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United States Patent	12396198
Kind Code	B2
Date of Patent	August 19, 2025
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Semiconductor device

Abstract

A semiconductor device includes a channel layer, a barrier layer disposed above the channel layer, a protective layer disposed on the barrier layer, and an insulating layer disposed on the protective layer. A composition of the barrier layer is represented by $\text{In}_{x1}\text{Al}_{x2}\text{Ga}_{1-x1-x2}\text{N}$, where $0.00 \leq x1 \leq 0.20$, and $0.10 \leq x2 \leq 1.00$, and a composition of the protective layer is represented by $\text{In}_{y1}\text{Al}_{y2}\text{Ga}_{1-y1-y2}\text{N}$, where $0.00 \leq y1 \leq 0.20$, and $0.10 \leq y2 \leq 1.00$, $x2 < y2$. The protective layer is an amorphous layer.

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Appl. No.:	17/929398
Filed:	September 02, 2022

Prior Publication Data

Document Identifier	Publication Date
US 20230170409 A1	Jun. 01, 2023

Foreign Application Priority Data

JP	2021-193857	Nov. 30, 2021
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Publication Classification

Int. Cl.: H10D30/47 (20250101); H10D62/85 (20250101)

U.S. Cl.:

Field of Classification Search

USPC: None

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

(1) This application is based upon and claims the benefit of priority of the prior Japanese Patent Application No. 2021-193857, filed on Nov. 30, 2021, the entire contents of which are incorporated herein by reference.

FIELD

(2) The embodiments discussed herein are related to semiconductor devices.

BACKGROUND

(3) With regard to semiconductor devices using nitride semiconductors, many reports have been made on field effect transistors (FETs), and particularly high electron mobility transistors (HEMTs). As HEMTs using nitride semiconductors, there is a known HEMT using a GaN layer as

a channel layer, and an AlGa_N layer or an InAlGa_N layer as a barrier layer. The InAlGa_N layer is more easily lattice-matched to the Ga_N layer when compared to the AlGa_N layer, even when the InAlGa_N layer has a high Al composition, and is preferable from a viewpoint of increasing a density of two-dimensional electron gas (2DEG).

(4) A current gain cutoff frequency f_{T} , that is an index of high-frequency characteristics of the HEMT, can be represented by the following formula (1), where C_{gs} denotes a gate-source capacitance, and g_m denotes a transconductance.

$$(5) f_T = \frac{g_m}{2\pi C_{gs}} \quad (1)$$

(6) In addition, the transconductance g_m can be represented by the following formula (2), where ϵ_s denotes a dielectric constant, W_g denotes a gate width, v_s denotes a saturated drift velocity, d denotes a thickness of the barrier layer, and Δd denotes a thickness of the 2DEG.

$$(7) g_m = \frac{\epsilon_s W_g v_s}{d + \Delta d} \quad (2)$$

(8) As may be seen from the formula (1), the current gain cutoff frequency f_{T} can be increased by increasing the transconductance g_m , and the transconductance g_m can be increased by decreasing the thickness of the barrier layer. In other words, the high-frequency characteristics can be improved by decreasing the thickness of the barrier layer.

(9) Examples of related art include Japanese Laid-Open Patent Publication No. 2017-34201, Japanese Laid-Open Patent Publication No. 2017-147320, U.S. Patent Application Publication No. 2006/0011915, and H. Wang et al, "High-Performance LPCVD-SiN_x/InAlGa_N/Ga_N MIS-HEMTs with 850-V 0.98-m Ω .cm for Power Device Applications", IEEE Journal of the Electron Devices Society, 6, pp. 1136-1141, 2018, for example.

(10) Although an insulating layer, such as a SiN layer or the like, is formed on the barrier layer by plasma chemical vapor deposition (CVD), the InAlGa_N layer is more susceptible to surface damage by the plasma when compared to the AlGa_N layer. The presence of a defect caused by the surface damage of the barrier layer may reduce electron mobility of the 2DEG and increase sheet resistance. As described above, making the barrier layer thin is effective for improving the high-frequency characteristics, but the thinner the barrier layer becomes, the shorter the distance between the surface of the barrier layer and the 2DEG becomes. For this reason, when the barrier layer is made thin, the 2DEG is particularly susceptible to the effects of the surface defect of the barrier layer, and the sheet resistance is likely to increase. A proposal has also been made to form the insulating layer by thermal CVD to reduce the surface damage, however, the InAlGa_N layer is also susceptible to thermal damage, and the sheet resistance is likely to increase.

SUMMARY

(11) Accordingly, it is an object in one aspect of the embodiments to provide a semiconductor device capable of reducing an increase in sheet resistance even when a barrier layer is made thin.

