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Schottky barrier diode

Abstract

A Schottky barrier diode includes a semiconductor substrate made of gallium oxide, a drift layer made of gallium oxide and formed on the semiconductor substrate, an anode electrode brought into Schottky contact with the drift layer, a cathode electrode brought into ohmic contact with the semiconductor substrate, an insulating film covering the inner wall of a trench formed in the drift layer, and a protective film covering the anode electrode, wherein a part of the protective film is embedded in the trench. The part of the protective film is thus embedded in the trench, so that adhesion performance between the anode electrode and protective film is enhanced. This makes it possible to prevent peeling at the boundary between the anode electrode and the protective film.

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS

(1) This application is the U.S. National Phase under 35 U.S.C. § 371 of International Application No. PCT/JP2020/037723, filed on Oct. 5, 2020, which claims the benefit of Japanese Patent Application No. 2019-228556, filed on Dec. 18, 2019, the entire contents of each are hereby incorporated by reference.

TECHNICAL FIELD

(2) The present invention relates to a Schottky barrier diode and, more particularly, to a Schottky barrier diode using gallium oxide.

BACKGROUND ART

(3) A Schottky barrier diode is a rectifying element utilizing a Schottky barrier generated due to bonding between metal and a semiconductor and is lower in forward voltage and higher in switching speed than a normal diode having a PN junction. Thus, the Schottky barrier diode is sometimes utilized as a switching element for a power device.

(4) When the Schottky barrier diode is utilized as a switching element for a power device, it is necessary to ensure a sufficient backward withstand voltage, so that, silicon carbide (SiC), gallium nitride (GaN), or gallium oxide (Ga.sub.2O.sub.3) having a larger band gap is sometimes used in place of silicon (Si). Among them, gallium oxide has a very large band gap (4.8 eV to 4.9 eV) and a large breakdown field (about 8 MV/cm), so that a Schottky barrier diode using gallium oxide is very promising as the switching element for a power device. An example of the Schottky barrier diode using gallium oxide is described in Patent Documents 1 and 2.

(5) In Schottky barrier diodes described in Patent Documents 1 and 2, a plurality of trenches are provided in a gallium oxide layer. With the above structure, where the plurality of trenches are formed in the gallium oxide layer, when a reverse voltage is applied, a mesa region positioned between adjacent trenches becomes a depletion layer, so that a channel region of a drift layer is pinched off. Thus, a leak current upon application of the reverse voltage can be significantly reduced.

CITATION LIST

Patent Document

(6) [Patent Document 1] JP 2017-199869A [Patent Document 2] JP 2019-079984A

SUMMARY OF THE INVENTION

Problem to be Solved by the Invention

(7) In an actual device, a protective film is formed on an anode electrode to thereby provide electrical insulation from external circuits. However, adhesion performance between a metal anode electrode and a protective film made of SiN or the like is low, so that peeling is likely to occur at the interface therebetween.

(8) It is therefore an object of the present invention to prevent, in a Schottky barrier diode using gallium oxide, peeling at the interface between an anode electrode and a protective film.

Means for Solving the Problem

(9) A Schottky barrier diode according to the present invention includes: a semiconductor substrate made of gallium oxide; a drift layer made of gallium oxide and formed on the semiconductor substrate; an anode electrode brought into Schottky contact with the drift layer; a cathode electrode brought into ohmic contact with the semiconductor substrate; an insulating film covering the inner wall of a trench formed in the drift layer; and a protective film covering the anode electrode, wherein a part of the protective film is embedded in the trench.

(10) According to the present invention, a part of the protective film is embedded in the trench, thus enhancing adhesion performance between the anode electrode and the protective film. This makes it possible to prevent peeling at the interface between the anode electrode and the protective film.

(11) In the present invention, the trench may be formed in a ring shape and filled with a part of the protective film and a metal member electrically connected to the anode electrode. Thus, the presence of the ring-shaped trench allows an electric field applied to the drift layer to be relaxed.

(12) The trench may have a flat side wall part, and the boundary between the protective film and the metal member may terminate at the side wall part. Further, the trench may have a flat bottom surface part, and the boundary between the protective film and the metal member may terminate at the bottom surface part. This makes it possible to relax an electric field applied to the drift layer in the vicinity of the end position of the metal member.

