US 20200251887A1

(19) **United States**
(12) **Patent Application Publication**
NODA et al.
(10) **Pub. No.: US 2020/0251887 A1**
(43) **Pub. Date: Aug. 6, 2020**

(54) **SURFACE-EMITTING LASER AND METHOD FOR MANUFACTURING SURFACE-EMITTING LASER**

(71) Applicants: **KYOTO UNIVERSITY**, SAKYO-KU, KYOTO-SHI, KYOTO (JP); **STANLEY ELECTRIC CO., LTD.**, Meguro-ku, Tokyo (JP)

(72) Inventors: **Susumu NODA**, Kyoto (JP); **Yoshinori TANAKA**, Kyoto (JP); **Menaka DE ZOYSA**, Kyoto (JP); **Junichi SONODA**, Tokyo (JP); **Tomoaki KOIZUMI**, Tokyo (JP); **Kei EMOTO**, Tokyo (JP)

(73) Assignees: **KYOTO UNIVERSITY**, SAKYO-KU, KYOTO-SHI, KYOTO (JP); **STANLEY ELECTRIC CO., LTD.**, MEGURO-KU, TOKYO (JP)

(21) Appl. No.: **16/488,595**

(22) PCT Filed: **Feb. 27, 2018**

(86) PCT No.: **PCT/JP2018/007272**
§ 371 (c)(1),
(2) Date: **Aug. 25, 2019**

(30) **Foreign Application Priority Data**

Feb. 27, 2017 (JP) 2017-035504

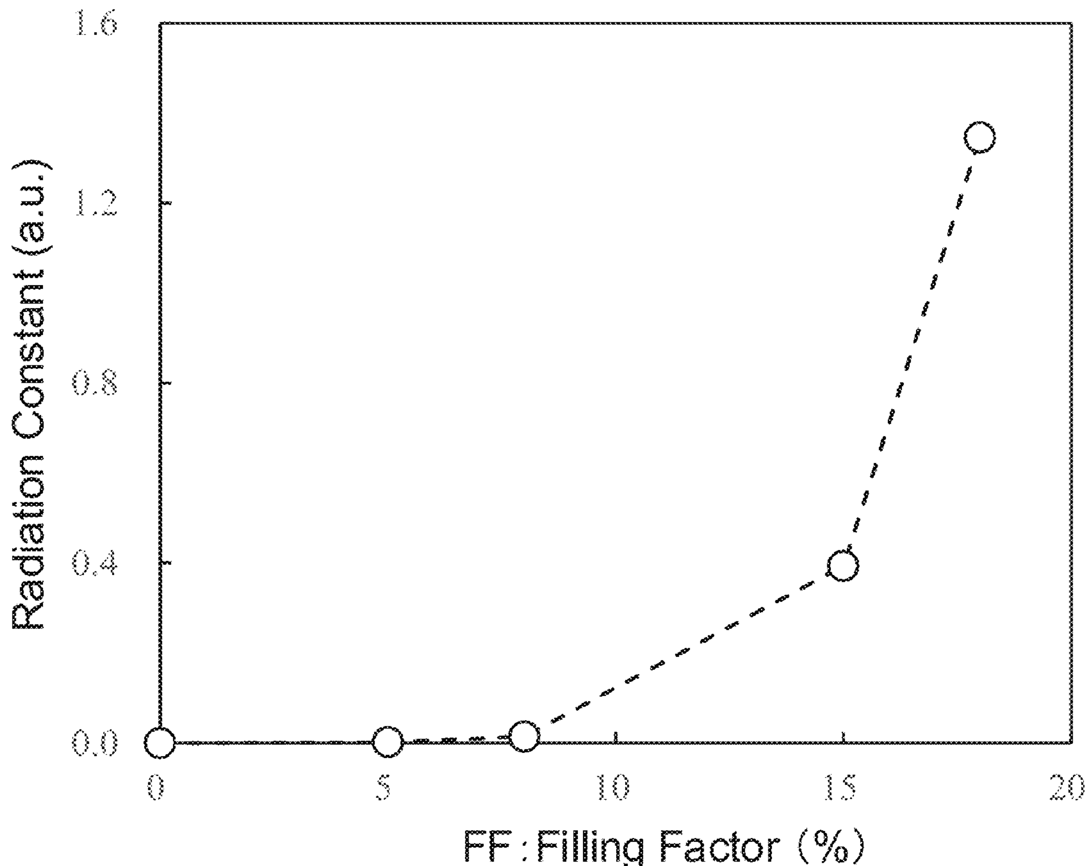
Publication Classification

(51) **Int. Cl.**
H01S 5/22 (2006.01)
H01S 5/18 (2006.01)
H01S 5/32 (2006.01)