(12) According to one aspect of the embodiments, a semiconductor device includes a channel layer; a barrier layer disposed above the channel layer; a protective layer disposed on the barrier layer; and an insulating layer disposed on the protective layer, wherein a composition of the barrier layer is represented by In_{x1}Al_{x2}Ga_{1-x1-x2}N, where $0.00 \leq x1 \leq 0.20$, and $0.10 \leq x2 \leq 1.00$, a composition of the protective layer is represented by In_{y1}Al_{y2}Ga_{1-y1-y2}N, where $0.00 \leq y1 \leq 0.20$, and $0.10 \leq y2 \leq 1.00$, $x2 < y2$, and the protective layer is an amorphous layer.

(13) The object and advantages of the invention will be realized and attained by means of the elements and combinations particularly pointed out in the claims.

(14) It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are not restrictive of the invention, as claimed.

Description

BRIEF DESCRIPTION OF DRAWINGS

- (1) FIG. 1 is a cross sectional view illustrating a semiconductor device according to a first embodiment;
- (2) FIG. 2 is a cross sectional view (part 1) illustrating a method for manufacturing the semiconductor device according to the first embodiment;
- (3) FIG. 3 is a cross sectional view (part 2) illustrating the method for manufacturing the semiconductor device according to the first embodiment;
- (4) FIG. 4 is a cross sectional view (part 3) illustrating the method for manufacturing the semiconductor device according to the first embodiment;
- (5) FIG. 5 is a cross sectional view (part 4) illustrating the method for manufacturing the semiconductor device according to the first embodiment;
- (6) FIG. 6 is a cross sectional view (part 5) illustrating the method for manufacturing the semiconductor device according to the first embodiment;
- (7) FIG. 7 is a cross sectional view (part 6) illustrating the method for manufacturing the semiconductor device according to the first embodiment;
- (8) FIG. 8 is a cross sectional view (part 7) illustrating the method for manufacturing the semiconductor device according to the first embodiment;
- (9) FIG. 9 is a cross sectional view (part 8) illustrating the method for manufacturing the semiconductor device according to the first embodiment;
- (10) FIG. 10 is a diagram illustrating changes in sheet resistances;
- (11) FIG. 11 is a cross sectional view illustrating the semiconductor device according to a modification of the first embodiment;
- (12) FIG. 12 is a cross sectional view illustrating the semiconductor device according to a second embodiment;
- (13) FIG. 13 is a cross sectional view illustrating the method for manufacturing the semiconductor device according to the second embodiment;
- (14) FIG. 14 is a diagram illustrating a discrete package according to a third embodiment;
- (15) FIG. 15 is a circuit diagram illustrating a PFC circuit according to a fourth embodiment;
- (16) FIG. 16 is a circuit diagram illustrating a power supply device according to a fifth embodiment; and
- (17) FIG. 17 is a circuit diagram illustrating an amplifier according to a sixth embodiment.

DESCRIPTION OF EMBODIMENTS

- (18) Preferred embodiments of the present invention will be described with reference to the accompanying drawings.
- (19) A description will now be given of a semiconductor device according to embodiments and modifications of the present invention, with reference to the accompanying drawings. In the present specification and the drawings, constituent elements having substantially the same function or configuration are designated by the same reference numerals, and a repeated description thereof may be omitted.

First Embodiment

- (20) A first embodiment will be described. The first embodiment relates to a semiconductor device including a High Electron Mobility Transistor (HEMT). FIG. 1 is a cross sectional view illustrating the semiconductor device according to the first embodiment.
- (21) As illustrated in FIG. 1, in a semiconductor device 100 according to the first embodiment, a nitride semiconductor laminated structure (or nitride semiconductor stacked structure) 107 is formed above a substrate 101. The nitride semiconductor laminated structure 107 includes a nucleation layer 102, a channel layer 103, a spacer layer 104, a barrier layer 105, and a protective

layer **106**. The nucleation layer **102** is formed on the substrate **101**. The channel layer **103** is formed on the nucleation layer **102**. The spacer layer **104** is formed on the channel layer **103**. The barrier layer **105** is formed on the spacer layer **104**. The protective layer **106** is formed on the barrier layer **105**.