Advantageous Effects of the Invention

(13) As described above, according to the present invention, it is possible to prevent, in a Schottky barrier diode using gallium oxide, peeling at the interface between the anode electrode and the protective film.

Description

BRIEF DESCRIPTION OF DRAWINGS

- (1) FIG. 1 is a schematic plan view illustrating the configuration of a Schottky barrier diode 11 according to a first embodiment of the present invention.
- (2) FIG. 2 is a schematic cross-sectional view taken along line A-A in FIG. 1.
- (3) FIG. 3 is a process view for explaining the manufacturing method for the Schottky barrier diode 11.
- (4) FIG. 4 is a process view for explaining the manufacturing method for the Schottky barrier diode 11.
- (5) FIG. 5 is a process view for explaining the manufacturing method for the Schottky barrier diode 11.
- (6) FIG. 6 is a process view for explaining the manufacturing method for the Schottky barrier diode 11.
- (7) FIG. 7 is a process view for explaining the manufacturing method for the Schottky barrier diode 11.
- (8) FIG. 8 is a process view for explaining the manufacturing method for the Schottky barrier diode 11.
- (9) FIG. 9 is a schematic plan view illustrating the configuration of a Schottky barrier diode 12 according to a second embodiment of the present invention.
- (10) FIG. 10 is a schematic cross-sectional view taken along line B-B in FIG. 9.
- (11) FIG. 11 is a schematic plan view illustrating the configuration of a Schottky barrier diode 13 according to a third embodiment of the present invention.
- (12) FIG. 12 is a schematic plan view illustrating the configuration of a Schottky barrier diode 14 according to a fourth embodiment of the present invention.
- (13) FIG. 13 is a schematic plan view illustrating the configuration of a Schottky barrier diode 15 according to a fifth embodiment of the present invention.
- (14) FIG. 14 is a schematic plan view illustrating the configuration of a Schottky barrier diode 15A according to a modification of the fifth embodiment.
- (15) FIG. 15 is a schematic plan view illustrating the configuration of a Schottky barrier diode 16 according to a sixth embodiment of the present invention.
- (16) FIG. 16 is a schematic plan view illustrating the configuration of a Schottky barrier diode 17 according to a seventh embodiment of the present invention.

(17) FIG. 17 is a graph showing a simulation result of an Example 1.

(18) FIG. 18 is a graph showing a simulation result of an Example 2.

(19) FIG. 19 is a graph showing a simulation result of an Example 3.

MODE FOR CARRYING OUT THE INVENTION

(20) Preferred embodiments of the present invention will be explained below in detail with reference to the accompanying drawings.

First Embodiment

(21) FIG. 1 is a schematic plan view illustrating the configuration of a Schottky barrier diode 11 according to a first embodiment of the present invention. FIG. 2 is a schematic cross-sectional view taken along line A-A in FIG. 1.

(22) As illustrated in FIGS. 1 and 2, the Schottky barrier diode 11 according to the present embodiment has a semiconductor substrate 20 and a drift layer 30, both of which are made of gallium oxide (β -Ga.sub.2O.sub.3). The semiconductor substrate 20 and the drift layer 30 are each introduced with silicon (Si) or tin (Sn) as an n-type dopant. The concentration of the dopant is higher in the semiconductor substrate 20 than in the drift layer 30, whereby the semiconductor substrate 20 and the drift layer 30 function as an n.sup.+ layer and an n.sup.- layer, respectively.

(23) The semiconductor substrate 20 is obtained by cutting a bulk crystal formed using a melt-growing method, and the thickness thereof is about 250 μ m. Although there is no particular restriction on the planar size of the semiconductor substrate 20, the planar size is generally selected in accordance with the amount of current flowing in the element and, when the maximum amount of forward current is about 20 A, the size may be set to about 2.4 mm \times 2.4 mm in a plan view.

