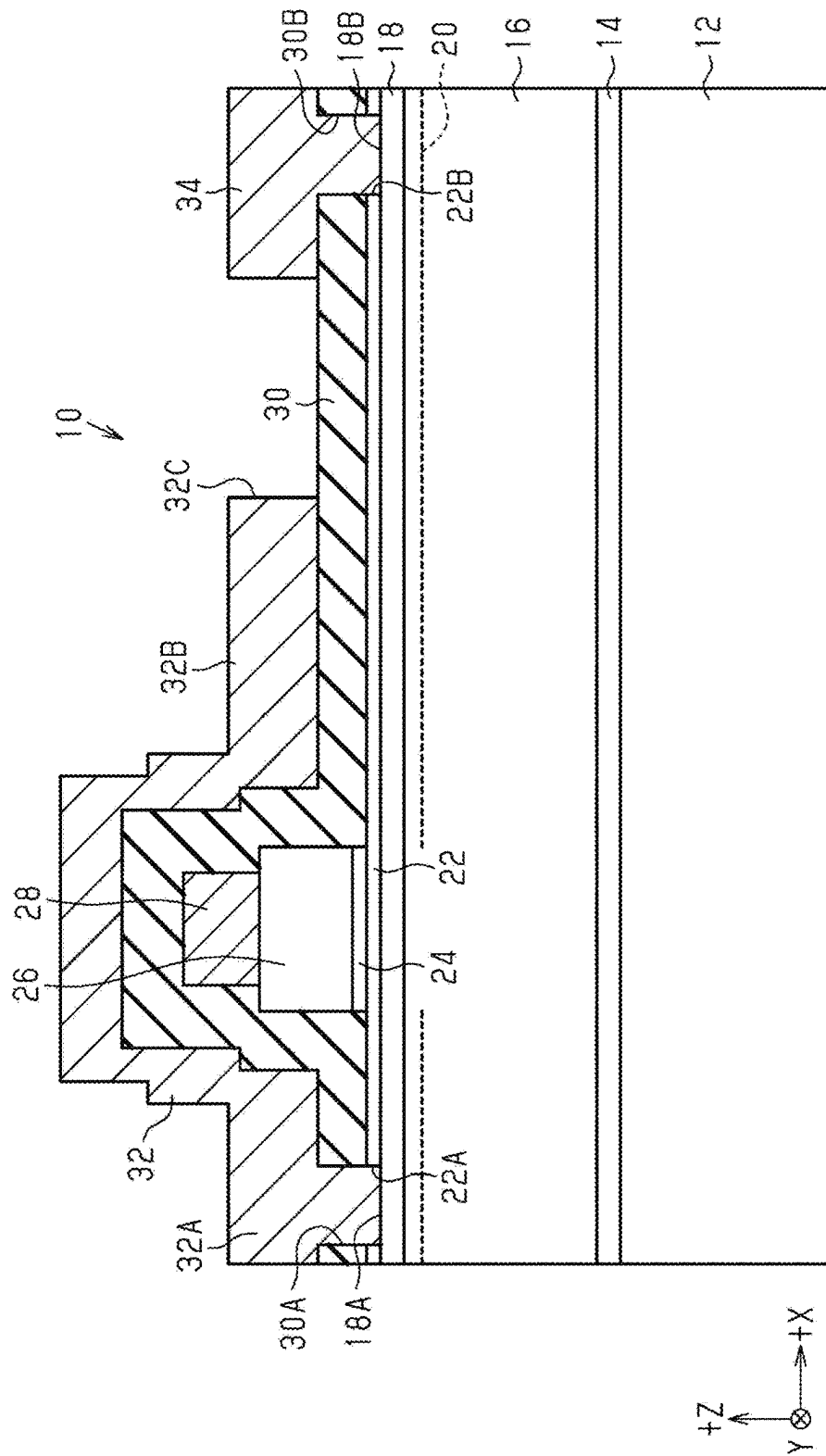


FIG. 1

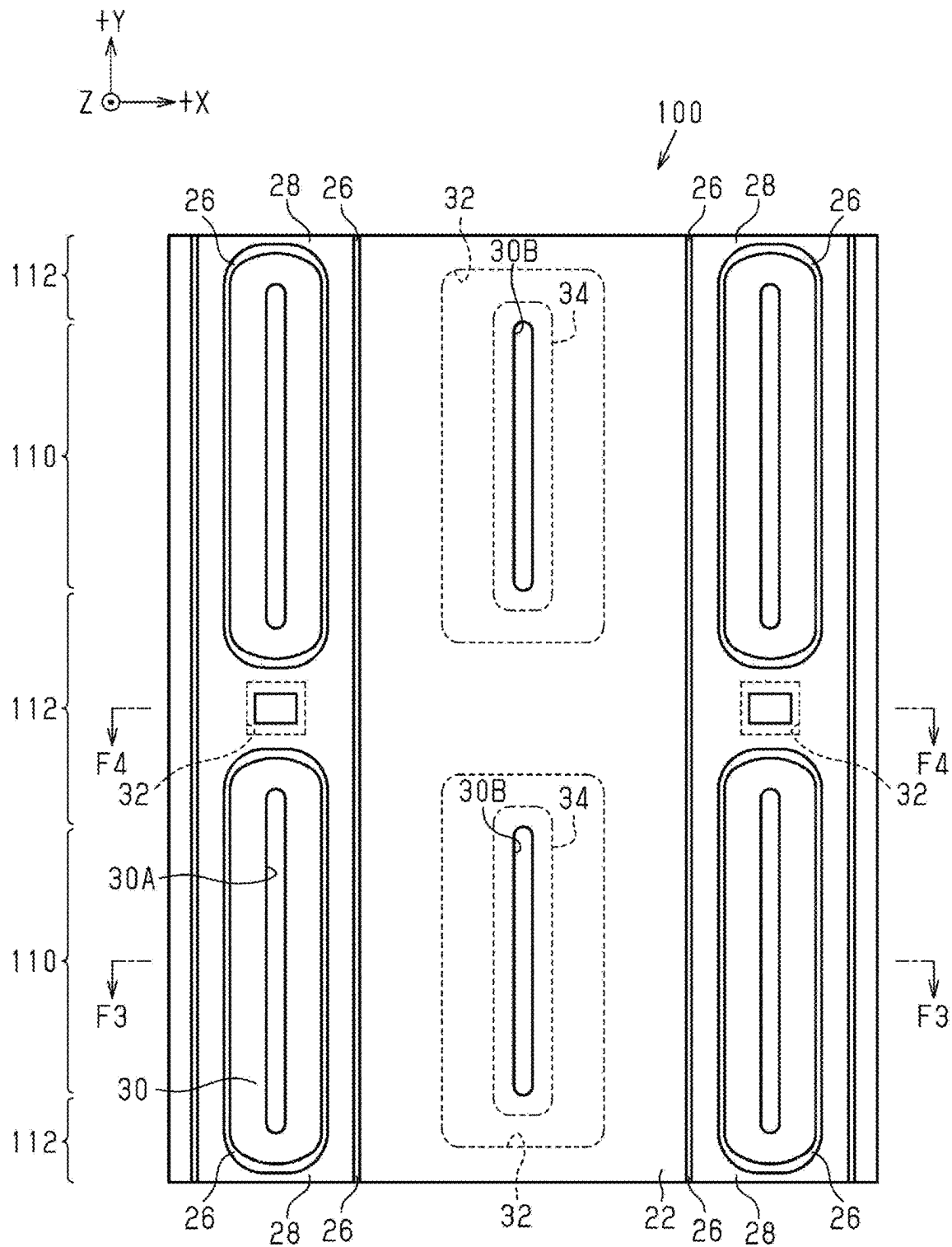


FIG. 2

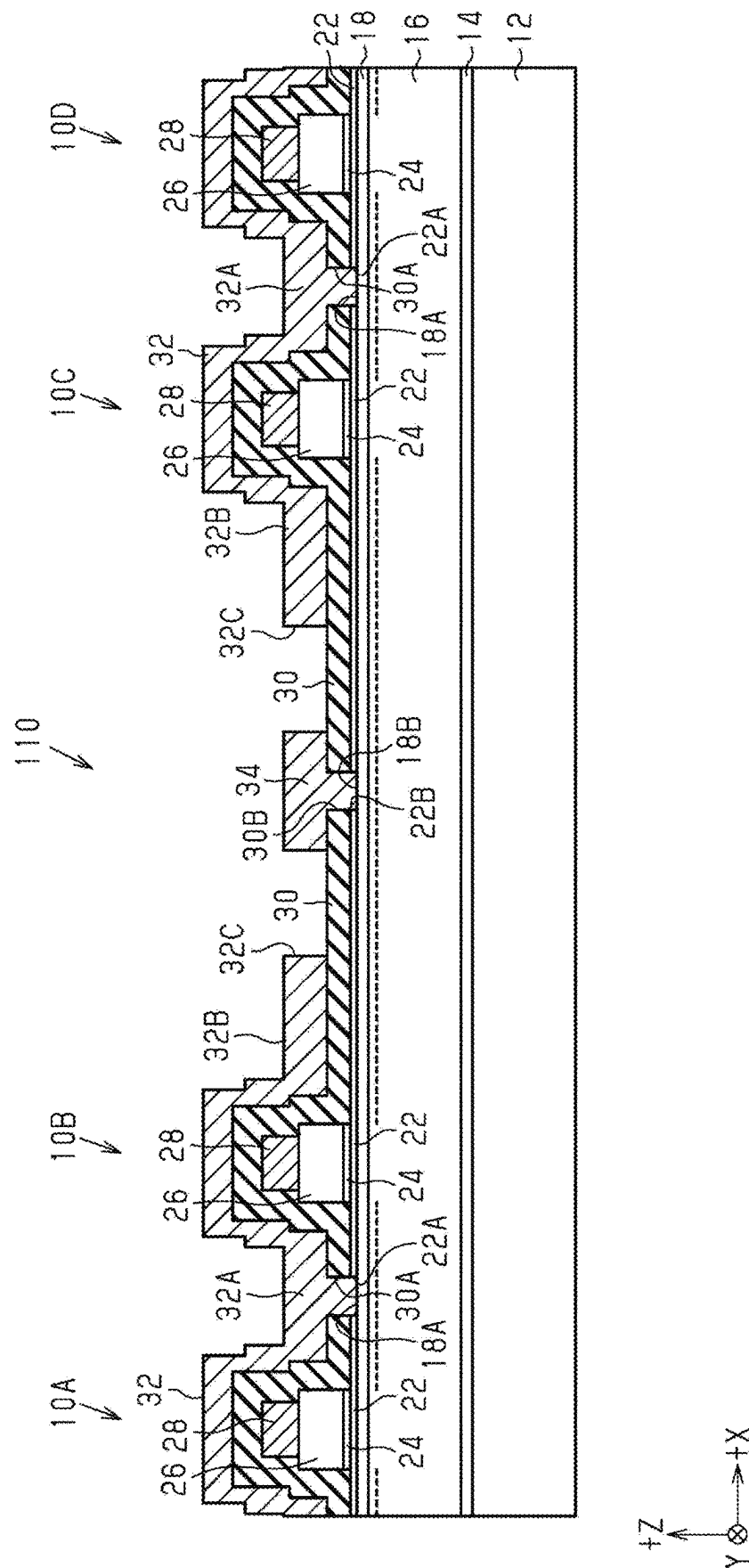


FIG. 3

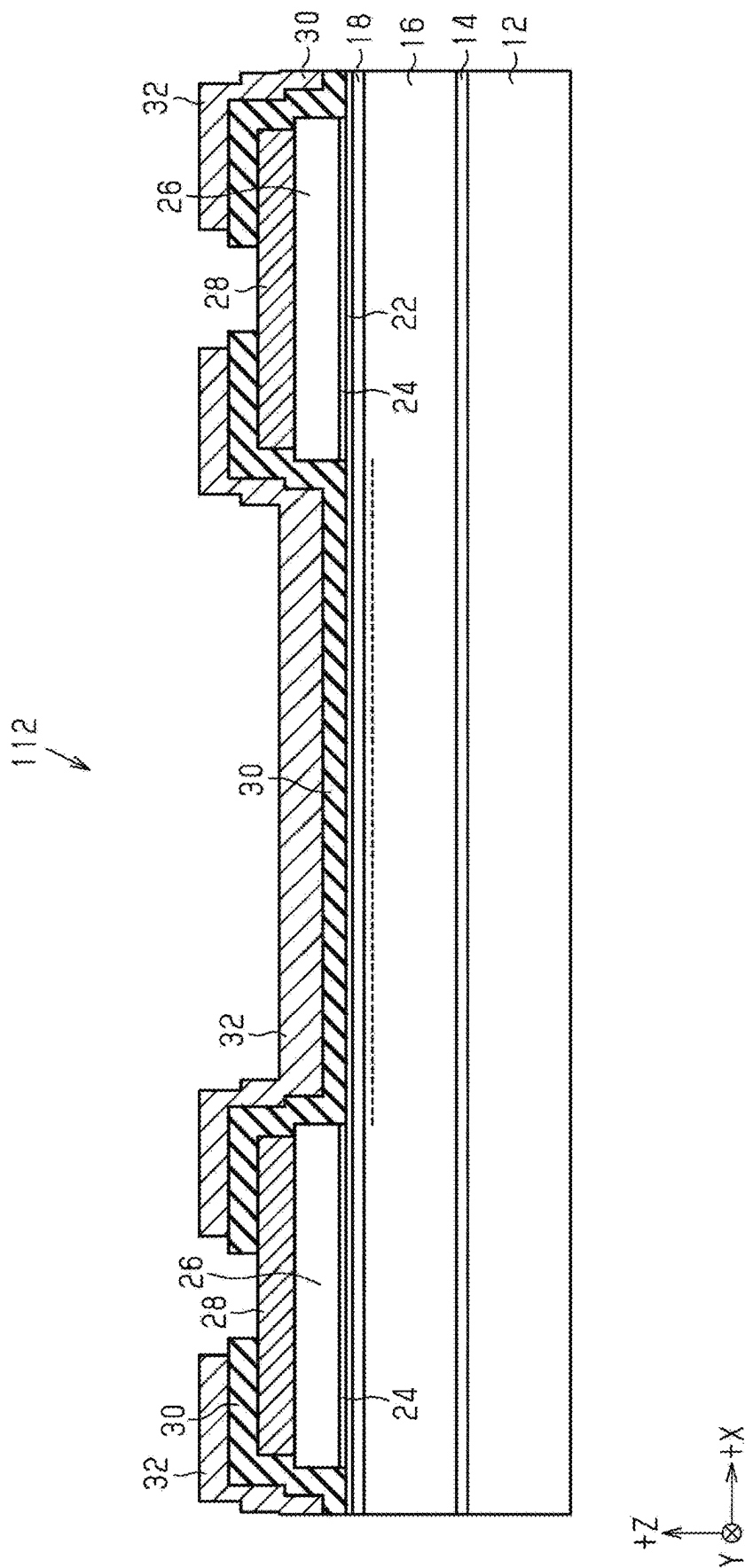


FIG. 4

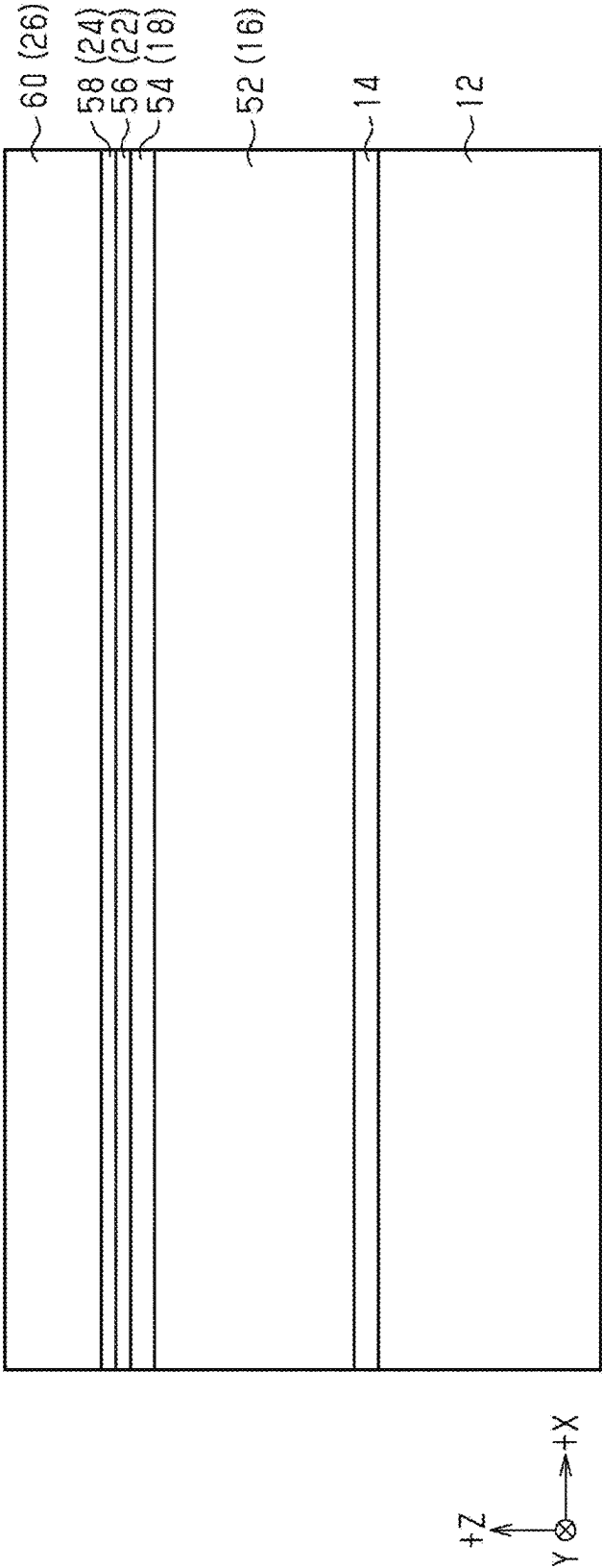


FIG. 5

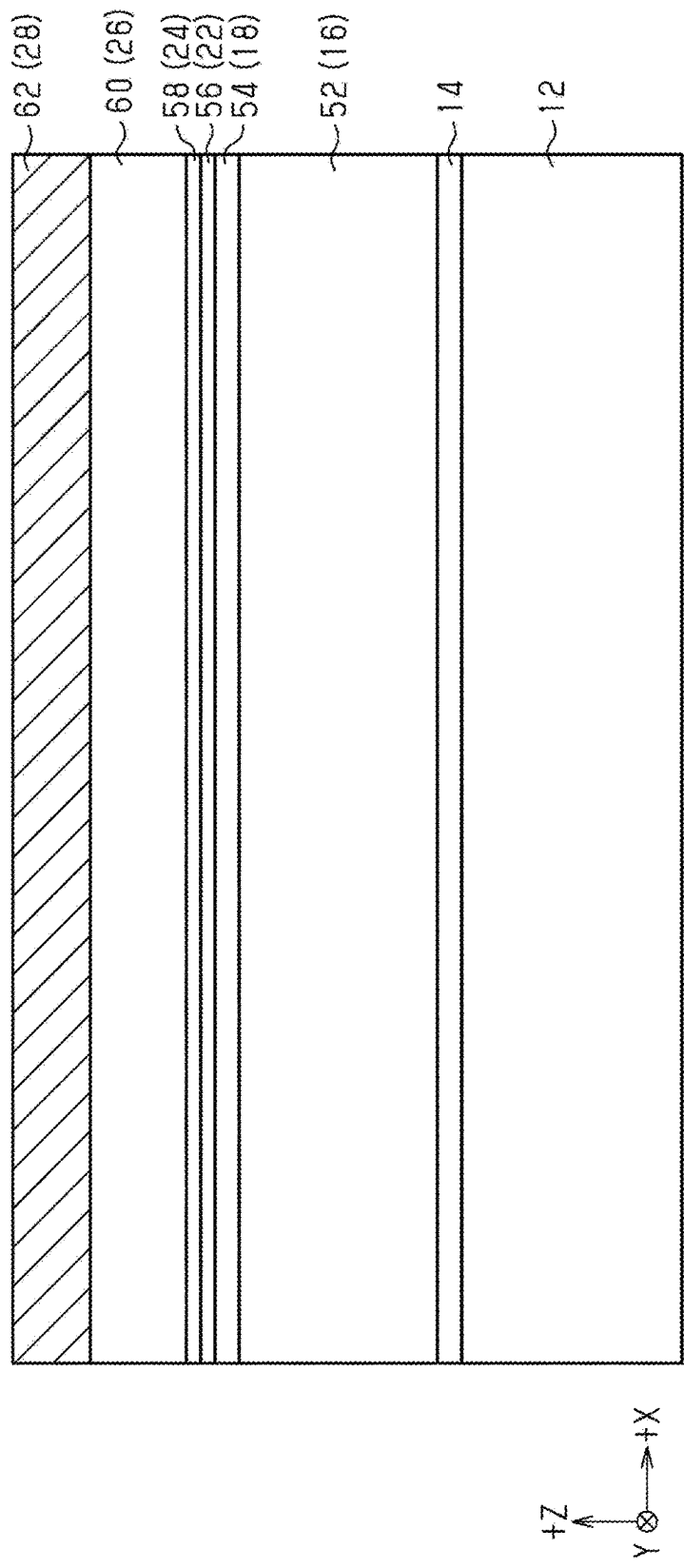


FIG. 6

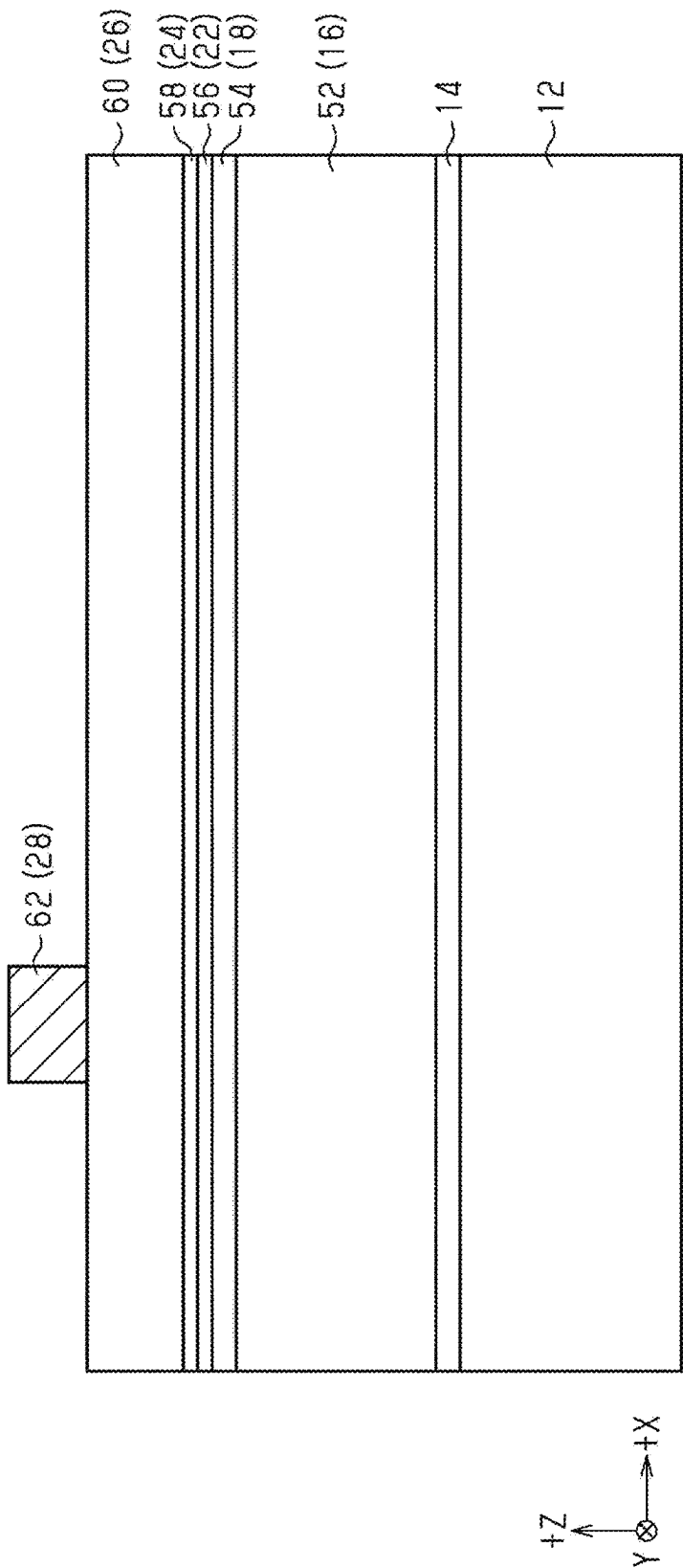


FIG. 7



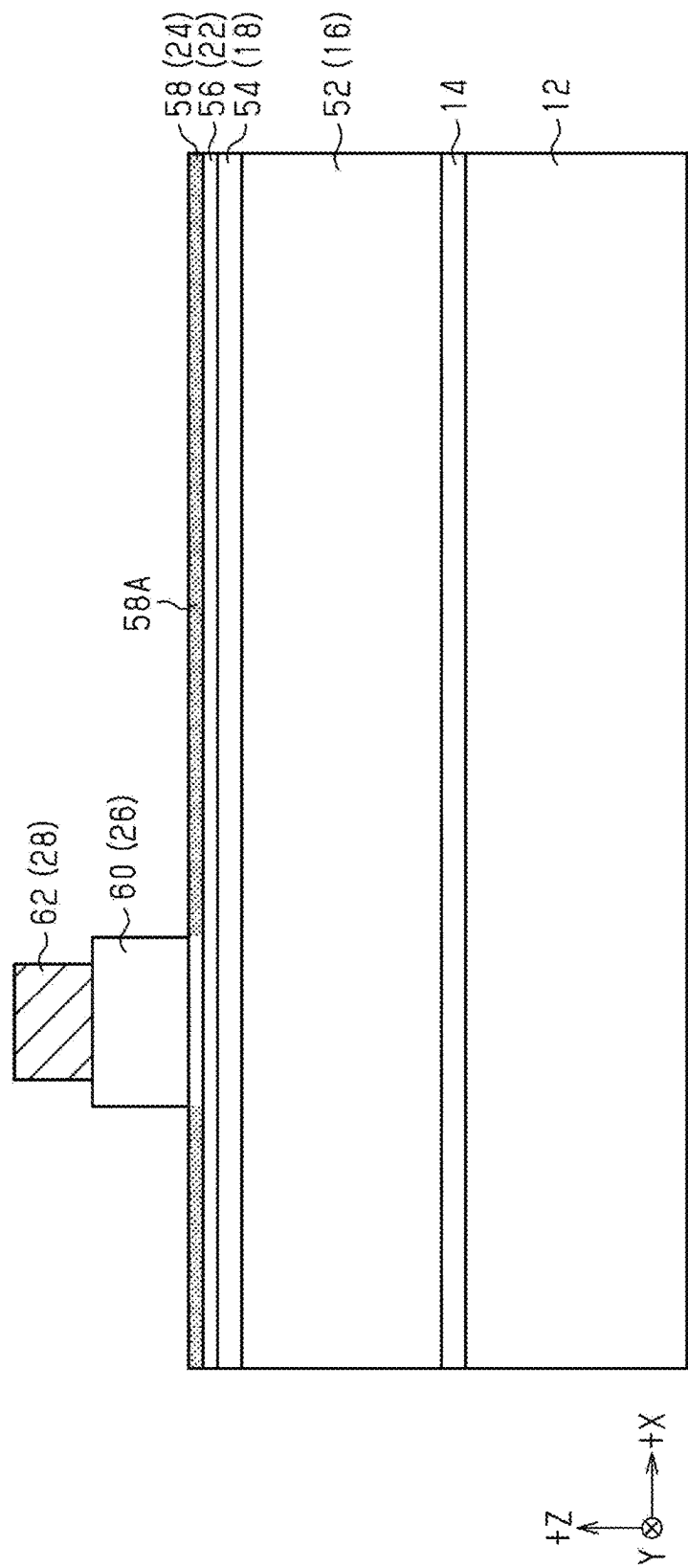


FIG. 8

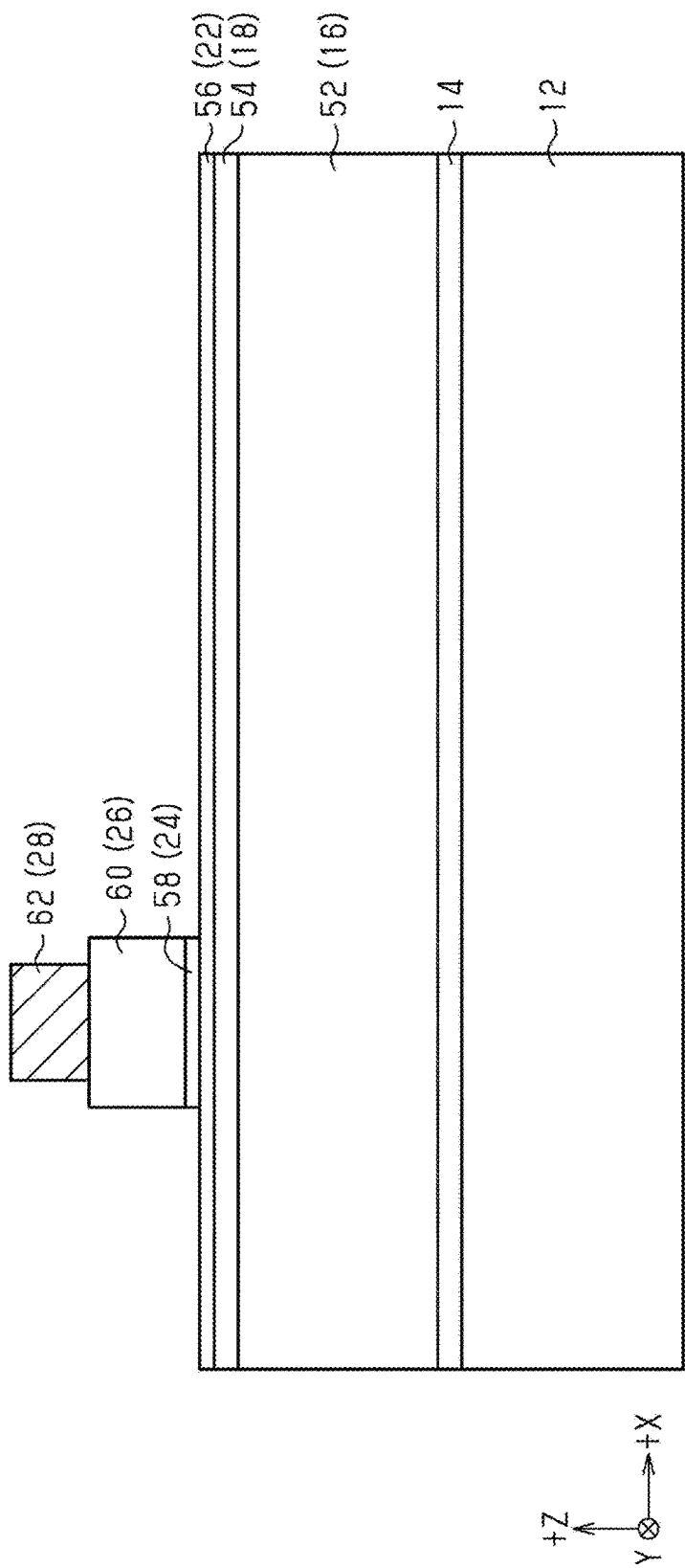


FIG. 9

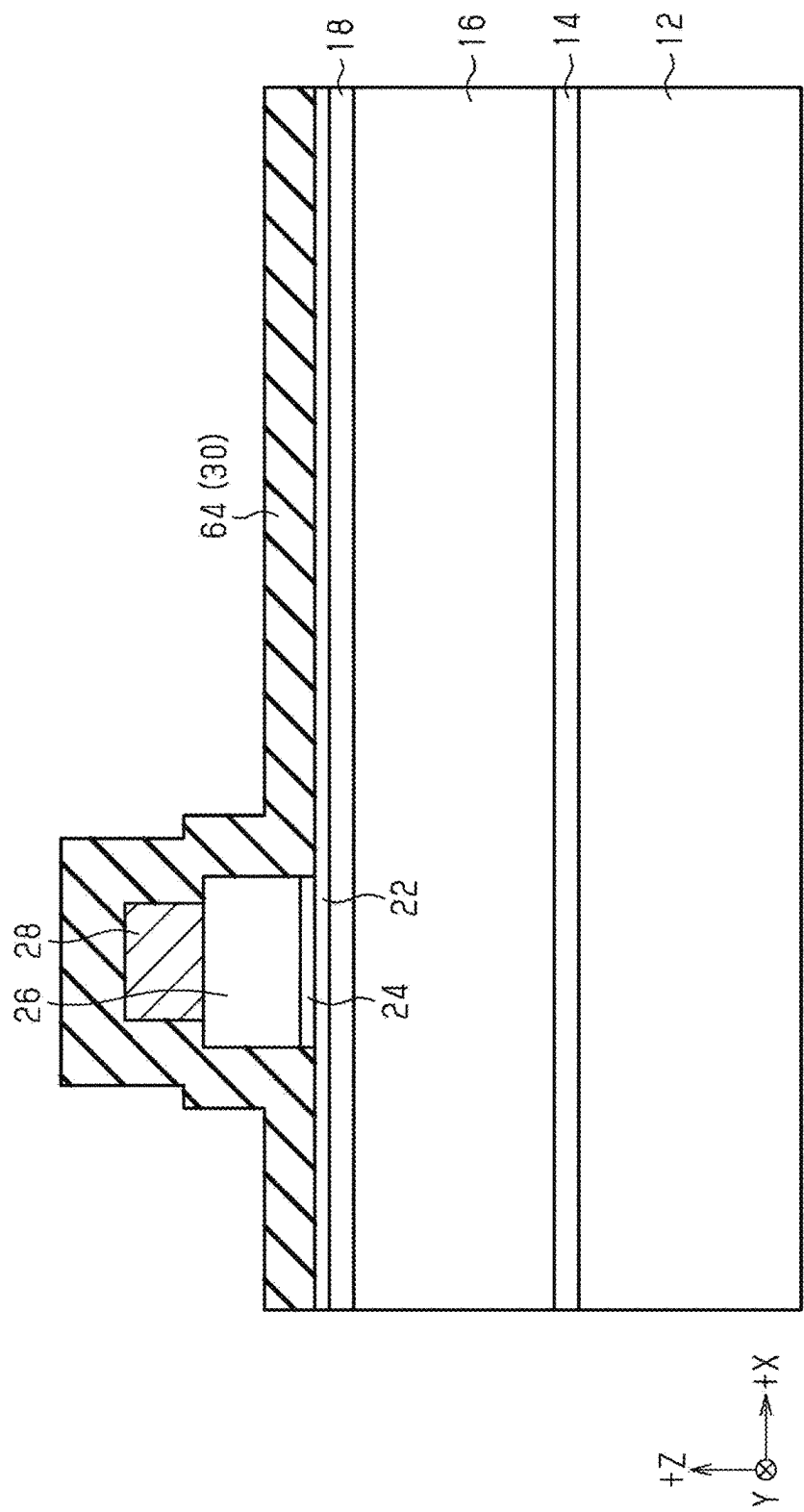


FIG. 10

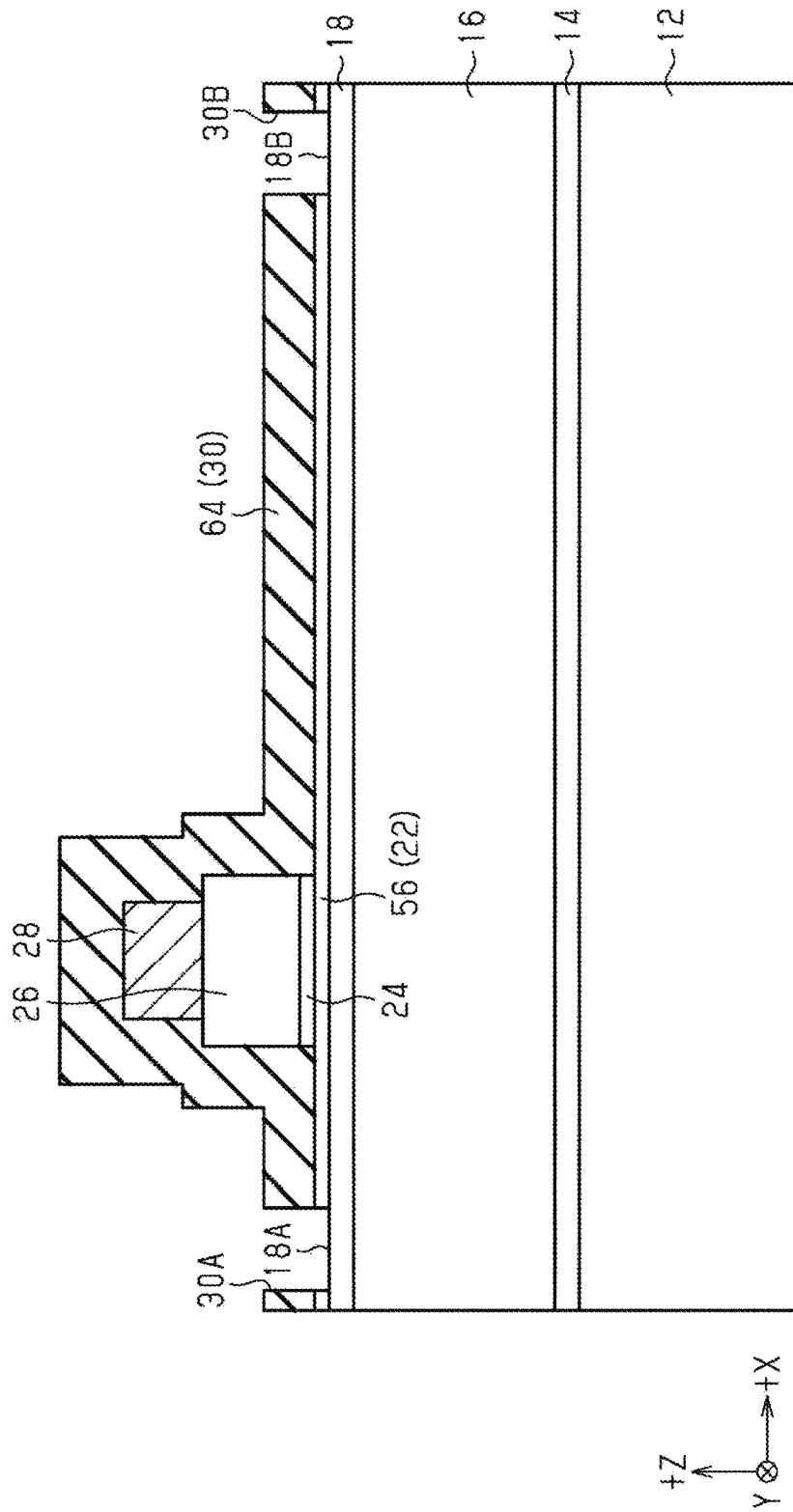


FIG. 11

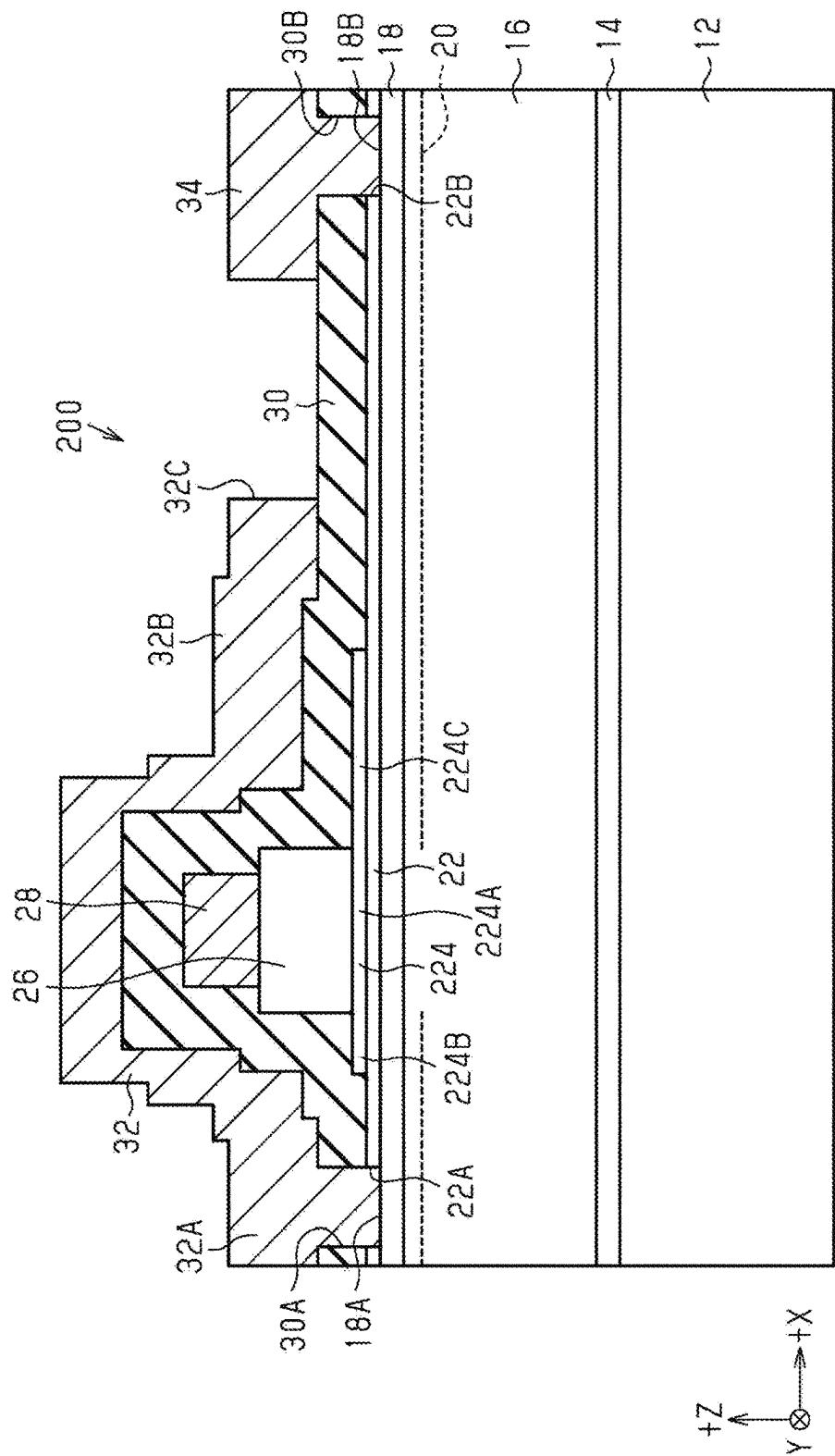


FIG. 12

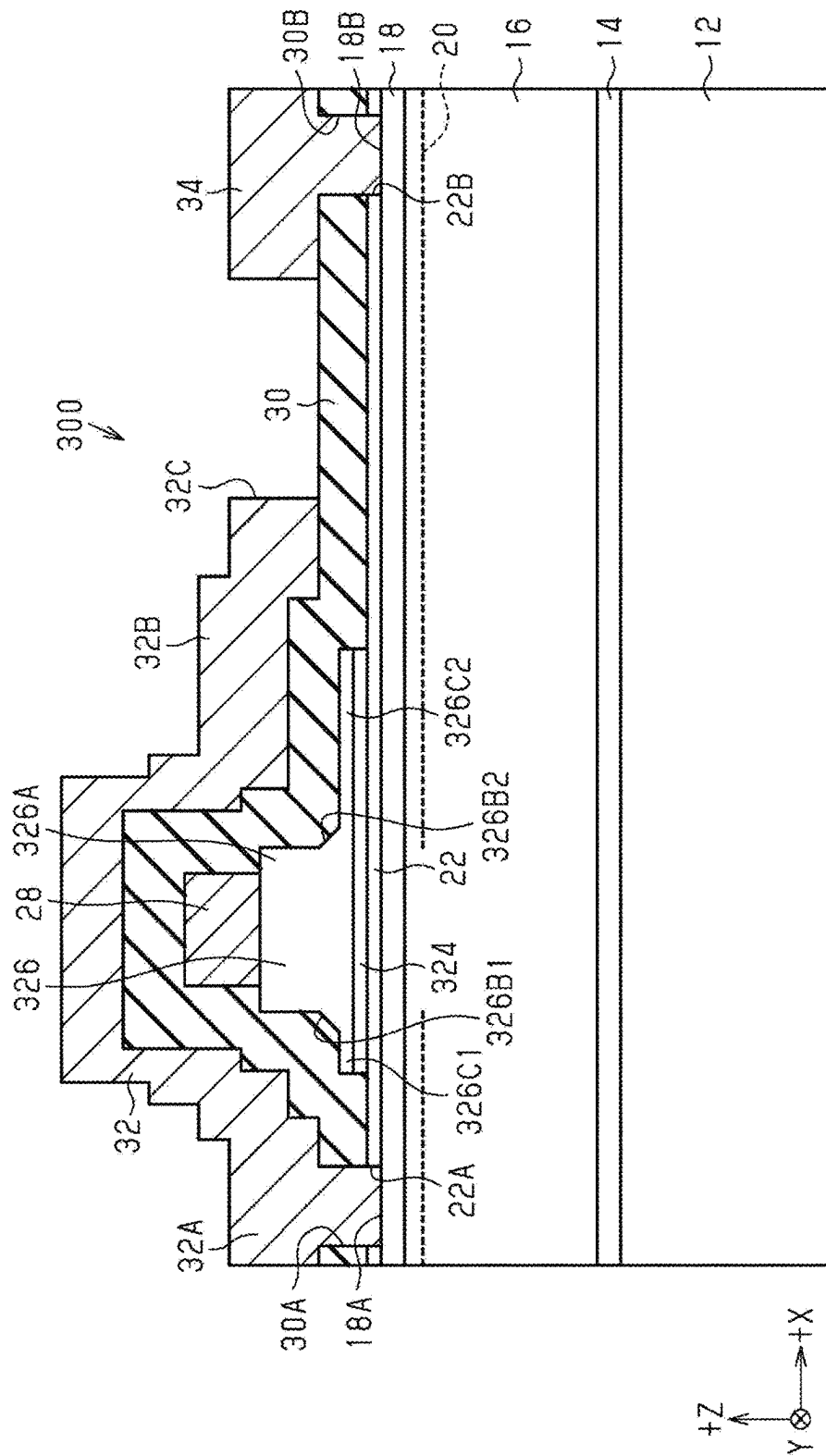


FIG. 13

1

**NITRIDE SEMICONDUCTOR DEVICE****CROSS-REFERENCE TO RELATED APPLICATION**

The present application is based upon and claims the benefit of priority to Japanese Patent Application No. 2021-114156, filed on Jul. 9, 2021, the entire contents of which are herein incorporated by reference.

**TECHNICAL FIELD**

The present disclosure relates to a nitride semiconductor device.

**BACKGROUND**

Current products using high-electron-mobility transistors (HEMTs) of a nitride semiconductor are constantly evolving. When an HEMT is applied to a power device, based on the concern of fail safe, the implementation of a normally closed operation that cuts off a current path (channel) between the source and the drain at zero bias is required.

Patent publication 1 discloses a normally closed nitride semiconductor HEMT. The HEMT described in patent document 1 includes an electron transport layer made of a gallium nitride (GaN) layer, and an electron supply layer made of an aluminum gallium nitride (AlGaN) layer. The channel of the HEMT is formed by a two-dimensional electron gas (2DEG) generated in the electron transport layer near a heterojunction interface between the electron transport layer and the electron supply layer. The HEMT described in patent document 1 implements the normally closed operation by providing a GaN layer (p-type GaN layer) containing an acceptor-type impurity under a gate electrode and cutting off the channel formed by the 2DEG.

**PRIOR ART DOCUMENT****Patent Publication**

[Patent document 1] Japan Patent Publication No. 2017-73506

**SUMMARY OF THE PRESENT DISCLOSURE****Problems to be Solved by the Present Disclosure**

It is one task of a nitride semiconductor HEMT to inhibit current collapse. The so-called current collapse refers to the situation below. That is, when a high voltage is applied to a drain electrode (between a source and a drain) when the HEMT is turned off, electrons are trapped by crystal defects or surface energy levels of the nitride semiconductor layer, such that the generation of the 2DEG is hindered in the subsequent on state, causing a reduced drain current (an increased on resistance). The occurrence of current collapse degrades the reliability of the nitride semiconductor HEMT.

**Technical Means for Solving the Problem**

According to an embodiment of the disclosure, a nitride semiconductor device includes: an electron transport layer, made of a nitride semiconductor; an electron supply layer, disposed on the electron transport layer and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer; a

2