(22) The substrate **101** is a semi-insulating SiC substrate, for example. The nucleation layer **102** is an AlN layer having a thickness in a range of 5 nm to 150 nm, for example. The channel layer **103** is a GaN layer having a thickness in a range of 1 μm to 5 μm , for example. The spacer layer **104** is an Al_{0.40-1.00}GaN layer (0.40 \leq z \leq 1.00) having a thickness in a range of 0.5 nm to 3 nm, for example. That is, the spacer layer **104** is an AlGaN layer having a thickness greater than or equal to 0.5 nm and less than or equal to 3 nm, and an Al composition z greater than or equal to 0.40 and less than or equal to 1.00, for example. The barrier layer **105** is an In_{0.00-0.20}Al_{0.10-1.00}GaN layer (0.00 \leq x₁ \leq 0.20, 0.10 \leq x₂ \leq 1.00) having a thickness in a range of 4 nm to 10 nm, for example. That is, the barrier layer **105** is an InAlGaN layer having a thickness greater than or equal to 4 nm and less than or equal to 10 nm, an In composition x₁ greater than or equal to 0.00 and less than or equal to 0.20, and an Al composition x₂ greater than or equal to 0.10 and less than or equal to 1.00, for example.

(23) The protective layer **106** is an amorphous In_{0.00-0.20}Al_{0.10-1.00}GaN layer (0.00 \leq y₁ \leq 0.20, 0.10 \leq y₂ \leq 1.00, x₂<y₂) having a thickness in a range of 2 nm to 6 nm, for example. That is, the protective layer **106** is an amorphous InAlGaN layer having a thickness greater than or equal to 2 nm and less than or equal to 6 nm, an In composition y₁ greater than or equal to 0.00 and less than or equal to 0.20, and an Al composition y₂ greater than or equal to 0.10 and less than or equal to 1.00, for example. The Al composition y₂ of the protective layer **106** is greater than the Al composition x₂ of the barrier layer **105**.

(24) The channel layer **103**, the spacer layer **104**, and the barrier layer **105** have an a-axis in a direction parallel to a principal surface of the channel layer **103**, and a c-axis in a direction perpendicular to the principal surface of the channel layer **103**. On the other hand, because the protective layer **106** is an amorphous layer, the protective layer **106** does not have a polarization aligned in a direction parallel to the c-axis of the channel layer **103**.

(25) A device isolation region defining a device region is formed in the nitride semiconductor laminated structure **107**, and an opening **106s** for the source and an opening **106d** for the drain are formed in the protective layer **106** inside the device region. In addition, a source electrode **108** is formed in the opening **106s**, and a drain electrode **109** is formed in the opening **106d**. An insulating layer **110**, that covers the source electrode **108** and the drain electrode **109**, is formed on the protective layer **106**. An opening **110g** is formed in the insulating layer **110** at a position between the source electrode **108** and the drain electrode **109** in the plan view. A gate electrode **111**, that makes contact with the protective layer **106** via the opening **110g**, is formed on the insulating layer **110**.

(26) The source electrode **108** and the drain electrode **109** include a Ta film having a thickness in a range of 10 nm to 50 nm, and an Al film formed on the Ta film and having a thickness in a range of 100 nm to 500 nm, for example, and make an ohmic contact with the nitride semiconductor laminated structure **107**, respectively. The gate electrode **111** includes a Ni film having a thickness in a range of 10 nm to 50 nm, and an Au film formed on the Ni film and having a thickness in a range of 300 nm to 500 nm, for example. The insulating layer **110** includes a layer of a nitride of Si, Al, Hf, Zr, Ti, Ta, or W, for example, and preferably includes a Si nitride (SiN) layer. The insulating layer **110** has a thickness in a range of 2 nm to 500 nm, and is preferably approximately 100 nm, for example.

(27) In the semiconductor device **100**, a 2DEG **150** is present in the channel layer **103** below the gate electrode **111**, in a state where no voltage is applied to the gate electrode **111**. That is, the semiconductor device **100** operates as a normally-on device.

(28) Next, a method for manufacturing the semiconductor device **100** according to the first

embodiment will be described. FIG. 2 through FIG. 9 are cross sectional views illustrating the method for manufacturing the semiconductor device **100** according to the first embodiment.

(29) First, as illustrated in FIG. 2, the nitride semiconductor laminated structure **107** is formed on the substrate **101**. When forming the nitride semiconductor laminated structure **107**, the nucleation layer **102**, the channel layer **103**, the spacer layer **104**, the barrier layer **105**, and the protective layer **106** are formed by a metal organic vapor phase epitaxy (MOVPE), for example. When forming the nitride semiconductor laminated structure **107**, a gas mixture of trimethylgallium (TMGa) gas that is a Ga source, and ammonia (NH_3) gas that is a N source, is used as a source gas for depositing a GaN layer. A gas mixture of trimethylaluminum (TMAI) gas that is an Al source, and NH_3 gas, is used as a source gas for depositing an AlN layer. A gas mixture of TMAI gas, TMGa gas, and NH_3 gas, is used as a source gas for depositing an AlGaIn layer. A gas mixture of TMAI gas, TMGa gas, trimethylindium (TMIn) gas, and NH_3 gas, is used as a source gas for depositing an InAlGaIn layer. Whether or not to supply the TMAI gas, the TMGa gas, and the TMIn gas, and a flow rate of such gases, can be set appropriately depending on the composition of the nitride semiconductor layer to be deposited. Hydrogen (H_2) gas or nitrogen (N_2) gas can be used as a carrier gas. A deposition pressure is in a range of approximately 1 kPa to approximately 100 kPa, and a deposition temperature is in a range of approximately 300° C. to approximately 1200° C., for example. However, the deposition temperature of the protective layer **106** is set lower than the deposition temperatures of the nucleating layer **102**, the channel layer **103**, the spacer layer **104**, and the barrier layer **105**, and the protective layer **106** is made an amorphous layer. The deposition temperature of the protective layer **106** is 350° C., for example.