(24) The semiconductor substrate 20 in a mounted state has an upper surface 21 positioned on its upper surface side and a back surface 22 positioned on its lower surface side (opposite to the upper surface side 21). The drift layer 30 is formed on the entire upper surface 21. The drift layer 30 is a thin film obtained by epitaxially growing gallium oxide on the upper surface 21 of the semiconductor substrate 20 using a reactive sputtering method, a PLD method, an MBE method, an MOCVD method, or an HVPE method. Although there is no particular restriction on the film thickness of the drift layer 30, the film thickness is generally selected in accordance with the backward withstand voltage of the element and, in order to ensure a withstand voltage of about 600 V, the film thickness may be set to, e.g., about 7 μ m.

(25) An anode electrode 40, which is brought into Schottky contact with the drift layer 30, is formed on an upper surface 31 of the drift layer 30. The anode electrode 40 is formed of metal such as platinum (Pt), palladium (Pd), gold (Au), nickel (Ni), molybdenum (Mo), Copper (Cu), or the like. The anode electrode 40 may have a multilayer structure of different metal films, such as Pt/Au, Pt/Al, Pd/Au, Pd/Al, Pt/Ti/Au, or Pd/Ti/Au. On the other hand, a cathode electrode 50, which is brought into ohmic contact with the semiconductor substrate 20, is formed on the back surface 22 of the semiconductor substrate 20. The cathode electrode 50 is formed of metal such as titanium (Ti). The cathode electrode 50 may have a multilayer structure of different metal films, such as Ti/Au or Ti/Al.

(26) In the present embodiment, an outer peripheral trench 61 having a ring shape is formed in the drift layer 30. The inner wall of the outer peripheral trench 61 includes a side wall part S1 positioned outside, a side wall part S2 positioned inside, and a bottom surface part B. In the present embodiment, the side wall parts S1, S2 and bottom surface part B are flat, and a corner part C positioned at the boundary between the side wall part S1 or side wall part S2 and the bottom surface part B has a curved shape. The inner wall of the outer peripheral trench 61 is covered with an insulating film 63 made of HfO.sub.2 or the like. Aside from HfO.sub.2, an insulating material such as Al.sub.2O.sub.3 can be used as the material of the insulating film 63. The outer peripheral trench 61 is mostly filled with a metal member 41. The material of the metal member 41 may be the same as that of the anode electrode 40 (that is, the metal member 41 may be a part of the anode electrode 40) or may be different therefrom.

(27) The outer peripheral portion of the anode electrode **40** is covered with a protective film **70**. The protective film **70** is made of a resin material such as epoxy resin, acrylic resin (polymethyl metacrylate, etc.), polyurethane, polyimide, polyvinyl alcohol, fluororesin, or polyolefin, or an inorganic insulating material including an inorganic oxide or nitride film, such as silicon oxide, aluminum oxide, or silicon nitride. The protective film **70** has an opening **71** exposing the center portion of the anode electrode **40** to which a bonding wire or the like is to be connected. The protective film **70** protects the anode electrode **40** and provides electrical insulation from the external circuits.

(28) As illustrated in FIG. 2, in the Schottky barrier diode **11** according to the present embodiment, a part **72** of the protective film **70** is embedded in the outer peripheral trench **61**. Adhesion performance between the metal anode electrode **40** and the protective film **70** made of SiN or the like is low, so that peeling is likely to occur at the interface therebetween; however, in the present embodiment, the part **72** of the protective film **70** is embedded in the outer peripheral trench **61**, so that performance is enhanced as compared to a case where the anode electrode **40** and the protective film **70** contact each other in one dimensional manner. This makes it possible to prevent peeling at the interface between the anode electrode **40** and the protective film **70**.

(29) Further, in the present embodiment, the boundary between the part **72** of the protective film **70** and the metal member **41**, both embedded in the outer peripheral trench **61**, contact the insulating film **63** on the outer side wall part **S1**. As described above, the side wall part **S1** is flat, and accordingly the boundary between the protective film **70** and the metal member **41**, i.e., the end portion of the metal member **41** terminates at a flat surface. Thus, as compared to a case where the metal member **41** terminates at a surface having a curved shape, such as the corner part **C**, an electric field applied to the drift layer **30** in the vicinity of the end portion of the metal member **41** can be relaxed.