first protective layer, disposed on the electron supply layer and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer; a second protective layer, disposed on a portion of the first protective layer and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer; a gate layer, disposed on the second protective layer, made of a nitride semiconductor that has a band gap less than the band gap of the nitride semiconductor of the second protective layer, and containing an acceptor-type impurity; a gate electrode, disposed on the gate layer; and a source electrode and a drain electrode, connected with the electron supply layer.

**Effects of the Present Disclosure**

The nitride semiconductor device according to the present disclosure is capable of inhibiting current collapse.

**BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a brief section diagram of an exemplary nitride semiconductor device according to a first embodiment.

FIG. 2 is a brief top plan view of an exemplary pattern formed in the nitride semiconductor device in FIG. 1.

FIG. 3 is a brief section diagram of an active area along the line F3-F3 in FIG. 2.

FIG. 4 is a brief section diagram of a non-active area along the line F4-F4 in FIG. 2.

FIG. 5 is a brief section diagram of an exemplary manufacturing step for the nitride semiconductor device in FIG. 1.

FIG. 6 is a brief section diagram of a manufacturing step following that in FIG. 5.

FIG. 7 is a brief section diagram of a manufacturing step following that in FIG. 6.

FIG. 8 is a brief section diagram of a manufacturing step following that in FIG. 7.

FIG. 9 is a brief section diagram of a manufacturing step following that in FIG. 8.

FIG. 10 is a brief section diagram of a manufacturing step following that in FIG. 9.

FIG. 11 is a brief section diagram of a manufacturing step following that in FIG. 10.

FIG. 12 is a brief section diagram of an exemplary nitride semiconductor device according to a second embodiment.

FIG. 13 is a brief section diagram of an exemplary nitride semiconductor device according to a third embodiment.

**DETAILED DESCRIPTION OF THE EMBODIMENTS**

Details of several embodiments of a nitride semiconductor device of the present disclosure are given with the accompanying drawings below. The constituting elements shown in the drawings may be partially enlarged in some cases to achieve the object of easy understanding and clarity, and are not necessarily depicted according to actual scales. Moreover, for better understanding, shading lines may be omitted from the section diagrams. It should be noted that the drawings are for illustrating examples of the embodiments of the present disclosure, and are not to be construed as limitations to the present disclosure.

The description below includes details for substantively implementing a device, a system and a method of the embodiments of the present disclosure. The detailed descrip-

tion is intended for illustration purposes and is not to be construed as limitations to the embodiments of the present disclosure or applications and uses of these embodiments.

#### First Embodiment

FIG. 1 shows a brief section diagram of an exemplary nitride semiconductor device 10 according to a first embodiment. The nitride semiconductor device 10 is implemented by a nitride semiconductor HEMT. For example, the nitride semiconductor device can be implemented by a gallium nitride (GaN) HEMT.

In the first embodiment, the nitride semiconductor device 10 includes a substrate 12, a buffer layer 14 disposed on the substrate 12, an electron transport layer 16 disposed on the buffer layer 14, and an electron supply layer 18 disposed on the electron transport layer 16.