(30) Next, the device isolation region, that defines the device region, is formed in the nitride semiconductor laminated structure **107**. When forming the device isolation region, a photoresist pattern that exposes an area where the device isolation region is to be formed, is formed on the nitride semiconductor laminated structure **107**, for example, and an ion implantation of Ar or the like is performed using the photoresist pattern as a mask. The photoresist pattern can be used as an etching mask when performing a dry etching using a chlorine-based gas.

(31) Thereafter, as illustrated in FIG. 3, a surface protective film **121** is formed on the protective layer **106**. The surface protective film **121** includes a layer of an oxide, a nitride, or an oxynitride of Si, Al, Hf, Zr, Ti, Ta, or W, for example, and preferably includes a Si oxide (SiO_2) layer. The surface protective film **121** can be formed by plasma CVD, for example. The surface protective film **121** can be formed by atomic layer deposition (ALD) or sputtering.

(32) Next, as illustrated in FIG. 4, openings **121s** and **121d** are formed in the surface protective film **121**, and the openings **106s** and **106d** are formed in the protective layer **106**. When forming the openings **121s**, **121d**, **106s**, and **106d**, a photoresist pattern that exposes areas where the openings **106s** and **106d** are to be formed by photolithography, for example, is formed on the surface protective film **121**. Then, the photoresist pattern is used as an etching mask when performing a dry etching using a fluorine-based gas or a chlorine-based gas.

(33) Next, the surface protective film **121** is removed as illustrated in FIG. 5.

(34) Thereafter, as illustrated in FIG. 6, the source electrode **108** is formed inside the opening **106s**, and the drain electrode **109** is formed inside the opening **106d**. The source electrode **108** and the drain electrode **109** can be formed by a lift-off method, for example. That is, the photoresist pattern, that exposes the areas where the source electrode **108** and the drain electrode **109** are to be formed, is formed, the photoresist pattern is used as a deposition mask to form a metal film by deposition, and the photoresist pattern is removed together with the metal film formed thereon. When forming the metal film, a Ta film is formed, and an Al film is formed on the Ta film, for example. Next, a heat treatment is performed at a temperature in a range of 400° C. to 1000° C., for example, in a nitrogen atmosphere, to obtain ohmic characteristics. The heat treatment can be performed at 550° C., for example.

(35) Then, as illustrated in FIG. 7, the insulating layer **110**, that covers the source electrode **108** and

the drain electrode **109**, is formed on the protective layer **106**. The insulating layer **110** can be formed by plasma CVD, for example. The insulating layer **110** can be formed by ALD or sputtering. By forming the insulating layer **110**, it is possible to increase a density of the 2DEG **150** near an upper surface of the channel layer **103**, below a region between the source electrode **108** and the drain electrode **109**.

(36) Next, as illustrated in FIG. **8**, the opening **110g** is formed in the insulating layer **110**. When forming the openings **110g**, a photoresist pattern that exposes an area where the opening **110g** is to be formed by photolithography, for example, is formed on the insulating layer **110**. Then, the photoresist pattern is used as an etching mask when performing a dry etching using a fluorine-based gas or a chlorine-based gas. A wet etching using a fluoric acid, buffered fluoric acid, or the like may be performed in place of the dry etching.

(37) Thereafter, as illustrated in FIG. **9**, the gate electrode **111**, that makes contact with the protective layer **106** via the opening **110g**, is formed on the insulating layer **110**. The gate electrode **111** can be formed by a lift-off method, for example. That is, the photoresist pattern, that exposes the area where the gate electrode **111** is to be formed, is formed, a metal film is formed by deposition using the photoresist pattern as a deposition mask, and the photoresist pattern is removed together with the metal film formed thereon. When forming the metal film, a Ni film is formed, and an Au film is formed on the Ni film, for example.

(38) The semiconductor device **100** according to the first embodiment can be manufactured in the manner described above.