(30) The following describes a manufacturing method for the Schottky barrier diode **11** according to the present embodiment.

(31) FIGS. 3 to 8 are process views for explaining the manufacturing method for the Schottky barrier diode **11** according to the present embodiment, each of which corresponds to the cross section illustrated in FIG. 2.

(32) First, as illustrated in FIG. 3, the semiconductor substrate **20** made of gallium oxide is prepared, and then the drift layer **30** made of gallium oxide is formed on the upper surface **21** of the semiconductor substrate **20**. As described above, the drift layer **30** can be formed by epitaxially growing gallium oxide on the upper surface **21** of the semiconductor substrate **20** using a reactive sputtering method, a PLD method, an MBE method, an MOCVD method, or an HVPE method.

(33) Then, as illustrated in FIG. 4, dry-etching using BCl₃ or the like is performed to form the ring-shaped outer peripheral trench **61** in the drift layer **30**. Etching conditions are set such that at least the side wall parts **S1** and **S2** each become a substantially vertical flat surface. Preferably, the bottom surface part **B** is also made to be a substantially vertical flat surface.

(34) Subsequently, as illustrated in FIG. 5, the insulating film **63** is formed on the surface of the drift layer **30**. The insulating film **63** can be formed using a commonly known film forming method such as an ALD method. Thereafter, the insulating film **63** formed on the upper surface **31** of the drift layer **30** is removed by commonly known treatment such as wet-etching, dry-etching, or CMP. As a result, the upper surface **31** of the drift layer **30** is exposed, and the inner wall of the outer peripheral trench **61** is covered with the insulating film **63**. At this time, the upper surface **31** of the drift layer **30** may be removed partly.

(35) Then, as illustrated in FIG. 6, the anode electrode **40** is formed on the entire surface. The metal member **41** to be filled in the outer peripheral trench **61** may be made of a material different from the material of the anode electrode **40**. In this case, the anode electrode **40** may be formed before the metal member **41** made of a material different from that of the anode electrode **40** is filled in the outer peripheral trench **61**, or the metal member **41** made of a material different from that of the

anode electrode **40** may be first filled in the outer peripheral trench **61** as long as the different material does not remain on the surface **31** of the drift layer **30**. With this configuration, the metal member **41** embedded in the outer peripheral trench **61** is electrically connected to the anode electrode **40** and hence has the same potential as the anode electrode **40**.

(36) Then, as illustrated in FIG. **7**, a resist **R** is formed so as to cover the center portion of the anode electrode **40** and expose the outer peripheral portion thereof. The resist **R** can be patterned by a photolithography method. An outer edge **E0** of the resist **R** is designed so as to be positioned between an outer edge **E1** of the outer peripheral trench **61** and an inner edge **E2** of the outer peripheral trench **61**. That is, the outer diameter of the resist **R** is made smaller than the outer diameter of the outer peripheral trench **61** and larger than the inner diameter of the outer peripheral trench **61** such that the outer edge **E0** of the resist **R** is positioned inside the outer peripheral trench **61**.

(37) Then, as illustrated in FIG. **8**, the anode electrode **40** is etched with the resist **R** as a mask. In the etching process of the anode electrode **40**, after the upper surface **31** of the drift layer **30** is exposed by the etching, over-etching is performed to partly remove a part of the metal member **41** that is embedded in the outer peripheral trench **61**, to thereby forming a cavity **42**. Thereafter, the resist **R** is removed.

(38) Then, the cathode electrode **50** is formed on the back surface **22** of the semiconductor substrate **20**, and the protective film **70** is formed so as to cover the anode electrode **40**, whereby the part **72** of the protective film **70** is embedded in the cavity **42**. When a resin material is used as the material of the protective film **70**, there are available methods of: applying and drying a resin solution to obtain a resin film; applying or vapor-depositing a resin monomer, followed by polymerization; and applying crosslinking treatment after film formation. When an inorganic insulating material is used as the material of the protective film **70**, a vacuum process such as a sputtering or vapor-deposition method, or a solution process such as a sol-gel method may be used. Thus, the Schottky barrier diode **11** according to the present embodiment is completed.