Moreover, unless otherwise specified, the term “top plan view” used in the present disclosure refers that the nitride semiconductor device 10 is observed in a Z direction where X, Y and Z axes (for example, refer to FIG. 1) are orthogonal to one another. In the present disclosure, the Z direction is a direction orthogonal to a face of the substrate 12 on which the electron transport layer 16 is disposed (interposed by the buffer layer 14 in the first embodiment). For better understanding of the description below, the +Z direction is sometimes referred to as up, the -Z direction is sometimes referred to as down, the +X direction is sometimes referred to as right, and the -X direction is referred to as left.

The substrate 12 can be, for example, made of silicon (Si), silicon carbide (SiC), GaN, sapphire, or other substrate materials. The thickness of the substrate 12 is set to, for example, 200  $\mu\text{m}$  or more and 1500  $\mu\text{m}$  or less.

The buffer layer 14 can be made of any material that can alleviate lattice mismatch between the substrate 12 and the electron transport layer 16. For example, the buffer layer 14 can include one or more nitride semiconductor layers. For example, the buffer layer 14 can include at least one of an aluminum nitride (AlN) layer, aluminum gallium nitride (AlGa<sub>N</sub>) layer, and a graded AlGa<sub>N</sub> layer with different aluminum (Al) compositions. For example, the buffer layer 14 can be formed by one single AlN layer, one single AlGa<sub>N</sub> layer, a layer having an AlGa<sub>N</sub>/GaN superlattice structure, a layer having an AlN/AlGa<sub>N</sub> superlattice structure, or a layer having an AlN/GaN superlattice structure.

In one embodiment, the buffer layer 14 can also be a multi-layer buffer layer including a first buffer layer and a second buffer layer, wherein the first buffer layer is an AlN layer disposed on the substrate 12, and the second buffer layer is a graded AlGa<sub>N</sub> layer disposed on the AlN layer. In this case, the thickness of the first buffer layer is set to, for example, 80 nm or more and 500 nm or less. The second buffer layer can include, for example, three AlGa<sub>N</sub> layers sequentially having Al compositions of 75%, 50% and 25%, starting from one side close to the first buffer layer. The thickness of the second buffer layer (the total thickness of the three AlGa<sub>N</sub> layers) can be set to, for example, 300 nm or more and 1  $\mu\text{m}$  or less. The number of the graded AlGa<sub>N</sub> layers is not limited to three, and can be set to any other appropriate number of layers. Regarding the graded AlGa<sub>N</sub> layers, the thicknesses of the AlGa<sub>N</sub> layers can be the same or different. Moreover, to suppress a leakage current in the buffer layer 14, an impurity can be introduced to a part of the buffer layer 14 such that a region other than a surface-layer region of the buffer layer 14 is semi-insulative. In this case, the impurity is, for example, carbon (C) or iron (Fe), and can have a concentration set to  $4 \times 10^{16} \text{ cm}^{-3}$  or more.

The electron transport layer 16 is made of a nitride semiconductor, and is, for example, a GaN layer. The thickness of the electron transport layer 16 is set to, for example, 0.5  $\mu\text{m}$  or more and 2  $\mu\text{m}$  or less. Moreover, to suppress a leakage current in the electron transport layer 16, an impurity can be introduced to a part of the electron transport layer 16 such that a region other than a surface-layer region of the electron transport layer 16 is semi-insulative. In this case, the impurity is, for example, C, and can have a concentration set to  $4 \times 10^{16} \text{ cm}^{-3}$  or more.