(39) Next, functions and effects of the protective layer **106** will be described, by referring to a reference example. In the reference example, the protective layer **106** is omitted, and the insulating layer **110** is formed on the barrier layer **105** by plasma CVD, so as to make direct contact with the barrier layer **105**. In the reference example, it is assumed that an InAlGaN layer having a thickness of 6 nm is used as the barrier layer **105**, an amorphous AlN layer having a thickness of 4 nm is used as the protective layer **106**, and a SiN layer is used as the insulating layer **110**.

(40) FIG. **10** illustrates changes in sheet resistances of the first embodiment and the reference example. FIG. **10** illustrates the sheet resistance before and after forming the insulating layer **110**. As illustrated in FIG. **10**, in the first embodiment, the sheet resistance decreases due to forming the insulating layer **110**, as indicated by a dashed line. The sheet resistance decreases in the first embodiment because a band structure of the nitride semiconductor laminated structure **107** changes due to forming the insulating layer **110**, thereby increasing the density of the 2DEG **150**. On the other hand, in the reference example, the sheet resistance increases due to forming the insulating layer **110**, as indicated by a solid line. The sheet resistance increases in the reference example because the band structure of the nitride semiconductor laminated structure **107** changes due to forming the insulating layer **110**, thereby increasing the density of the 2DEG **150**, but generating defects on the surface of the barrier layer **105** caused by plasma when forming the insulating layer **110**, and deteriorating electron mobility.

(41) Further, in the reference example, because the insulating layer **110** is directly connected to the barrier layer **105**, interdiffusion occurs between Si included in the insulating layer **110** and Ga included in the barrier layer **105**. The Si diffused into the barrier layer **105** functions as an n-type impurity, and can function as an electron trap for the 2DEG **150**. In contrast, in the first embodiment, because the protective layer **106** is provided between the insulating layer **110** and the barrier layer **105**, it is possible to reduce the interdiffusion that occurs in the reference example.

(42) In FIG. **10**, before the insulating layer **110** is formed, the sheet resistance of the first embodiment is lower than the sheet resistance of the reference example because a change occurs in the band structure due to forming the protective layer **106**. Hence, according to the first embodiment, the density of the 2DEG **150** can be increased, and the sheet resistance can be reduced, also by the change in the band structure associated with forming the protective layer **106**.

(43) Accordingly, it is possible to reduce an increase in sheet resistance even when the barrier layer

105 of the semiconductor device **100** is made thin.

(44) Although a composition of the barrier layer **105** can be represented by

$\text{In.sub.x1Al.sub.x2Ga.sub.1-x1-x2N}$ ($0.00 \leq x1 \leq 0.20$, $0.10 \leq x2 \leq 1.00$), it is preferable that the Al composition $x2$ is greater than or equal to 0.10 and less than or equal to 0.70, and that the barrier layer **105** includes Ga. Alternatively, the Al composition $x2$ may be greater than or equal to 0.15 and less than or equal to 1.00, or greater than or equal to 0.15 and less than or equal to 0.70.

(45) When the thickness of the barrier layer **105** is greater than 10 nm, the transconductance increases, and high-frequency characteristics may deteriorate. For this reason, the thickness of the barrier layer **105** is preferably less than or equal to 10 nm. That is, a distance between the upper surface of the channel layer **103** and a lower surface of the protective layer **106** is preferably less than or equal to 10 nm. The thickness of the barrier layer **105** is more preferably less than or equal to 9 nm, and even more preferably less than or equal to 8 nm. Further, when the thickness of the barrier layer **105** is less than 4 nm, the 2DEG **150** having a sufficiently high density may not be obtainable. Thus, the thickness of the barrier layer **105** is preferably greater than or equal to 4 nm.

(46) A composition of the protective layer **106** is represented by $\text{In.sub.y1Al.sub.y2Ga.sub.1-y1-y2N}$ ($0.00 \leq y1 \leq 0.20$, $0.10 \leq y2 \leq 1.00$, $x2 < y2$), but the In composition $y1$ can be 0.00, the Al composition $y2$ can be 1.00, and the protective layer **106** can be an AlN layer.

(47) The protective layer **106** preferably does not include Si, Ge, Sn, and O. In contrast, the insulating layer **110** preferably includes Si, Ge, Sn, O, or any combination thereof. That is, the insulating layer **110** preferably includes at least one of Si, Ge, Sn, and O.

(48) When the thickness of the protective layer **106** is greater than 6 nm, the transconductance increases, and the high-frequency characteristics may deteriorate. For this reason, the thickness of the protective layer **106** is preferably less than or equal to 6 nm. The thickness of the protective layer **106** is more preferably less than or equal to 5 nm, and even more preferably less than or equal to 4 nm.