(39) As described above, in the Schottky barrier diode **11** according to the present embodiment, the part **72** of the protective film **70** is embedded in the outer peripheral trench **61**, thus enhancing adhesion performance between the anode electrode **40** and the protective film **70**. This makes it possible to prevent peeling at the interface between the anode electrode **40** and the protective film **70**.

Second Embodiment

(40) FIG. **9** is a schematic plan view illustrating the configuration of a Schottky barrier diode **12** according to a second embodiment of the present invention. FIG. **10** is a schematic cross-sectional view taken along the line B-B in FIG. **9**.

(41) As illustrated in FIGS. **9** and **10**, the Schottky barrier diode **12** according to the second embodiment differs from the Schottky barrier diode **11** according to the first embodiment in that a plurality of center trenches **62** are formed in the drift layer **30**. Other basic configurations are the same as those of the Schottky barrier diode **11** according to the first embodiment, so the same reference numerals are given to the same elements, and overlapping description will be omitted.

(42) The center trenches **62** are formed in an area surrounded by the outer peripheral trench **61** so as to overlap the anode electrode **40** in a plan view. The outer peripheral trench **61** and center trenches **62** need not be completely separated from each other and may be connected to each other as illustrated in FIG. **9**.

(43) A part of the drift layer **30** that is defined by the trenches **61** and **62** constitutes a mesa region **M**. The mesa region **M** becomes a depletion layer when a reverse voltage is applied between the anode electrode **40** and the cathode electrode **50**, so that a channel region of the drift layer **30** is pinched off. Thus, a leak current upon application of the reverse voltage can be significantly reduced.

(44) Although not particularly limited, assuming that the widths of the outer peripheral trench **61**

and center trench **62** are **W1** and **W2**, respectively,

(45) $W1 > W2$ is satisfied in the present embodiment. This is to prevent dielectric breakdown at the bottom portion of the outer peripheral trench **61** on which an electric field concentrates particularly. That is, an increase in the width **W1** of the outer peripheral trench **61** increases the distance between the two corner parts **C** when the outer peripheral trench **61** is viewed in the cross section. This makes it less likely to cause dielectric breakdown in the vicinity of the bottom portion of the outer peripheral trench **61**. The depth of the outer peripheral trench **61** and that of the center trench **62** are the same.

(46) In the present embodiment as well, the part **72** of the protective film **70** is embedded in the outer peripheral trench **61**, thus enhancing adhesion performance between the anode electrode **40** and the protective film **70**. As exemplified by the present embodiment, when the outer peripheral and center trenches **61** and **62** are formed in the drift layer **30**, it is possible to prevent peeling of the protective film **70** by embedding the part **72** of the protective film **70** in the outer peripheral trench **61**.

Third Embodiment

(47) FIG. **11** is a schematic cross-sectional view illustrating the configuration of a Schottky barrier diode **13** according to a third embodiment of the present invention.

(48) As illustrated in FIG. **11**, the Schottky barrier diode **13** according to the third embodiment differs from the Schottky barrier diode **12** according to the second embodiment in that the boundary between the part **72** of the protective film **70** and the metal member **41** reaches the bottom surface part **B** of the outer peripheral trench **61** in which they are embedded. Other basic configurations are the same as those of the Schottky barrier diode **12** according to the second embodiment, so the same reference numerals are given to the same elements, and overlapping description will be omitted.

(49) In the present embodiment, the part **72** of the protective film **70** is embedded deeper in the outer peripheral trench **61**, and the bottom portion of the part **72** contacts the insulating film **63** covering the bottom surface part **B**, thus making it possible to prevent peeling of the protective film **70** more effectively. Further, as described above, the bottom surface part **B** is flat, and accordingly the boundary between the protective film **70** and metal member **41**, i.e., the end portion of the metal member **41** terminates at a flat surface. Thus, as compared to a case where the metal member **41** terminates at a surface having a curved shape, such as the corner part **C**, an electric field applied to the drift layer **30** in the vicinity of the end portion of the metal member **41** can be relaxed.