The electron supply layer 18 is made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer 16, and is, for example, an AlGa<sub>N</sub> layer. The band gap gets larger as the Al composition increases, and so the electron supply layer 18 implemented by an AlGa<sub>N</sub> layer has a band gap greater than the band gap of the nitride semiconductor of the electron transport layer 16 implemented by a GaN layer. For example, the electron supply layer 18 is made of Al<sub>x</sub>Ga<sub>1-x</sub>N, where x is, for example,  $0 < x < 0.4$ , and preferably  $0.1 < x < 0.3$ . The thickness of the electron support layer 18 can be set to, for example, 5 nm or more and 20 nm or less.

The electron transport layer 16 and the electron supply layer 18 are made of nitride semiconductors having different lattice constants from each other. Thus, a combination of the nitride semiconductor (for example, GaN) forming the electron transport layer 16 and the nitride semiconductor (for example, AlGa<sub>N</sub>) forming the electron supply layer 18 contains lattice mismatch. Due to spontaneous polarization of the electron transport layer 16 and the electron supply layer 18 and piezoelectric polarization caused by stress upon a heterojunction of the electron supply layer 18, a conduction band energy level of the electron transport layer 16 near a heterojunction interface between the electron transport layer 16 and the electron supply layer 18 is lower than a Fermi level. Thus, at a position near the heterojunction interface between the electron transport layer 16 and the electron supply layer 18 (for example, a position distanced from the interface by approximately several nm), a two-dimensional electron gas (2DEG) 20 is diffused in the electron transport layer 16.

The nitride semiconductor device 10 includes a first protective layer 22 disposed on the electron supply layer 18, a second protective layer 24 disposed on a portion of the first protective layer 22, a gate layer 26 disposed on the second protective layer 24, and gate electrode 28 disposed on the gate layer 26.

The nitride semiconductor device 10 further includes a passivation layer 30, a source electrode 32 and a drain electrode 34. The passivation layer 30 is disposed on the first protective layer 22, and covers the second protective layer 24, the gate layer 26 and the gate electrode 28. The source electrode 32 and the drain electrode 34 pass through the passivation layer 30 and are connected with the electron supply layer 18.

The passivation layer 30 includes a source-side through hole 30A and a drain-side through hole 30B. The first protective layer 22 includes a source-side opening 22A and a drain-side opening 22B. The source-side opening 22A communicates with the source-side through hole 30A, and exposes a portion of the electron supply layer 18 as a source contact 18A. The drain-side opening 22B communicates with the drain-side through hole 30B, and exposes a portion of the electron supply layer 18 as a drain contact 18B. The source electrode 32 is in ohmic contact with the source contact 18A via the source-side through hole 30A and the source-side opening 22A. The drain electrode 34 is in ohmic



5

contact with the drain contact 18B via the drain-side through hole 30B and the drain-side opening 22B. Moreover, the source electrode 32 is electrically connected to the substrate 12, with such related drawing omitted.