(49) A composition of the spacer layer **104** is represented by $\text{Al.sub.zGa.sub.1-zN}$

($0.40 \leq z \leq 1.00$), but the Al composition z can be 1.00, and the spacer layer **104** can be an AlN layer.

(50) The spacer layer **104** may be omitted, and the barrier layer **105** may be in direct contact with the channel layer **103**. The same applies to embodiments and modifications which will be described later.

Modification of First Embodiment

(51) A modification of the first embodiment will be described. The modification of the first embodiment differs from the first embodiment mainly in the configuration of the nitride semiconductor laminated structure. FIG. **11** is a cross sectional view illustrating the semiconductor device according to the modification of the first embodiment.

(52) As illustrated in FIG. **11**, in a semiconductor device **100A** according to the modification of the first embodiment, the nitride semiconductor laminated structure **107** includes a cap layer **120** between the barrier layer **105** and the protective layer **106**. The cap layer **120** is a GaN layer having a thickness in a range of 8 nm to 12 nm, for example.

(53) Otherwise, the configuration of the modification is similar to that of the first embodiment.

Second Embodiment

(54) A second embodiment will be described. The second embodiment differs from the first embodiment mainly in the configuration of the insulating layer. FIG. **12** is a cross sectional view illustrating the semiconductor device according to the second embodiment.

(55) As illustrated in FIG. **12**, a semiconductor device **200** according to the second embodiment includes an insulating layer **210** in place of the insulating layer **110**. Similar to the insulating layer **110**, the insulating layer **210** includes a layer of a nitride of Si, Al, Hf, Zr, Ti, Ta, or W, for example, and preferably includes a Si nitride (SiN) layer. The insulating layer **210** has a thickness in a range of 2 nm to 500 nm, and is preferably approximately 100 nm, for example. However, an opening

corresponding to the opening **110g** is not formed in the insulating layer **210**, and the entire lower surface of the gate electrode **111** makes contact with the insulating layer **210**. The gate electrode **111** does not make contact with the protective layer **106**.

(56) Otherwise, the configuration of the second embodiment is similar to that of the first embodiment.

(57) Next, a method for manufacturing the semiconductor device **200** according to the second embodiment will be described. FIG. **13** is a cross sectional view illustrating the method for manufacturing the semiconductor device **200** according to the second embodiment.

(58) First, similar to the first embodiment, the processes up to forming the source electrode **108** and the drain electrode **109** are performed, as illustrated in FIG. **6**. Then, as illustrated in FIG. **13**, the insulating layer **210**, that covers the source electrode **108** and the drain electrode **109**, is formed on the protective layer **106**. The insulating layer **210** can be formed by plasma CVD, for example. The insulating layer **210** can be formed by ALD or sputtering. By forming the insulating layer **210**, it is possible to increase the density of the 2DEG **150** near the upper surface of the channel layer **103**, below the region between the source electrode **108** and the drain electrode **109**.

(59) Thereafter, the gate electrode **111** is formed on the insulating layer **210**. The gate electrode **111** can be formed by a lift-off method, for example, similar to the first embodiment.

(60) The semiconductor device **200** according to the second embodiment can be manufactured in the manner described above.

(61) The semiconductor device **200** according to the second embodiment employs a metal-insulator-semiconductor (MIS) type gate structure. Similar to the first embodiment, it is possible to reduce an increase in sheet resistance even when the barrier layer **105** of the semiconductor device **200** is made thin.

Third Embodiment

(62) Next, a third embodiment will be described. The third embodiment relates to a discrete package of HEMT. FIG. **14** is a diagram illustrating the discrete package according to the third embodiment.

(63) As illustrated in FIG. **14**, in the third embodiment, a back surface of a semiconductor device **1210** having a configuration similar to that of the first or second embodiment is fixed to a land (die pad) **1233** using a die attach agent **1234**, such as a solder or the like. In addition, one end of a wire **1235d**, such as an Al wire or the like, is connected to a drain pad **1226d** to which the drain electrode **109** is connected, and the other end of the wire **1235d** is connected to a drain lead **1232d** integral with the land **1233**. One end of a wire **1235s**, such as an Al wire or the like, is connected to a source pad **1226s** to which the source electrode **108** is connected, and the other end of the wire **1235s** is connected to a source lead **1232s** independent of the land **1233**. One end of a wire **1235g**, such as an Al wire or the like, is connected to a gate pad **1226g** to which the gate electrode **111** is connected, and the other end of the wire **1235g** is connected to a gate lead **1232g** independent of the land **1233**. The, the land **1233**, the semiconductor device **1210**, or the like are packaged into a package by a mold resin **1231**, so that a portion of the gate lead **1232g**, a portion of the drain lead **1232d**, and a portion of the source lead **1232s** protrude from the package.