Fourth Embodiment

(50) FIG. **12** is a schematic cross-sectional view illustrating the configuration of a Schottky barrier diode **14** according to a fourth embodiment of the present invention.

(51) As illustrated in FIG. **12**, the Schottky barrier diode **14** according to the fourth embodiment differs from the Schottky barrier diode **12** according to the second embodiment in that the boundary between the part **72** of the protective film **70** and the metal member **41** terminates at the inner side wall part **S2** of the outer peripheral trench **61** in which they are embedded. Other basic configurations are the same as those of the Schottky barrier diode **12** according to the second embodiment, so the same reference numerals are given to the same elements, and overlapping description will be omitted.

(52) In the present embodiment, the part **72** of the protective film **70** is embedded deeper in the outer peripheral trench **61**, and the bottom portion of the part **72** contacts the insulating film **63** covering the side wall part **S2**, thus making it possible to prevent peeling of the protective film **70** more effectively. Further, the part **72** of the protective film **70** is shaped so as to have a large diameter at the bottom portion of the outer peripheral trench **61** and a small diameter at the entrance thereof, so that a so-called anchor effect is also expected. Furthermore, as described above, the side wall part **S2** is flat, and accordingly the boundary between the protective film **70** and the metal member **41**, i.e., the end portion of the metal member **41** terminates at a flat surface.

Thus, as compared to a case where the metal member **41** terminates at a surface having a curved shape, such as the corner part C, an electric field to be applied to the drift layer **30** in the vicinity of the end portion of the metal member **41** can be relaxed.

Fifth Embodiment

(53) FIG. **13** is a schematic cross-sectional view illustrating the configuration of a Schottky barrier diode **15** according to a fifth embodiment of the present invention.

(54) As illustrated in FIG. **13**, the Schottky barrier diode **15** according to the fifth embodiment differs from the Schottky barrier diode **12** according to the second embodiment in that the part **72** of the protective film **70** embedded in the outer peripheral trench **61** does not contact the insulating film **63**. Other basic configurations are the same as those of the Schottky barrier diode **12** according to the second embodiment, so the same reference numerals are given to the same elements, and overlapping description will be omitted.

(55) As exemplified by the present embodiment, the part **72** of the protective film **70** embedded in the outer peripheral trench **61** may not necessarily contact the insulating film **63**.

(56) FIG. **14** is a schematic cross-sectional view illustrating the configuration of a Schottky barrier diode **15A** according to a modification of the fifth embodiment.

(57) As illustrated in FIG. **14**, the Schottky barrier diode **15A** according to the fifth embodiment differs from the Schottky barrier diode **15** according to the fifth embodiment in that the outer peripheral portion of the anode electrode **40** is positioned on the drift layer **30** with a field insulating film **80** interposed therebetween. Other basic configurations are the same as those of the Schottky barrier diode **15** according to the fifth embodiment, so the same reference numerals are given to the same elements, and overlapping description will be omitted.

(58) As exemplified by the present modification, when the outer peripheral portion of the anode electrode **40** and the drift layer **30** overlap each other, the field insulating film **80** is interposed therebetween, whereby the concentration of an electric field can be relaxed. As the material of the field insulating film **80**, SiO₂ or the like may be used.

Sixth Embodiment

(59) FIG. **15** is a schematic cross-sectional view illustrating the configuration of a Schottky barrier diode **16** according to a sixth embodiment of the present invention.

(60) As illustrated in FIG. **15**, the Schottky barrier diode **16** according to the sixth embodiment differs from the Schottky barrier diode **11** according to the first embodiment in that the bottom surface part B of the outer peripheral trench **61** is not flat but curved as a whole. Other basic configurations are the same as those of the Schottky barrier diode **11** according to the first embodiment, so the same reference numerals are given to the same elements, and overlapping description will be omitted.

(61) Even when the bottom surface part B of the outer peripheral trench **61** is curved as a whole, it is possible to relax an electric field applied to the drift layer **30** in the vicinity of the end portion of the metal member **41** as in the Schottky barrier diode **11** according to the first embodiment as long as the boundary between the part **72** of the protective film **70** and the metal member **41** terminates at the flat side wall part S1 of the outer peripheral trench **61** in which they are embedded.