The first protective layer 22 is provided to protect the electron supply layer 18. Moreover, the shape of the first protective layer 22 after the nitride semiconductor device 10 is manufactured is shown in FIG. 1. During the manufacturing process of the nitride semiconductor device 10, that is, when used as a protective layer for the electron supply layer 18, the first protective layer 22 has a shape different from that in FIG. 1.

The first protective layer 22 is made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer 18. For example, when the electron supply layer 18 is an AlGaIn layer, the first protective layer 22 can be a GaN layer. The first protective layer 22 is disposed almost on the entire electron supply layer 18. For example, the first protective layer 22 is disposed on an upper surface of the electron supply layer 18 excluding the source contact 18A and the drain contact 18B.

Moreover, in the example shown in FIG. 1, the first protective layer 22 is in contact with the source electrode 32 and the drain electrode 34, but can also be spaced from the source electrode 32 and the drain electrode 34. In other words, the first protective layer 22 can also be not in contact with the source electrode 32 and the drain electrode 34.

Further, the thickness of the first protective layer 22 is set to be less than the thickness of the gate layer 26. That is to say, the first protective layer 22 is thinner than the gate layer 26. Thus, a good normally closed operation can be maintained. The thickness of the gate layer 26 can be set to 100 nm or more and 140 nm or less, for example, 110 nm. The thickness of the first protective layer 22 can be set to 5 nm or more and 20 nm or less, for example, 15 nm or less.

The thickness of the first protective layer 22 is set in the consideration of the thickness of the electron supply layer 18, so as to prevent hindering of forming of the 2DEG 20 in the electron transport layer 16. That is to say, the thickness of the first protective layer 22 is set corresponding to the thickness of the electron supply layer 18 such that the concentration of the 2DEG 20 is maintained. For example, the thickness of the first protective layer 22 is set to be less than the thickness of the electron supply layer 18. The concentration of the 2DEG 20 can also be controlled by adjusting the Al composition of the electron supply layer 18.

The first protective layer 22 can also provide a function of hole diffusion. For example, if a larger positive bias is applied to the gate electrode 28, holes are injected from the gate electrode 28 into the gate layer 26. In this case, the holes are diffused in the first protective layer 22, accordingly reducing the density of holes at a junction interface between the first protective layer 22 and the electron supply layer 18. In other words, the first protective layer 22 inhibits partial hole accumulation that can possibly occur at the junction interface between the gate layer 26 and the electron supply layer 18 when the two are directly joined. Thus, band bending of the electron supply layer 18 implemented by an AlGaIn layer as well as a gate leakage current accordingly generated can be suppressed, so as to increase a gate withstand voltage.

The first protective layer 22 can also contain, for example, at least one of magnesium (Mg) and zinc (Zn) as an acceptor-type impurity, as desired. For example, the first protective layer 22 can also be a p-type GaN layer. In the case where the first protective layer 22 contains an acceptor-

6

type impurity, when a voltage in zero bias is not applied to the gate electrode 28, in a region directly below the gate electrode 28, the 2DEG 20 in the electron transport layer 16 can be eliminated, thereby enhancing the reliability of the normally closed operation.

The second protective layer 24 is provided to protect the electron supply layer 18 and the first protective layer 22. FIG. 1 shows the shape of the second protective layer 24 after the nitride semiconductor device 10 is manufactured. During the manufacturing process of the nitride semiconductor device 10, that is, when used as a protective layer for the electron supply layer 18 and the first protective layer 22, the second protective layer 24 has a shape different from that in FIG. 1.

The second protective layer 24 is made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer 22. For example, when the first protective layer 22 is a GaN layer, the second protective layer 24 can be an AlGaIn layer. In this case, the Al composition of the second protective layer 24 (an AlGaIn layer) is set to be less than the Al composition of the electron supply layer 18 (an AlGaIn layer). That is to say, the Al compositions of the electron supply layer 18 and the second protective layer 24 are set such that the second protective layer 24 has a band gap less than the band gap of the electron supply layer 18.

In one example, the electron supply layer 18 is formed by  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  (for example,  $0 < x < 0.4$ , preferably  $0.1 < x < 0.3$ ), and the second protective layer 24 is formed by  $\text{Al}_y\text{Ga}_{1-y}\text{N}$  (for example,  $0 < y < x$ , preferably  $0.05 < y < x$ ). Moreover, the Al composition of the second protective layer 24 (an AlGaIn layer) can also be determined by considering, for example, an etching selectivity ratio (an etching selectivity ratio of a layer forming the gate layer 26 relative to forming the second protective layer 26) when the gate layer 26 is formed by etching.

In a region directly below the gate layer 26, the second protective layer 24 is disposed on the first protective layer 22. In the first embodiment, an area of the second protective layer 24 is same as an area of a bottom surface of the gate layer 26 in a top plan view. Thus, the second protective layer 24 has a same width as the width of the gate layer 26. Moreover, unless otherwise specified, the term "width" used in the present disclosure is defined as a length along the X axis in FIG. 1.

The thickness of the second protective layer 24 is set to be less than the thickness of the electron supply layer 18. That is to say, the second protective layer 24 is thinner than the electron supply layer 18. For example, the thickness of the second protective layer 24 can be set to 2 nm or more. In addition, when the thickness of the electron supply layer 18 is, for example, 20 nm or less, and the thickness of the second protective layer 24 can be set to, for example, 10 nm or less. Alternatively, when the thickness of the electron supply layer 18 is, for example, 15 nm or less, and the thickness of the second protective layer 24 can be set to, for example, 7 nm or less. As such, the thickness of the second protective layer 24 is set to be  $\frac{1}{2}$  or less of the thickness of the electron supply layer 18.

Moreover, the relation between the thickness of the first protective layer 22 and the thickness of the second protective layer 24 is not specifically defined; for example, the second protective layer 24 can also have a same thickness as the thickness of the first protective layer 22. Alternatively, the second protective layer 24 can also have a thickness

more than the thickness of the first protective layer 22, or can have a thickness less than the thickness of the first protective layer 22.

The second protective layer 24 can also contain, for example, at least one of Mg and Zn as an acceptor-type impurity, as desired. For example, the second protective layer 24 can also be a p-type GaN layer. When the second protective layer 24 contains an acceptor-type impurity, during zero bias, in a region directly below the gate electrode 28, the 2DEG 20 in the electron transport layer 16 can be eliminated, thereby enhancing the reliability of the normally closed operation.

The gate layer 26 is made of a nitride semiconductor that has a band gap less than the band gap of the nitride semiconductor of the second protective layer 24, and contains an acceptor-type impurity. For example, when the second protective layer 24 is an AlGaIn layer, the gate layer 26 can be a GaN layer (p-type GaN layer) doped with an acceptor-type impurity. In this embodiment, the gate layer 26 is disposed over the entire second protective layer 24. Moreover, the shape of the gate layer 26 is not specifically defined. For example, in FIG. 1, the gate layer 26 has a rectangular cross section, but can also have a trapezoidal cross section or a ridged cross section. The thickness and the width of the gate layer 26 can be determined in the consideration of a maximum forward rated voltage of the gate, that is, the withstand voltage of the gate. The thickness of the gate layer 26 can be set to 100 nm or more and 140 nm or less, for example, 110 nm. The width (for example, a bottom width) of the gate layer 26 can be set to 0.4  $\mu\text{m}$  or more and 1.0  $\mu\text{m}$  or less, for example, 0.5

The acceptor-type impurity doped in the gate layer 26 can also include at least one of Mg, Zn and C, and is Mg in the first embodiment. In this case, the average concentration of Mg in the gate layer 26 can be set to, for example,  $1 \times 10^{19} \text{ cm}^{-3}$  or more and  $3 \times 10^{19} \text{ cm}^{-3}$  or less, and is preferably set to  $2 \times 10^{19} \text{ cm}^{-3}$ . Moreover, the average doping concentration of the acceptor-type impurity in the gate layer 26 is set to be higher than the average doping concentrations of the acceptor-type impurities (when including acceptor-type impurities) in the first and second protective layers 22 and 24. During zero bias of the gate layer 26, in a region directly below the gate layer 26, the 2DEG 20 formed in the electron transport layer 16 is depleted.

The gate electrode 28 is disposed, for example, on a portion of an upper surface of the gate layer 26. The gate electrode 28 and the gate layer 26 form a Schottky junction. The gate electrode 28 is made of one or more metal layers, which are, for example, a titanium nitride (TiN) layer. Alternatively, the gate electrode 28 can also be made of a first metal layer and a second metal layer, wherein the first metal layer is formed of Ti, and the second metal layer is disposed on the first metal layer and is formed of TiN. The thickness of the gate electrode 28 can be set to, for example, 50 nm or more and 300 nm or less.

The passivation layer 30 covers the first protective layer 22, the second protective layer 24, the gate layer 26 and the gate electrode 28. The passivation layer 30 can be set to be a layer formed using any one of SiN, silicon dioxide ( $\text{SiO}_2$ ), silicon oxynitride (SiON), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), AlN and aluminum oxynitride (AlON), or a composite layer formed of two or more of the above. For example, the passivation layer 30 is a SiN layer. In the first embodiment, the passivation layer 30 covers an upper surface of the first protective layer 22, a side surface of the second protective

layer 24, a side surface and an upper surface of the gate layer 26, and a side surface and an upper surface of the gate electrode 28.

The source electrode 32 and the drain electrode 34 are made of one or more metal layers. The source electrode 32 includes a source electrode portion 32A, and a source field plate portion 32B continuous with the source electrode portion 32A.

The source electrode portion 32A includes a filling region filled in the source-side through hole 30A, and an upper region as a formed integral with the filling region and located in a peripheral region of the source-side through hole 30A and a region above the gate electrode 28 in a top plan view. The source field plate portion 32B is a formed integral with the upper region of the source electrode portion 32A, and has an end portion 32C near the drain electrode 34. The length of the source field plate portion 32B from an end portion of the gate layer 26 to the end portion 32C in a direction along the X axis in FIG. 1 is defined as a source field plate length. The source field plate 32B functions as below; that is, when a high voltage is applied to a source-drain voltage  $V_{ds}$  while a gate-source voltage  $V_{gs}=0 \text{ V}$  (the transistor is off), a depletion layer is caused to extend to a region directly below the source field plate portion 32B. Thus, electric field concentration near the end portion of the gate electrode 28 can be alleviated, thereby inhibiting the occurrence of current collapse.

FIG. 2 shows a brief top plan view of an exemplary pattern 100 formed in the nitride semiconductor device 10 in FIG. 1. FIG. 3 shows a brief section diagram of an active area 110 along the line F3-F3 in FIG. 2, and FIG. 4 shows a brief section diagram of a non-active area along the line F4-F4 in FIG. 2. Moreover, for better understanding, in FIG. 2 to FIG. 4, the constituting elements that is the same as the constituting elements in FIG. 1 are denoted by the same numerals or symbols. In addition, to avoid complications of the drawings, the source electrode 32 and the drain electrode 34 are depicted in dotted lines.

As shown in FIG. 2, the pattern 100 formed includes the active area 110 that contributes to transistor operations, and the non-active area 112 that does not contribute to transistor operations. The active area 110 refers to a region in which a current flows between the source and the drain when a voltage is applied to the gate electrode 28.

As shown in FIG. 3, in the active area 110, multiple (four in the example in FIG. 3) nitride semiconductor devices (nitride semiconductor HEMTs) 10A to 10D are continuously formed in the X axis direction. Each of the nitride semiconductor devices 10A to 10D is identically structured as the nitride semiconductor device 10 in FIG. 1. In the active area 110, the first protective layer 22 is disposed on an upper surface of the electron supply layer 18 excluding the source contact 18A and the drain contact 18B. In a region directly below the gate layer 26 of each of the nitride semiconductor devices 10A to 10D, the second protective layer 24 is disposed on the first protective layer 22.

As shown in FIG. 4, the drain electrode 34 is not formed in the non-active area 112. The passivation layer 30 and the source electrode 32 are continuously formed along the X-axis direction. In addition, in the non-active area 112, the first protective layer 22 is also disposed on the entire upper surface of the electron supply layer 18. In a region directly below the gate layer 26, the second protective layer 24 is disposed on the first protective layer 22.

As shown in FIG. 2, the first protective layer 22, the gate layer 26, the gate electrode 28 and the source electrode 32 are continuously formed between the active area 110 and the

non-active area **112** along the Y-axis direction. Moreover, the second protective layer **24** is also continuously formed in the active area **110** and the non-active area **112**, with associated details omitted from the drawings.

Next, a manufacturing method for the nitride semiconductor device **10** in FIG. **1** is described below. FIG. **5** to FIG. **11** show brief section diagrams of exemplary manufacturing steps for the nitride semiconductor device **10**. In FIG. **5** to FIG. **11**, for better understanding, for final constituting elements or corresponding constituting elements included in the nitride semiconductor device **10**, the reference numerals or symbols in FIG. **1** are partially marked with parentheses in these drawings.

As shown in FIG. **5**, the manufacturing method for the nitride semiconductor device **10** includes a step of forming a first nitride semiconductor layer **52**, wherein the first nitride semiconductor layer **52** forms the electron transport layer **16**. The manufacturing method further includes a step of forming a second nitride semiconductor layer **54** on the first nitride semiconductor layer **52**, wherein the second nitride semiconductor layer **54** has a band gap greater than a band gap of the first nitride semiconductor layer **52** and forms the electron supply layer **18**.

The manufacturing method for the nitride semiconductor device **10** further includes a step of forming a third nitride semiconductor layer **56** on the second nitride semiconductor layer **54**, wherein the third nitride semiconductor layer **56** has a bandgap less than the band gap of the second nitride semiconductor layer **54**. The third nitride semiconductor layer **56** is used to form the first protective layer **22**.

The manufacturing method for the nitride semiconductor device **10** further includes a step of forming a fourth nitride semiconductor layer **58** on the third nitride semiconductor layer **56**, wherein the fourth nitride semiconductor layer **58** has a band gap greater than the band gap of the third nitride semiconductor layer **56**. The fourth nitride semiconductor layer **58** is used to form the second protective layer **24**.

The manufacturing method for the nitride semiconductor device **10** further includes a step of forming a fifth nitride semiconductor layer **60** on the fourth nitride semiconductor layer **58**, wherein the fifth nitride semiconductor layer **60** has a bandgap less than the band gap of the fourth nitride semiconductor layer **58**, and contains an acceptor-type impurity. The fifth nitride semiconductor layer **60** is used to form the gate layer **26**.