(64) Such a discrete package can be manufactured in the following manner, for example. First, the semiconductor device **1210** is fixed to the land **1233** of a lead frame using the die attach agent **1234**, such as the solder or the like. Then, the gate pad **1226g** is connected to the gate lead **1232g** of the lead frame, the drain pad **1226d** is connected to the drain lead **1232d** of the lead frame, and the source pad **1226s** is connected to the source lead **1232s** of the lead frame, by bonding using the wires **1235g**, **1235d**, and **1235s**, respectively. Thereafter, an encapsulation is performed using the mold resin **1231**, by transfer molding. The lead frame is then separated from the mold resin **1231**.

Fourth Embodiment

(65) Next, a fourth embodiment will be described. The fourth embodiment relates to a power factor correction (PFC) circuit including the HEMT. FIG. **15** is a circuit diagram illustrating the PFC

circuit according to the fourth embodiment.

(66) A PFC circuit **1250** includes a switching device (or transistor) **1251**, a diode **1252**, a choke coil **1253**, capacitors **1254** and **1255**, a diode bridge **1256**, and an AC power supply **1257**. A drain electrode of the switching device **1251** is connected to an anode terminal of the diode **1252** and one terminal of the choke coil **1253**. A source electrode of the switching device **1251**, one terminal of the capacitor **1254**, and one terminal of the capacitor **1255** are connected. The other terminal of the capacitor **1254** and the other terminal of the choke coil **1253** are connected. The other terminal of the capacitor **1255** and a cathode terminal of the diode **1252** are connected. In addition, a gate driver is connected to the gate electrode of the switching device **1251**. The AC power supply **1257** is connected between the two terminals of the capacitor **1254** via the diode bridge **1256**. A DC power supply is connected between the two terminals of the capacitor **1255**. In this embodiment, a semiconductor device having a configuration similar to that of the first or second embodiment is used for the switching device **1251**.

(67) When manufacturing the PFC circuit **1250**, the switching device **1251** is connected to the diode **1252**, the choke coil **1253**, or the like, using a solder or the like.

Fifth Embodiment

(68) Next, a fifth embodiment will be described. The fifth embodiment relates to a power supply device including the HEMT, suitable for use as a server power supply. FIG. **16** is a circuit diagram illustrating the power supply device according to the fifth embodiment.

(69) The power supply device includes a high voltage primary circuit **1261**, a low voltage secondary circuit **1262**, and a transformer **1263** disposed between the primary circuit **1261** and the secondary circuit **1262**.

(70) The primary circuit **1261** is provided with the PFC circuit **1250** according to the fourth embodiment, and an inverter circuit, such as a full bridge inverter circuit **1260**, connected between the two terminals of the capacitor **1255** of the PFC circuit **1250**. The full bridge inverter circuit **1260** includes a plurality of switching devices. More particularly, the full bridge inverter circuit **1260** includes four switching devices **1264a**, **1264b**, **1264c**, and **1264d** in this example.

(71) The secondary circuit **1262** includes a plurality of switching devices. More particularly, the secondary circuit **1262** includes three switching devices **1265a**, **1265b**, and **1265c** in this example.

(72) In this embodiment, a semiconductor device having a configuration similar to that of the first or second embodiment is used for the switching device **1251** of the PFC circuit **1250**, and the switching devices **1264a**, **1264b**, **1264c**, and **1264d** of the full bridge inverter circuit **1260**, respectively forming the primary circuit **1261**. On the other hand, a conventional MIS type field effect transistor (FET) using silicon is used for the switching devices **1265a**, **1265b**, and **1265c** of the secondary circuit **1262**.

Sixth Embodiment

(73) Next, a sixth embodiment will be described. The sixth embodiment relates to an amplifier including the HEMT. FIG. **17** is a circuit diagram illustrating the amplifier according to the sixth embodiment.

(74) The amplifier according to the sixth embodiment includes a digital predistortion circuit **1271**, mixers **1272a** and **1272b**, and a power amplifier **1273**.

(75) The digital predistortion circuit **1271** compensates for a nonlinear distortion of an input signal. The mixer **1272a** mixes the input signal, compensated of the non-linear distortion, and an AC signal. The power amplifier **1273** includes a semiconductor device having a configuration similar to that of the first or second embodiment, and amplifies the input signal mixed with the AC signal. In this embodiment, an output signal can be mixed with the AC signal by the mixer **1272b**, and supplied to the digital predistortion circuit **1271**, by switching a switching device, for example. This amplifier can be used as a high-frequency amplifier, a high-power amplifier, or the like. The high-frequency amplifier can be used in transmitting and receiving devices for cellular base stations, radar devices, and microwave generators, for example.