Seventh Embodiment

(62) FIG. **16** is a schematic cross-sectional view illustrating the configuration of a Schottky barrier diode **17** according to a seventh embodiment of the present invention.

(63) As illustrated in FIG. **16**, the Schottky barrier diode **17** according to the seventh embodiment differs from the Schottky barrier diode **16** according to the sixth embodiment in that the boundary between the part **72** of the protective film **70** and the metal member **41** terminates at the inner side wall part S2 of the outer peripheral trench **61** in which they are embedded. Other basic configurations are the same as those of the Schottky barrier diode **16** according to the sixth embodiment, so the same reference numerals are given to the same elements, and overlapping description will be omitted.

(64) Even when the bottom surface part B of the outer peripheral trench **61** is curved as a whole, it is possible to relax an electric field applied to the drift layer **30** in the vicinity of the end portion of the metal member **41** as in the Schottky barrier diode **11** according to the first embodiment as long as the boundary between the part **72** of the protective film **70** and the metal member **41** terminates at the flat side wall part S2 of the outer peripheral trench **61** in which they are embedded.

(65) While the preferred embodiments of the present invention have been described, the present invention is not limited to the above embodiments, and various modifications may be made within the scope of the present invention, and all such modifications are included in the present invention.

EXAMPLES

Example 1

(66) A simulation model of Example 1 having the same configuration as the Schottky barrier diode **12** illustrated in FIG. **10** was assumed, and electric field strength was simulated with an 800 V reverse voltage applied between the anode electrode **40** and the cathode electrode **50**. The dopant concentration of the semiconductor substrate **20** was set to $1 \times 10^{18} \text{ cm}^{-3}$, and the dopant concentration of the drift layer **30** was to $2 \times 10^{16} \text{ cm}^{-3}$. The thickness of the drift layer **30** was set to 7 μm . The width W1 of the outer peripheral trench **61** was set to 10 μm , the width of the center trench was to 2 μm , and the depths of the trenches **61** and **62** were to 3 μm . Further, the width of a part of the drift layer **30** that contacts the anode electrode **40**, i.e., the width of the mesa region M was set to 2 μm . The insulating film **63** was an HfO_2 film having a thickness of 50 nm. As the material of the protective film **70**, SiN was used.

(67) Then, electric field strength applied to the corner part C was simulated with a depth position x of the boundary between the part **72** of the protective film **70** and the metal member **41** changed from 0 μm to 3 μm . The depth position x refers to, as illustrated in FIG. **10**, the boundary position between the part **72** of the protective film **70** and the metal member **41** from the bottom portion of the outer peripheral trench **61**. The simulation result is illustrated in FIG. **17**.

(68) As illustrated in FIG. **17**, when the depth position x is 0.9 μm or more, the electric field strength applied to the corner part C sufficiently falls below 8 MV/cm which is the dielectric breakdown electric field strength of gallium oxide. However, when the depth position x is 3.0 μm , i.e., when the protective film **70** is not embedded in the outer peripheral trench **61** at all, adhesion enhancing effect cannot be obtained, and peeling is more likely to occur. On the other hand, when the depth position x is 0.6 μm or less, the electric field strength applied to the corner part C becomes 8 MV/cm or more. This is considered because when the depth position x is too small, the boundary between the part **72** of the protective film **70** and the metal member **41** terminates at the curved surface of the corner part C.

Example 2

(69) A simulation model of Example 2 having the same configuration as the Schottky barrier diode **13** illustrated in FIG. **11** was assumed, and electric field strength was simulated with an 800 V reverse voltage applied between the anode electrode **40** and the cathode electrode **50**. The simulation model of Example 2 was different from the simulation model of Example 1 in that the boundary between the part **72** of the protective film **70** and the metal member **41** terminates at the bottom surface part B. The parameters in the simulation model of Example 2 were the same as those in the simulation model of Example 1.

(70) Then, electric field strength applied to the corner part C was simulated with a plane position x of the boundary between the part **72** of the protective film **70** and the metal member **41** changed from 0 μm to 10 μm . The plane position x refers to, as illustrated in FIG. **11**, the boundary position between the part **72** of the protective film **70** and the metal member **41** from the side wall part S2 of the outer peripheral trench **61**. The simulation result is illustrated in FIG. **18**.