In one example, as shown in FIG. **5**, on the substrate **12** implemented by a Si substrate, the buffer layer **14**, the first nitride semiconductor layer **52**, the second nitride semiconductor layer **54**, the third nitride semiconductor layer **56**, the fourth nitride semiconductor layer **58** and the fifth nitride semiconductor layer **60** are sequentially formed by means of epitaxial growth. The epitaxial growth process can be implemented by, for example, metal organic chemical vapor deposition (MOCVD).

The buffer layer **14** is, for example, a multi-layer buffer layer; that is, an AlN layer (a first buffer layer) is formed on the substrate **12**, and then a graded AlGaIn layer (a second buffer layer) is formed on the AlN layer. However, associated details are omitted from the drawings. The graded AlGaIn layer is formed by sequentially depositing three AlGaIn layers respectively having Al compositions of 75%, 50% and 25%, starting from one side close to the AlN layer.

In the first embodiment, a GaN layer as the first nitride semiconductor layer **52** is formed on the buffer layer **14**, and an AlGaIn layer as the second nitride semiconductor layer **54** is formed on the first nitride semiconductor layer **52**. The first nitride semiconductor layer **52** corresponds to the

electron transport layer **16** in FIG. **1**, and the second nitride semiconductor layer **54** corresponds to the electron supply layer **18** in FIG. **1**.

Next, a GaN layer as the third nitride semiconductor layer **56** is formed on the second nitride semiconductor layer **54**, and an AlGaIn layer as the fourth nitride semiconductor layer **58** is formed on the third nitride semiconductor layer **56**. Next, a p-type GaN layer as the fifth nitride semiconductor layer **60** is formed on the fourth nitride semiconductor layer **58**.

As shown in FIG. **6** and FIG. **7**, the manufacturing method for the nitride semiconductor device **10** further includes a step of forming the gate electrode **28** on the fifth nitride semiconductor layer **60**. First of all, as shown in FIG. **6**, a metal layer **62** is formed on the fifth nitride semiconductor layer **60**. In the first embodiment, a TiN layer as the metal layer **62** is formed, for example, by means of sputtering.

Next, as shown in FIG. **7**, the metal layer **62** is selectively etched to form the gate electrode **28**. For example, at a position corresponding to an area where the gate electrode **28** is disposed, a mask (omitted from the drawings) is formed on an upper surface of the metal layer **62** in FIG. **6**. Then, the metal layer **62** is etched (for example, dry etching) by using the mask to form the gate electrode **28**. Next, the mask is removed by using, for example, a stripping fluid.

As shown in FIG. **8**, the manufacturing method for the nitride semiconductor device **10** further includes a step of using the fourth nitride semiconductor layer **58** as an etch stop layer to selectively etch the fifth nitride semiconductor layer **60**, accordingly forming the gate layer **26**. In this step, for example, at a position corresponding to an area where the gate layer **26** is disposed, a mask (omitted from the drawings) covering the gate electrode **28** is formed on an upper surface of the fifth nitride semiconductor layer **60** in FIG. **7**. Then, the fifth nitride semiconductor layer **60** is etched by using the mask to form the gate layer **26**. Moreover, in FIG. **8**, the gate layer **26** has a rectangular cross section, but can also have a trapezoidal cross section or a ridged cross section. Next, the mask is removed by using, for example, a stripping fluid.

Moreover, as described above, when the fifth nitride semiconductor layer **60** is etched to form the gate layer **26**, the fourth nitride semiconductor layer **58** (a layer forming the second protective layer **24**) is used as an etch stop layer. Thus, when etching is performed to form the gate layer **26**, etch damage on the second nitride semiconductor layer **54** (the electron supply layer **18**) and the third nitride semiconductor layer **56** (a layer forming the first protective layer **22**) can be restrained.

Etching of the fifth nitride semiconductor layer **60** can be, for example, dry etching that uses a mixed gas of chlorine-based gas and an additive gas as an etching gas. An example of the chlorine-based gas is chlorine ( $\text{Cl}_2$ ) gas or silicon tetrachloride ( $\text{SiCl}_4$ ) gas. An example of the additive gas is a nitrogen-containing gas (e.g.,  $\text{N}_2$  gas), argon (Ar), a fluorine-containing gas (e.g., carbon tetrafluoride ( $\text{CF}_4$ ) gas), an oxygen-containing gas (e.g.,  $\text{O}_2$  gas), or a combination of two or more of the above.

In the dry etching, etching conditions such as an etching time of the fifth nitride semiconductor layer **60** and an etching selectivity ratio of the fifth nitride semiconductor layer **60** to the fourth nitride semiconductor layer **58** can be modified by changing, for example, the type of the additive gas. Moreover, etching of the fifth nitride semiconductor layer **60** can also be performed by drying etching for multiple times using different etching conditions.

## 11

In addition, regarding etching of the fifth nitride semiconductor layer 60, when the upper surface of the fourth nitride semiconductor layer 58 used as an etch stop layer is exposed, etching conditions can also be selected so as to obtain a higher etching selectivity ratio, for example, an etching selectivity ratio of 10 or more. For example, when the upper surface of the fourth nitride semiconductor layer 58 is exposed, a fluorine-containing gas (e.g., carbon tetrafluoride (CF<sub>4</sub>) gas) or an oxygen-containing gas (e.g., O<sub>2</sub> gas) can also be used as an additive gas so as to obtain a higher etching selectivity ratio.

The dry etching can be performed by using, for example, an inductively coupled plasma (ICP) etching device. The ICP etching device includes a plasma generation power supply that supplies power to generate a plasma from an etching gas, and a bias power supply that supplies ion pulling power for pulling ions in the plasma toward an etching target (for example, the fifth nitride semiconductor layer 60). However, associated details are omitted from the drawings. The etching selectivity ratio can also be adjusted by controlling the ion pulling power supplied by the bias power supply.

Moreover, when the fourth nitride semiconductor layer 58 (AlGa<sub>x</sub>N<sub>1-x</sub> layer) is doped with Zn as an acceptor-type impurity, Zn causes the plasma to emit light once etching of the fifth nitride semiconductor layer 60 reaches the fourth nitride semiconductor layer 58. By determining light emission of the plasma, stop of etching of the fifth nitride semiconductor layer 60 can be more accurately controlled.

The manufacturing method for the nitride semiconductor device 10 further includes a step of oxidizing and removing at least a part of a portion 58A (a dot-shaded portion in FIG. 8) of the fourth nitride semiconductor layer 58 exposed from the gate layer 26.

As shown in FIG. 8, in the first embodiment, the entire of the portion 58A of the fourth nitride semiconductor layer 58 exposed from the gate layer 26 is oxidized. The oxidation treatment can be implemented by, for example, oxygen plasma treatment. For example, a mask (omitted from the drawings) that covers the gate layer 26 and the gate electrode 28 and exposes the portion 58A of the fourth nitride semiconductor layer 58 is formed, and the mask is used to perform oxygen plasma treatment on the portion 58A of the fourth nitride semiconductor layer 58 located directly below the gate layer 26 is not oxidized.

Moreover, in the first embodiment, the fourth nitride semiconductor layer 58 is an AlGa<sub>x</sub>N<sub>1-x</sub> layer, and the third nitride semiconductor layer 56 is a GaN layer. It is more difficult to oxidize a GaN layer than an AlGa<sub>x</sub>N<sub>1-x</sub> layer. Hence, when the portion 58A of the fourth nitride semiconductor layer 58 is oxidized by oxygen plasma treatment, it is unlikely that the third nitride semiconductor layer 56 becomes oxidized.

Next, the oxidized portion 58A of the fourth nitride semiconductor layer 58 is removed by means of etching. Accordingly, as shown in FIG. 9, the second protective layer 22 is formed on a portion of the third nitride semiconductor layer 56 (the layer forming the first protective layer 22). The etching treatment can be, for example, wet etching that uses hydrofluoric acid (HF) as an etching liquid. The wet etching is to continue using the mask used in the oxidation treatment in FIG. 8, and then the mask is removed by using, for example, a stripping liquid.

As such, the portion 58A of the fourth nitride semiconductor layer 58 is removed by means of wet etching, and compared to when dry etching (plasma etching) is used, etch

## 12

damage resulted on the third nitride semiconductor layer 56 (the layer forming the first protective layer 22) can be restrained. Particularly, in the first embodiment, the fourth nitride semiconductor layer 58 is an AlGa<sub>x</sub>N<sub>1-x</sub> layer, and the third nitride semiconductor layer 56 is a GaN layer. A GaN layer is less likely to be damaged by wet etching compared to an AlGa<sub>x</sub>N<sub>1-x</sub> layer. Thus, the first protective layer 22 with less damage can be formed.

In addition, the portion 58A of the fourth nitride semiconductor layer 58 removed by the step in FIG. 9 is a portion used as an etch stop layer when dry etching (plasma etching) is performed on the fifth nitride semiconductor layer 60 to form the gate layer 26. Thus, the portion 58A of the fourth nitride semiconductor layer 58 is a portion damaged by the dry etching. The damaged portion 58A is removed by the wet etching in FIG. 9. Thus, the nitride semiconductor device 10 (refer to FIG. 1) manufactured as a final device does not contain the portion 58A that is a result of damage of the dry etching performed on the fifth nitride semiconductor layer 60.

As shown in FIG. 10, the manufacturing method for the nitride semiconductor device 10 further includes a step of forming a dielectric layer 64 on the first protective layer 22 to cover the second protective layer 24, the gate layer 26 and the gate electrode 28. The dielectric layer 64 corresponds to the passivation layer 30 in FIG. 1. In the first embodiment, for example, a SiN layer is formed as the dielectric layer 64.

As shown in FIG. 11, the manufacturing method for the nitride semiconductor device 10 further includes a step of forming the source-side through hole 30A and the drain-side through hole 30B passing through the dielectric layer 64 (the passivation layer 30) and the source-side opening 22A and the drain-side opening 22B passing through the third nitride semiconductor layer 56 (the first protective layer 22). The source-side opening 22A communicates with the source-side through hole 30A, and exposes a portion of the upper surface of the electron supply layer 18 as the source contact 18A. The drain-side opening 22B communicates with the drain-side through hole 30B, and exposes a portion of the upper surface of the electron supply layer 18 as the drain contact 18B.

After the step in FIG. 11, the manufacturing method for the nitride semiconductor device 10 further includes a step of forming the source electrode 32 (refer to FIG. 1) and the drain electrode 34 (refer to FIG. 1) connected with the electron supply layer 18. In this step, the source-side through hole 30A and the drain-side through hole 30B are filled to form one or more metal layers covering the passivation layer 30. Then, the metal layer is patterned by means of lithography and etching to accordingly form the source electrode 32 and the drain electrode 34. As such, the nitride semiconductor device 10 in FIG. 1 can be obtained.

Next, functions of the nitride semiconductor device 10 in FIG. 1 are described below.

As shown in FIG. 1, the nitride semiconductor device 10 includes: the first protective layer 22, disposed on the upper surface of the electron supply layer 18 excluding the source contact 18A and the drain contact 18B; and the second protective layer 24, located in an area directly below the gate electrode 28, and disposed on the first protective layer 22. As shown in FIG. 8, the first protective layer 22 is formed by the third nitride semiconductor layer 56, and the second protective layer 24 is formed by the fourth nitride semiconductor layer 58.

The fourth nitride semiconductor layer 58 is used as an etch stop layer when the fifth nitride semiconductor layer 60 is patterned by means of dry etching to form the gate layer

13

26. Thus, when dry etching is performed to form the gate layer 26, etch damage on the third nitride semiconductor layer 56 (the layer forming the first protective layer 22) as a layer located below the fourth nitride semiconductor layer 58 (the layer forming the second protective layer 24) and on the second nitride semiconductor layer 54 (the electron supply layer 18) can be restrained.

The portion 58A (the portion shaded by dots in FIG. 8) of the fourth nitride semiconductor layer 58 exposed from the gate layer 26 is used as an etch stop layer and is thus damaged by dry etching. The portion 58A of the fourth nitride semiconductor layer 58 that is damaged is removed by means of wet etching (refer to FIG. 9). Thus, the nitride semiconductor device 10 (refer to FIG. 1) manufactured as a final device does not contain the portion 58A that is a result of damage of the dry etching, and more particularly a dry etched surface, is prone to electron trapping that leads to current collapse. Hence, if the portion 58A damaged by dry etching is present in the nitride semiconductor device 10, electrons can be easily trapped at the portion 58A to thereby cause current collapse. Therefore, by removing the portion 58A damaged by dry etching, current collapse caused by the portion 58A damaged by dry etching can be prevented.

Moreover, since the portion 58A is removed by means of wet etching, compared to when dry etching is used, etch damage resulted on the third nitride semiconductor layer 56 (the layer forming the first protective layer 22) can be restrained. Particularly, in the first embodiment, the fourth nitride semiconductor layer 58 is an AlGaN layer, and the third nitride semiconductor layer 56 is a GaN layer. A GaN layer is less likely to be damaged by wet etching using HF compared to an AlGaN layer. Thus, the first protective layer 22 with less damage can be formed, thereby inhibiting the occurrence of current collapse.

The nitride semiconductor device 10 of the first embodiment provides the following advantages.

(1-1) The nitride semiconductor device 10 includes the first protective layer 22 disposed on the electron supply layer 18, and the second protective layer 24 disposed on a portion of the first protective layer 22. The first protective layer 22 is formed by the third nitride semiconductor layer 56, and the second protective layer 24 is formed by the fourth nitride semiconductor layer 58 (refer to FIG. 8).

According to the configuration above, the electron supply layer 18 is protected by the first protective layer 22, and so damage caused on the electron supply layer 18 can be restrained. In addition, the fourth nitride semiconductor layer 58 is used as an etch stop layer when the fifth nitride semiconductor layer 60 is patterned by means of dry etching to form the gate layer 26. Thus, when dry etching is performed to form the gate layer 26, etch damage on the third nitride semiconductor layer 56 (the layer forming the first protective layer 22) as a layer located below the fourth nitride semiconductor layer 58 (the layer forming the second protective layer 24) and on the second nitride semiconductor layer 54 (the electron supply layer 18) can be restrained. Accordingly, current collapse as a result of the damage caused by the dry etching on the first protective layer 22 and the electron supply layer 18 can be inhibited, thereby enhancing reliability of the nitride semiconductor device 10 (nitride semiconductor HEMT).