(76) The substrate may be a silicon carbide (SiC) substrate, a sapphire substrate, a silicon substrate, an AlN substrate, a GaN substrate, a diamond substrate, or the like. The substrate may be conductive, semi-insulating, or insulating.

(77) The configurations of the gate electrode, the source electrode, and the drain electrode are not limited to those of the embodiments described above. For example, each electrode may be formed by a single layer. In addition, the method for forming each electrode is not limited to the lift-off method. Further, as long as the ohmic characteristics are obtainable, the heat treatment after forming the source electrode and the drain electrode may be omitted. The heat treatment may be performed after forming the gate electrode.

(78) Moreover, an n-type GaN region may be formed in a portion of the nitride semiconductor laminated structure directly below the source electrode and the drain electrode. This n-type GaN region can be formed by ion implantation, or regrown, for example.

(79) According to the present disclosure, it is possible to provide a semiconductor device capable of reducing an increase in sheet resistance even when a barrier layer is made thin.

(80) Although the embodiments are numbered with, for example, “first,” “second,” “third,” “fourth,” “fifth,” or “sixth,” the ordinal numbers do not imply priorities of the embodiments. Many other variations and modifications will be apparent to those skilled in the art.

(81) All examples and conditional language recited herein are intended for pedagogical purposes to aid the reader in understanding the invention and the concepts contributed by the inventor to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions, nor does the organization of such examples in the specification relate to a showing of the superiority and inferiority of the invention. Although the embodiments of the present invention have been described in detail, it should be understood that the various changes, substitutions, and alterations could be made hereto without departing from the spirit and scope of the invention.

Claims

1. A semiconductor device comprising: a channel layer; a barrier layer disposed above the channel layer; a protective layer disposed on the barrier layer; and an insulating layer disposed on the protective layer, wherein a composition of the barrier layer is represented by $\text{In}_{x1}\text{Al}_{1-x1-x2}\text{Ga}_{x2}\text{N}$, where $0.00 \leq x1 \leq 0.20$, and $0.10 \leq x2 \leq 1.00$, a composition of the protective layer is represented by $\text{In}_{y1}\text{Al}_{1-y1-y2}\text{Ga}_{y2}\text{N}$, where $0.00 \leq y1 \leq 0.20$, and $0.10 \leq y2 \leq 1.00$, $x2 < y2$, and the protective layer is an amorphous layer.
2. The semiconductor device as claimed in claim 1, wherein the protective layer does not include Si, Ge, Sn, and O.
3. The semiconductor device as claimed in claim 1, wherein the protective layer does not have a polarization aligned in a direction parallel to a c-axis of the channel layer.
4. The semiconductor device as claimed in claim 1, wherein the protective layer is an AlN layer.
5. The semiconductor device as claimed in claim 1, wherein the barrier layer includes Ga.
6. The semiconductor device as claimed in claim 1, wherein the insulating layer includes Si, Ge, Sn, O, or any combination thereof.
7. The semiconductor device as claimed in claim 1, wherein a distance between an upper surface of the channel layer and a lower surface of the protective layer is less than or equal to 10 nm.
8. The semiconductor device as claimed in claim 1, wherein a thickness of the protective layer is less than or equal to 6 nm.
9. The semiconductor device as claimed in claim 1, further comprising: a spacer layer disposed between the channel layer and the barrier layer.
10. The semiconductor device as claimed in claim 1, further comprising: a cap layer disposed between the barrier layer and the protective layer.

11. The semiconductor device as claimed in claim 1, further comprising: a gate electrode, a source electrode, and a drain electrode disposed above the barrier layer, wherein a two-dimensional electron gas is present in the channel layer below the gate electrode, in a state where no voltage is applied to the gate electrode.

12. A power factor correction circuit comprising: the semiconductor device according to claim 1.

13. An amplifier comprising: the semiconductor device according to claim 1.

14. The amplifier as claimed in claim 13, further comprising: a digital predistortion circuit configured to compensate for a nonlinear distortion of an input signal thereto; a mixer configured to mix an AC signal, and the input signal compensated of the nonlinear distortion by the digital predistortion circuit; and a power amplifier, including the semiconductor device, and configured to amplify the input signal mixed with the AC signal by the mixer.

15. A power supply device comprising: the semiconductor device according to claim 1.

16. The power supply device as claimed in claim 15, further comprising: a high voltage primary circuit including the semiconductor device; a low voltage secondary circuit; and a transformer disposed between the high voltage primary circuit and the low voltage secondary circuit.