(71) As illustrated in FIG. **18**, when the plane position x falls within the range of 0.5 μm to 9.5 μm , electric field strength applied to the corner part C sufficiently falls below 8 MV/cm which is the dielectric breakdown electric field strength of gallium oxide. On the other hand, when the plane

position x becomes close to 0 μm or 10 μm , the electric field strength applied to the corner part C becomes 8 MV/cm or more. This is considered because when the plane position x is too small or too large, the boundary between the part 72 of the protective film 70 and the metal member 41 terminates at the curved surface of the corner part C.

Example 3

(72) A simulation model of Example 3 having the same configuration as the Schottky barrier diode 14 illustrated in FIG. 12 was assumed, and electric field strength was simulated with an 800 V reverse voltage applied between the anode electrode 40 and the cathode electrode 50. The simulation model of Example 3 was different from the simulation model of Example 1 in that the boundary between the part 72 of the protective film 70 and the metal member 41 terminates at the side wall part S2. The parameters in the simulation model of Example 3 were the same as those in the simulation model of Example 1.

(73) Then, electric field strength applied to the corner part C was simulated with a depth position x of the boundary between the part 72 of the protective film 70 and metal member 41 changed from 0 μm to 3 μm . The depth position x refers to, as illustrated in FIG. 12, the boundary position between the part 72 of the protective film 70 and the metal member 41 from the bottom portion of the outer peripheral trench 61. The simulation result is illustrated in FIG. 19.

(74) As illustrated in FIG. 19, when the depth position x is 0.2 μm or more, the electric field strength applied to the corner part C sufficiently falls below 8 MV/cm which is the dielectric breakdown electric field strength of gallium oxide. However, when the depth position x becomes close to 0 μm , electric field strength applied to the corner part C becomes 8 MV/cm or more. This is considered because when the depth position x is too small, the boundary between the part 72 of the protective film 70 and the metal member 41 terminates at the curved surface of the corner part C.

REFERENCE SIGNS LIST

(75) 11-17, 15A Schottky barrier diode 20 semiconductor substrate 21 upper surface of semiconductor substrate 22 back surface of semiconductor substrate 30 drift layer 31 upper surface of the drift layer 40 anode electrode 41 metal member 42 cavity 50 cathode electrode 61 outer peripheral trench 62 center trench 63 insulating film 70 protective film 71 opening 72 part of protective film 80 field insulating film B bottom surface part C corner part E0-E2 edge M mesa region R resist S1, S2 side wall part

Claims

1. A Schottky barrier diode comprising: a semiconductor substrate made of gallium oxide; a drift layer made of gallium oxide and formed on the semiconductor substrate; an anode electrode brought into Schottky contact with the drift layer; a cathode electrode brought into ohmic contact with the semiconductor substrate; an insulating film covering an inner wall of a trench formed in the drift layer; and a protective film covering the anode electrode, wherein the trench is filled with a part of the protective film and a metal member such that a first sidewall of the trench, the insulating film, the part of the protective film, the metal member, the insulating film, and a second sidewall of the trench are sequentially arranged in this order without intervening elements.
2. The Schottky barrier diode as claimed in claim 1, wherein the trench is formed in a ring shape and filled with the part of the protective film and the metal member electrically connected to the anode electrode.
3. The Schottky barrier diode as claimed in claim 2, wherein the first sidewall has a flat side wall part, and wherein a boundary between the protective film and the metal member ends at the side wall part.
4. The Schottky barrier diode as claimed in claim 2, wherein the trench has a flat bottom surface part, and wherein a boundary between the protective film and the metal member ends at the bottom

surface part.

5. The Schottky barrier diode as claimed in claim 1, wherein a boundary between the part of the protective film and the metal member meets a portion of the first sidewall of the trench that is located below a topmost edge of the trench.

6. The Schottky barrier diode as claimed in claim 1, wherein a boundary between the part of the protective film and the metal member meets a portion of a bottom of the trench.