(1-2) The portion 58A (refer to FIG. 8) of the fourth nitride semiconductor layer 58 that is damaged by dry etching of the fifth nitride semiconductor layer 60 is removed by means of wet etching (refer to FIG. 9). Thus, the nitride semiconductor device 10 (refer to FIG. 1) manufac-

14

tured as a final device does not contain the portion 58A that is a result of damage of the dry etching. Therefore, current collapse resulted by the portion 58A damaged by dry etching can be prevented.

(1-3) When the portion 58A damaged by dry etching is to be removed, the third nitride semiconductor layer 56 (the layer forming the first protective layer 22) that protects the second nitride semiconductor layer 54 (the electron supply layer 18) is present as a layer below the portion 58A. Accordingly, the electron supply layer 18 is not damaged when the damaged portion 58A is removed. Thus, the occurrence of current collapse on the upper surface of the electron supply layer 18 can be inhibited.

(1-4) The portion 58A that is damaged by dry etching is removed by means of wet etching. Compared to when dry etching is used, the use of wet etching can restrain etch damage resulted on the third nitride semiconductor layer 56 (the layer forming the first protective layer 22).

(1-5) The first protective layer 22 disposed on the electron supply layer 18 also provides a function of hole diffusion. For example, when a larger positive bias is applied to the gate electrode 28, holes injected from the gate electrode 28 into the gate layer 26 are diffused in the first protective layer 22. Accordingly, the density of holes at a junction interface between the first protective layer 22 and the electron supply layer 18 can be reduced, thereby suppressing a gate leakage current.

(1-6) The area of the second protective layer 24 is same as the area of the bottom surface of the gate layer 26 in a top plan view. In this configuration, the portion 58A of the fourth nitride semiconductor layer 58 that is damaged by dry etching of the fifth nitride semiconductor layer 60 is completely removed. Therefore, current collapse resulted by the portion 58A damaged by dry etching can be prevented.

(1-7) The first protective layer 22 is disposed on the upper surface of the electron supply layer 18 excluding the source contact 18A and the drain contact 18B. In this configuration, on the basis that conduction of the source contact 18A of the electron supply layer 18 and the source electrode 32 and conduction of the drain contact 18B of the electron supply layer 18 and the drain electrode 34 are maintained, the first protective layer 22 is used to cover substantially the entire upper surface of the electron supply layer 18. Thus, the occurrence of current collapse can be inhibited on the entire upper surface of the electron supply layer 18 between the source and the drain. A hole diffusion effect of the first protective layer 22 can be further enhanced.

(1-8) The second protective layer 24 has a thickness less than the thickness of the electron supply layer 18 and has a band gap less than the band gap of the electron supply layer 18. According to the configuration above, 2DEG can be suppressed from generating in the first protective layer 22 near the junction interface between the first protective layer 22 and the second protective layer 24, thereby hindering depletion of 2DEG 20 in the electron transport layer 16. Accordingly, reliability of the normally closed operation can be enhanced.

(1-9) At least one of the first protective layer 22 and the second protective layer 24 contains an acceptor-type impurity. According to the configuration above, during zero bias, in the region directly below the gate layer 26, the effect for depleting the 2DEG 20 in the electron transport layer 16 can be improved, thereby enhancing the reliability of the normally closed operation.

(1-10) The first protective layer 22 has a thickness less than the thickness of the gate layer 26. According to the

15

configuration above, reliability of the normally closed operation can be enhanced and on resistance can be reduced.

(1-11) In the first embodiment, the fourth nitride semiconductor layer **58** (the layer forming the second protective layer **24**) is an AlGaIn layer, and the third nitride semiconductor layer **56** (the layer forming the first protective layer **22**) is a GaN layer. A GaN layer is less likely to be damaged by wet etching compared to an AlGaIn layer. Thus, when the part **58A** damaged by dry etching is removed, etch damage on the first protective layer **22** can be restrained. As a result, the first protective layer **22** with less damage can be formed, thereby inhibiting the occurrence of current collapse.

#### Second Embodiment

FIG. **12** shows a brief section diagram of an exemplary nitride semiconductor device **200** according to a second embodiment. In FIG. **12**, constituting elements common with those of the first embodiment are represented by the same numerals and symbols. In the description below, associated details of the constituting elements common with those of the first embodiment are omitted for brevity, and only details of constituting elements different from those of the first embodiment are described.

The nitride semiconductor device **200** includes a second protective layer **224** in substitution for the second protective layer **24** of the first embodiment (refer to FIG. **1**). An area of the second protective layer **224** of the second embodiment is larger than the area of the bottom surface of the gate layer **26** in a top plan view. Except for the difference in terms of the area of the bottom surface of the gate layer **26**, the second protective layer **224** of the second embodiment can be identically structured as the second protective layer **24** of the first embodiment. For example, the second protective layer **224** of the second embodiment can be an AlGaIn layer, and can have the same characteristics as the AlGaIn layer forming the second protective layer **24** of the first embodiment.

The second protective layer **224** includes a base portion **224A**, a source-side extension portion **224B** and a drain-side extension portion **224C**. The base portion **224A** is located directly below the bottom surface of the gate layer **26**. The source-side extension portion **224B** is located outside the bottom surface of the gate layer **26** in a top plan view, and extends from the base portion **224A** toward the source contact **18A**. The drain-side extension portion **224C** is located outside the bottom surface of the gate layer **26** in a top plan view, and extends from the base portion **224A** toward the drain contact **18B**. The source-side extension portion **224B** and the drain-side extension portion **224C** can have a same thickness as a thickness of the base portion **224A**.

The second protective layer **224** of the second embodiment is formed by a same step as the step for forming the second protective layer **24** (refer to FIG. **8** and FIG. **9**) of the first embodiment, that is, by oxidizing and removing only a part of a portion of the fourth nitride semiconductor layer **58** exposed from the gate layer **26**.

In addition to the advantages (1-1) to (1-5) and (1-7) to (1-11) of the first embodiment, the nitride semiconductor device **200** of the second embodiment further provides the advantages below.

(2-1) The area of the second protective layer **224** is larger than the area of the bottom surface of the gate layer **26** in a top plan view. In this configuration, the second protective layer **224** has the source-side extension portion **224B** and the drain-side extension portion **224C**. Thus, compared to when

16

the second protective layer **24** of the first embodiment is used, the effect of hole diffusion of the second protective layer **224** can be enhanced.

#### Third Embodiment

FIG. **3** shows a brief section diagram of an exemplary nitride semiconductor device **300** according to a third embodiment. In FIG. **13**, constituting elements common with those of the first embodiment are represented by the same numerals and symbols. In the description below, associated details of the constituting elements common with those of the first embodiment are omitted for brevity, and only details of constituting elements different from those of the first embodiment are described.

The nitride semiconductor device **300** includes a second protective layer **324** in substitution for the second protective layer **24** of the first embodiment (refer to FIG. **1**), and includes a gate layer **326** in substitution for the gate layer **26** of the first embodiment (refer to FIG. **1**). In the third embodiment, an area of the second protective layer **324** is same as an area of a bottom surface of the gate layer **326** in a top plan view. Except for the difference in terms of being larger than the second protective layer **24** of the first embodiment, the second protective layer **324** of the third embodiment can be identically structured as the second protective layer **24** of the first embodiment. For example, the second protective layer **324** of the third embodiment can be an AlGaIn layer, and can have the same characteristics as the AlGaIn layer forming the second protective layer **24** of the first embodiment.

The gate layer **326** of the third embodiment includes a gate body **326A** on which the gate electrode **28** is located, and inclined portions **326B1** and **326B2** inclined outwardly from a side surface of the gate body **326A**. The gate layer **326** further includes a flat portion **326C1** extending from the inclined portion **326B1** along the second protective layer **324** to the source contact **18A**, and a flat portion **326C2** extending from the inclined portion **326B2** along the second protective layer **324** to the drain contact **18B**. The gate layer **326** of the third embodiment is formed by a same step as the step for forming the gate layer **26** (refer to FIG. **7**) of the first embodiment, that is, by patterning the fifth nitride semiconductor layer **60** by means of etching into the shape of the gate layer **326** shown in FIG. **11**.

Except for the difference in terms of a shape different from that of the gate layer **26** of the first embodiment, the gate layer **326** of the third embodiment can be identically structured as the gate layer **26** of the first embodiment. For example, the gate layer **326** of the third embodiment can be a GaN layer (or a p-type GaN layer), and can have the same characteristics as the GaN layer forming the gate layer **26** of the first embodiment.

In the third embodiment, a length (a width) of the flat portion **326C2** extending from the inclined portion **326B2** to the drain contact **18B** (toward the +X direction) is greater than a length (a width) of the flat portion **326C1** extending from the inclined portion **326B1** to the source contact **18A** (toward the -X direction). In this configuration, the passivation layer **30** located between the source field plate portion **32B** and the 2DEG **20** is thinner than that of the first embodiment. Accordingly, a depletion layer can be extended more effectively from the source field plate portion **32B** to the 2DEG **20**, thereby inhibiting the occurrence of current collapse.

In the third embodiment, a bottom surface of the gate layer **326** includes a bottom surface of the gate body **326A**,

17

bottom surfaces of the inclined portions **326B1** and **326B2**, and bottom surfaces of the flat portions **326C1** and **326C2**. The second protective layer **324** of the third embodiment is formed in a region directly below the bottom surface of the gate layer **326**. The second protective layer **324** is formed by a same step as the step for forming the second protective layer **24** (refer to FIG. 8 and FIG. 9) of the first embodiment, that is, by oxidizing and removing entire of a portion of the fourth nitride semiconductor layer **58** exposed from the gate layer **326**.

In addition to the advantages (1-1) to (1-11) of the first embodiment, the nitride semiconductor device **300** of the third embodiment further provides the advantages below.

(3-1) The gate layer **326** includes the gate body **326A**, the inclined portions **326B1** and **326B2**, and the flat portions **326C1** and **326C2**. By extending the flat portion **326C2** from the inclined portion **326B2** to the drain contact **18B**, the effect of inhibiting current collapse by using the source field plate portion **32B** can be enhanced.

(3-2) Because the gate layer **326** includes the inclined portions **326B1** and **326B2** and the flat portions **326C1** and **326C2**, an effect of hole diffusion of the gate layer **326** can be achieved.

(3-3) The second protective layer **325** is located in the region directly below the bottom surface of the gate layer **326**. Thus, in addition to the bottom surface of the gate body **326A**, the second protective layer **324** further exists in regions directly below the bottom surfaces of the inclined portions **326B1** and **326B2** and the bottom surfaces of the flat portions **326C1** and **326C2**. Accordingly, compared to the second protective layer **24** of the first embodiment is used, the effect of hole diffusion of the second protective layer **224** can be enhanced.

#### Variation Examples

The embodiments described above can be implemented according to the variations below. The embodiments described above and the variation examples can be implemented in combination, given that they are not technically contradictory.

In the embodiments, an acceptor-type impurity can be doped in only a partial region of the first protective layer **22**. For example, an acceptor-type impurity can be doped in a region directly below the gate layer **26** (the gate body **326A** of the third embodiment) in a top plan view. According to the configuration above, reliability of the normally closed operation can be enhanced.

The gate electrode **28** of the embodiments can be disposed on only at least a portion of the gate layer **26**. For example, in the first and second embodiments, the gate electrode **28** can be disposed over the entire gate layer **26**. Similarly, in the third embodiment, the gate electrode **28** can also be disposed over the entire gate body **326A**.

In the second protective layer **224** of the second embodiment, the source-side extension portion **224B** and the drain-side extension portion **224C** can have a thickness less than a thickness of the base portion **224A**. Moreover, the source-side extension portion **224B** and the drain-side extension portion **224C** can have the same length (width).

The gate layer **326** of the third embodiment can exclude the flat portions **326C1** and **326C2**. The gate layer **326** is formed by etching the fifth nitride semiconductor layer **60** (refer to FIG. 7). Thus, the flat portions **326C1**

18

and **326C2** are damaged by etching. If the flat portions **326C1** and **326C2** are not formed, a portion that is damaged by etching can be reduced.

In the gate layer **326** of the third embodiment, the flat portions **326C1** and **326C2** are not necessarily flat. For example, the flat portion **326C1** can also have a thickness that gradually decreases from the inclined portion **326B1** toward the source contact **18A**. Similarly, the flat portion **326C2** can also have a thickness that gradually decreases from the inclined portion **326B2** toward the drain contact **18B**.

In the gate layer **326** of the third embodiment, the flat portions **326C1** and **326C2** can have the same length (width).

The gate layer **326** of the third embodiment can exclude the inclined portions **326B1** and **326B2**.

The gate layer **326** of the third embodiment can be formed by the gate body **326A**, the inclined portion **326B1** and the flat portion **326C1**. That is to say, the inclined portion **326B2** and the flat portion **326C2** can be omitted. Alternatively, the gate layer **326** can be formed by the gate body **326A**, the inclined portion **326B2** and the flat portion **326C2**. That is to say, the inclined portion **326B1** and the flat portion **326C1** can be omitted.

Unless otherwise specified in the context, the term “on/over” used in the present disclosures include meanings of “on”, “over” and “above”. Thus, the expression “a first layer disposed on a second layer” can refer to that the first layer is in contact with the second layer and directly arranged on the second layer in some embodiments, or can refer to that the first layer is not in contact with the second layer and is configured over or above the second layer. That is to say, the expression “on/over” does not eliminate a structure of another layer between the first layer and the second layer. For example, various embodiments of the electron supply layer **18** disposed on the electron transport layer **16** also include an intermediate layer placed between the electron supply layer **18** and the electron transport layer **16** so as to stably form the 2DEG **20**.

The Z-axis direction used in the present disclosure is not necessarily a vertical direction, and is not necessarily completely consistent with the vertical direction. Thus, various structures (for example, the structure shown in FIG. 1) associated with the present disclosure are not limited to “up/top” and “down/bottom” of the Z-axis direction given in the description to be “up” and “down” of the vertical direction. For example, the X-axis direction can also be the vertical direction, or the Y-axis direction can also be the vertical direction.

The directional and spatial terms “vertical”, “horizontal”, “above”, “below”, “up/top”, “down/bottom”, “front”, “back”, “next to”, “left”, “right”, “before” and “behind” are determined on the basis of specific directions of devices in the description and the drawings. In the present disclosure, various substitutive directions are conceivable, and so these directional and spatial terms are not to be interpreted narrowly or exclusively.

[Notes]

The technical concepts that are conceivable based on the embodiments and the variation examples are recoded in the description below. Moreover, the reference numerals or symbols of the constituting elements embodiment corresponding to the constituting elements described in the notes are marked with parentheses. The numerals or symbols are used for understanding purposes, and the constituting ele-

## 19

ments in the notes are not to be construed as constituting elements indicated by the numerals or symbols.

(Note A1)

A nitride semiconductor device (10 (10A to 10D), 200, 300), comprising:

- an electron transport layer (16), made of a nitride semiconductor;
- an electron supply layer (18), disposed on the electron transport layer (16) and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer (16);
- a first protective layer (22), disposed on the electron supply layer (18) and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer (18);
- a second protective layer (24, 224, 324), disposed on a portion of the first protective layer (22) and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer (22);
- a gate layer (26, 326), disposed on the second protective layer (24, 224, 324), made of a nitride semiconductor that has a band gap less than the band gap of the nitride semiconductor of the second protective layer (24, 224, 324), and containing an acceptor-type impurity;
- a gate electrode (28), disposed on the gate layer (26, 326); and
- a source electrode (32) and a drain electrode (34), connected with the electron supply layer (18).

(Note A2)

The nitride semiconductor device (10 (10A to 10D), 300) according to note A1, wherein an area of the second protective layer (24, 324) is same as an area of a bottom surface of the gate layer (26, 326) in a top plan view.

(Note A3)

The nitride semiconductor device (200) according to note A1, wherein an area of the second protective layer (224) is greater than an area of a bottom surface of the gate layer (26) in a top plan view.

(Note A4)

The nitride semiconductor device (200, 300) according to note A2 or A3, wherein the gate layer (26, 326) includes:

- a gate body (326A), on which the gate electrode (28) is located; and
- an inclined portion (326B1, 326B2), inclined outwardly from a side surface of the gate body (326A).

(Note A5)

The nitride semiconductor device (200, 300) according to note A4, wherein the gate layer (26, 326) further includes a flat portion (326C1, 326C2) extending from the inclined portion (326B1, 326B2) along the second protective layer (24, 224, 324).

(Note A6)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A5, wherein the electron supply layer (18) includes:

- a source contact (18A), in contact with the source electrode (32); and
- a drain contact (18B), in contact with the drain electrode (34), and wherein the first protective layer (22) is disposed on an upper surface of the electron supply layer (18) excluding the source contact (18A) and the drain contact (18B).

(Note A7)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A5, further

## 20

including a passivation layer (30) that is disposed on the first protective layer (22), covers the second protective layer (24, 224, 324), the gate layer (26, 326) and the gate electrode (28) and includes a source-side through hole (30A) and a drain-side through hole (30B), and wherein the first protective layer (22) includes:

- a source-side opening (22A), communicating with the source-side through hole (30A) and exposing a portion of the electron supply layer (18) as a source contact (18A) in contact with the source electrode (32); and
- a drain-side opening (22B), communicating with the drain-side through hole (30B) and exposing a portion of the electron supply layer (18) as a drain contact (18B) in contact with the drain electrode (34).

(Note A8)

The nitride semiconductor device (200) according to note A3, wherein the electron supply layer (18) includes:

- a source contact (18A), in contact with the source electrode (32); and
- a drain contact (18B), in contact with the drain electrode (34), and wherein

the second protective layer (224) includes:

- a base portion (224A), located directly below the bottom surface of the gate layer (26);
- a source-side extension portion (224B), located outside the bottom surface of the gate layer (26) in the top plan view and extending from the base portion (224A) toward the source contact (18A); and
- a drain-side extension portion (224C), located outside the bottom surface of the gate layer (26) in the top plan view and extending from the base portion (224A) toward the drain contact (18B).

(Note A9)

The nitride semiconductor device (200) according to note A8, wherein the source-side extension portion (224B) and the drain-side extension portion (224C) have a same thickness as a thickness of the base portion (224A).

(Note A10)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A9, wherein the second protective layer (24, 224, 324) has a thickness less than a thickness of the electron supply layer (18) and has a band gap less than a band gap of the electron supply layer (18).

(Note A11)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A10, wherein at least one of the first protective layer (22) and the second protective layer (24, 224, 324) contains an acceptor-type impurity.

(Note A12)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A11, wherein the first protective layer (22) has a thickness less than a thickness of the gate layer (26, 326).

(Note A13)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A12, wherein the electron transport layer (16) is a GaN layer, the electron supply layer (18) is an AlGaN layer, the first protective layer (22) is a GaN layer, the second protective layer (24, 224, 324) is an AlGaN layer having an Al composition less than an Al composition of the electron supply layer (18), and wherein the gate layer (26, 326) is a GaN layer containing at least one of Mg and Zn as an acceptor type impurity.



## 21

(Note A14)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to note A13, wherein the electron supply layer (18) is an  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  layer (wherein  $0.1 < x < 0.3$ ), and the second protective layer (24, 224, 324) is an  $\text{Al}_y\text{Ga}_{1-y}\text{N}$  layer (wherein  $0.05 < y < x$ ). 5

(Note A15)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to note A13 or A14, wherein at least one of the first protective layer (22) and the second protective layer (24, 224, 324) contains at least one of Mg and Zn as an acceptor-type impurity. 10

(Note A16)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A15, wherein a thickness of the electron supply layer (18) is 20 nm or less, and a thickness of the second protective layer (24, 224, 324) is 10 nm or less. 15

(Note A17)

The nitride semiconductor device (10 (10A to 10D) 200, 300) according to any one of notes A1 to A16, wherein the thickness of the electron supply layer (18) is 15 nm or less, and the thickness of the second protective layer (24, 224, 324) is 7 nm or less. 20

(Note B1)

A manufacturing method for a nitride semiconductor device (10), comprising:

- forming a first nitride semiconductor layer (52) that forms an electron transport layer (16); 30
- forming a second nitride semiconductor layer (54) on the first nitride semiconductor layer (52), wherein the second nitride semiconductor layer (54) has a band gap greater than a band gap of the first nitride semiconductor layer (52) and forms an electron supply support layer (18); 35
- forming a third nitride semiconductor layer (56) on the second nitride semiconductor layer (54), wherein the third nitride semiconductor layer (56) has a band gap less than the band gap of the second nitride semiconductor layer (54); 40
- forming a fourth nitride semiconductor layer (58) on the third nitride semiconductor layer (56), wherein the fourth nitride semiconductor layer (58) has a band gap greater than the band gap of the third nitride semiconductor layer (56); 45
- forming a fifth nitride semiconductor layer (60) on the fourth nitride semiconductor layer (58), wherein the fifth nitride semiconductor layer (60) has a band gap less than the band gap of the fourth nitride semiconductor layer (58) and contains an acceptor-type impurity; 50
- forming a gate electrode (28) on the fifth nitride semiconductor layer (60);
- using the fourth nitride semiconductor layer (58) as an etch stop layer to selectively etch the fifth nitride semiconductor layer (60), accordingly forming a gate layer (26, 326); and
- oxidizing and removing at least a part of a portion (58A) of the fourth nitride semiconductor layer (58) exposed from the gate layer (26, 326). 60

(Note B2)

The manufacturing method for the nitride semiconductor device (10) according to note B1, wherein the step of oxidizing and removing the at least a part of the portion (58A) of the fourth nitride semiconductor layer (58) exposed from the gate layer (26, 326) includes: 65

## 22

oxidizing entire of the portion (58A) of the fourth nitride semiconductor layer (58) exposed from the gate layer (26, 326); and

removing entire of the oxidized portion (58A) of the fourth nitride semiconductor layer (58) by means of wet etching.

(Note B3)

The manufacturing method for the nitride semiconductor device (10) according to note B2, wherein the wet etching is wet etching using hydrofluoric acid (HF). 10

It should be noted that the description above are for illustrative and exemplary purposes. It can be conceived by the industrialist that, apart from the constituting elements and methods (manufacturing processes) enumerated in the technical details of the present disclosure, there are many other conceivable combinations and substitutions. The present disclosure is intended to encompass all substitutions, modifications and variations covered by the scope of claims of the present disclosure.

The invention claimed is:

1. A nitride semiconductor device, comprising:
  - an electron transport layer, made of a nitride semiconductor;
  - an electron supply layer, disposed on the electron transport layer and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer;
  - a first protective layer, disposed on the electron supply layer and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer;
  - a second protective layer, disposed on a portion of the first protective layer and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer;
  - a gate layer, disposed on the second protective layer and made of a nitride semiconductor that has a band gap less than the band gap of the nitride semiconductor of the second protective layer and contains acceptor-type impurities;
  - a gate electrode, disposed on the gate layer; and
  - a source electrode and a drain electrode, connected with the electron supply layer, wherein
    - an area of the second protective layer is same as an area of a bottom surface of the gate layer in a top plan view, the gate layer includes:
      - a gate body, on which the gate electrode is located; and
      - an inclined portion, inclined outwardly from a side surface of the gate body, and
    - the gate layer further includes a flat portion extending from the inclined portion along the second protective layer.
2. The nitride semiconductor device of claim 1, wherein the electron supply layer includes:
  - a source contact, in contact with the source electrode; and
  - a drain contact, in contact with the drain electrode, wherein
    - the first protective layer is disposed on an upper surface of the electron supply layer excluding the source contact and the drain contact.
3. The nitride semiconductor device of claim 1, further comprising a passivation layer that is
  - disposed on the first protective layer,
  - covering the second protective layer, the gate layer and the gate electrode and
  - including a source-side through hole and a drain-side through hole, wherein

## 23

the first protective layer includes:

a source-side opening, communicating with the source-side through hole and exposing a portion of the electron supply layer as a source contact in contact with the source electrode; and

a drain-side opening, communicating with the drain-side through hole and exposing a portion of the electron supply layer as a drain contact in contact with the drain electrode.

4. A nitride semiconductor device, comprising:

an electron transport layer, made of a nitride semiconductor;

an electron supply layer, disposed on the electron transport layer and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer;

a first protective layer, disposed on the electron supply layer and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer;

a second protective layer, disposed on a portion of the first protective layer and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer;

a gate layer, disposed on the second protective layer and made of a nitride semiconductor that has a band gap less than the band gap of the nitride semiconductor of the second protective layer and contains acceptor-type impurities;

a gate electrode, disposed on the gate layer; and

a source electrode and a drain electrode, connected with the electron supply layer, wherein

an area of the second protective layer is greater than an area of a bottom surface of the gate layer in a top plan view,

the electron supply layer includes:

a source contact, in contact with the source electrode; and

a drain contact, in contact with the drain electrode, and the second protective layer includes:

a base portion, located directly below the bottom surface of the gate layer;

a source-side extension portion, located outside the bottom surface of the gate layer in the top plan view and extending from the base portion toward the source contact; and

a drain-side extension portion, located outside the bottom surface of the gate layer in the top plan view and extending from the base portion toward the drain contact.

5. The nitride semiconductor device of claim 4, wherein the source-side extension portion and the drain-side extension portion have a same thickness as a thickness of the base portion.

6. The nitride semiconductor device of claim 4, wherein the gate layer includes:

a gate body, on which the gate electrode is located; and an inclined portion, inclined outwardly from a side surface of the gate body.

7. A nitride semiconductor device, comprising:

an electron transport layer, made of a nitride semiconductor;

an electron supply layer, disposed on the electron transport layer and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer;

## 24

a first protective layer, disposed on the electron supply layer and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer;

a second protective layer, disposed on a portion of the first protective layer and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer;

a gate layer, disposed on the second protective layer and made of a nitride semiconductor that has a band gap less than the band gap of the nitride semiconductor of the second protective layer and contains acceptor-type impurities;

a gate electrode, disposed on the gate layer; and

a source electrode and a drain electrode, connected with the electron supply layer, wherein

the second protective layer has a thickness less than a thickness of the electron supply layer and has a band gap less than a band gap of the electron supply layer.

8. A nitride semiconductor device, comprising:

an electron transport layer, made of a nitride semiconductor;

an electron supply layer, disposed on the electron transport layer and made of a nitride semiconductor having a band gap greater than a band gap of the nitride semiconductor of the electron transport layer;

a first protective layer, disposed on the electron supply layer and made of a nitride semiconductor having a band gap less than the band gap of the nitride semiconductor of the electron supply layer;

a second protective layer, disposed on a portion of the first protective layer and made of a nitride semiconductor having a band gap greater than the band gap of the nitride semiconductor of the first protective layer;

a gate layer, disposed on the second protective layer and made of a nitride semiconductor that has a band gap less than the band gap of the nitride semiconductor of the second protective layer and contains acceptor-type impurities;

a gate electrode, disposed on the gate layer; and

a source electrode and a drain electrode, connected with the electron supply layer, wherein

the first protective layer has a thickness less than a thickness of the gate layer.

9. The nitride semiconductor device of claim 8, wherein the electron transport layer is a GaN layer, the electron supply layer is an AlGa<sub>1-x</sub>N layer, the first protective layer is a GaN layer, the second protective layer is an AlGa<sub>1-x</sub>N layer having an Al composition less than an Al composition of the electron supply layer, and

the gate layer is a GaN layer containing at least one of Mg and Zn as an acceptor type impurity.

10. The nitride semiconductor device of claim 9, wherein the electron supply layer is an Al<sub>x</sub>Ga<sub>1-x</sub>N layer (0.1<x<0.3), and

the second protective layer is an Al<sub>y</sub>Ga<sub>1-y</sub>N layer (0.05<y<x).

11. The nitride semiconductor device of claim 9, wherein at least one of the first protective layer and the second protective layer contains at least one of Mg and Zn as an acceptor-type impurity.

12. The nitride semiconductor device of claim 8, wherein a thickness of the electron supply layer is less than 20 nanometers (nm), and a thickness of the second protective layer is less than 10 nm.

25

13. The nitride semiconductor device of claim 8, wherein  
 a thickness of the electron supply layer is less than 15 nm,  
 and  
 a thickness of the second protective layer is less than 7  
 nm.

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14. The nitride semiconductor device of claim 8, wherein  
 the electron supply layer includes:

a source contact, in contact with the source electrode; and  
 a drain contact, in contact with the drain electrode,  
 wherein

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the first protective layer is disposed on an upper surface  
 of the electron supply layer excluding the source con-  
 tact and the drain contact.

15. The nitride semiconductor device of claim 8, further  
 comprising a passivation layer that is

15

disposed on the first protective layer,  
 covering the second protective layer, the gate layer and  
 the gate electrode, and

including a source-side through hole and a drain-side  
 through hole, wherein

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the first protective layer includes:

a source-side opening, communicating with the source-  
 side through hole and exposing a portion of the  
 electron supply layer as a source contact in contact  
 with the source electrode; and

25

a drain-side opening, communicating with the drain-  
 side through hole and exposing a portion of the  
 electron supply layer as a drain contact in contact  
 with the drain electrode.

16. The nitride semiconductor device of claim 8, wherein  
 at least one of the first protective layer and the second  
 protective layer contains acceptor-type impurities.

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26