(52) **U.S. Cl.**
CPC ***H01S 5/2216*** (2013.01); ***H01S 5/3211*** (2013.01); ***H01S 5/18*** (2013.01)

(57) **ABSTRACT**

A method for manufacturing a surface emitting laser made of a group-III nitride semiconductor by an MOVPE method includes: (a) of growing a first cladding layer of a first conductive type on a substrate; (b) of growing a first optical guide layer of the first conductive type on the first cladding layer; (c) of forming holes having a two-dimensional periodicity in a plane parallel to the first optical guide layer, in the first optical guide layer by etching; (d) supplying a gas containing a group-III material and a nitrogen source and performing growth to form recessed portions having a facet of a predetermined plane direction above openings of the holes, thereby closing the openings of the holes; and (e) of planarizing the recessed portions by mass transport, after the openings of the holes have been closed, wherein after said the planarizing, at least one side surface of the holes is a {10-10} facet.



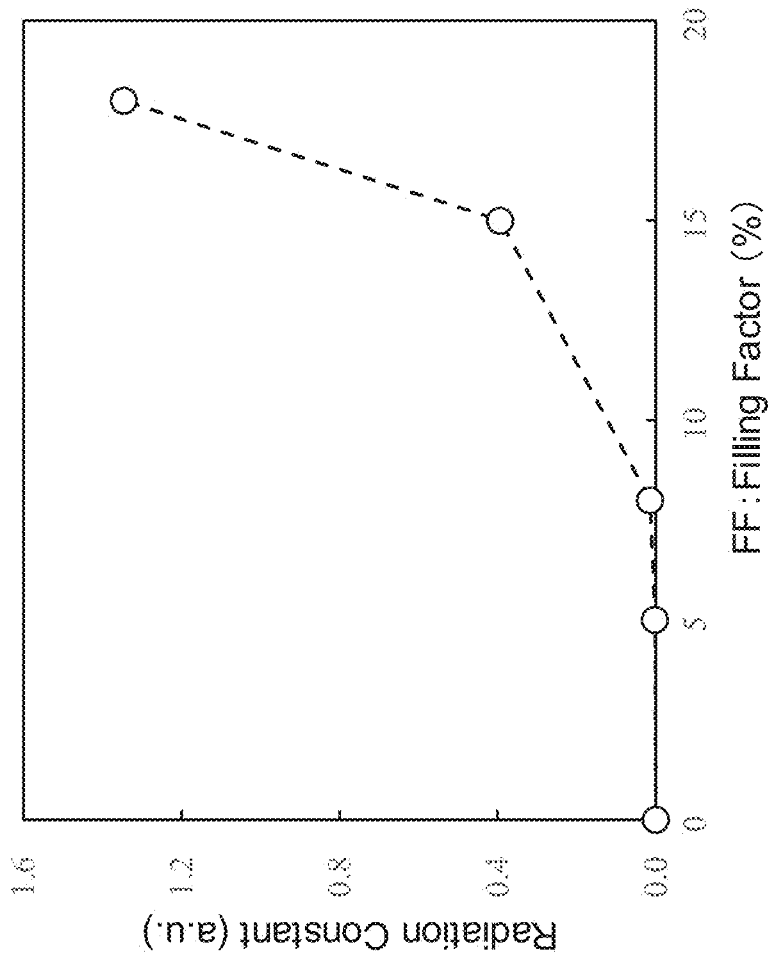


FIG.1

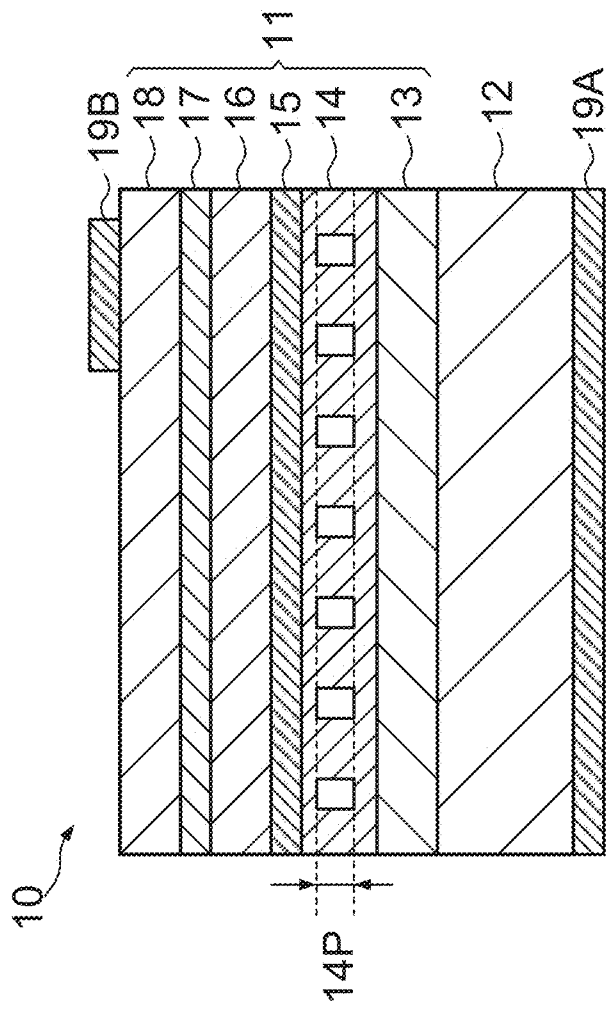


FIG.2

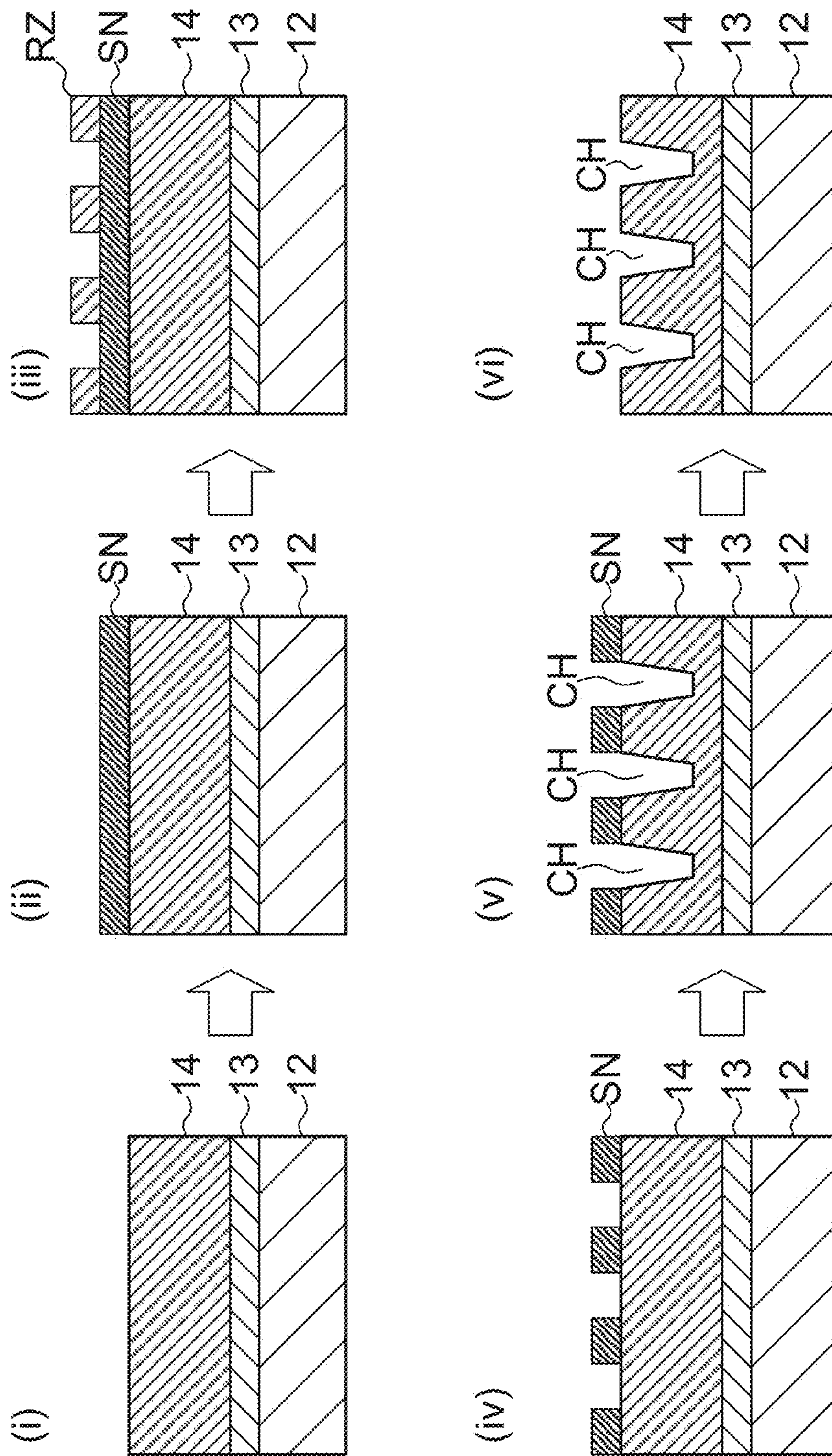


FIG.3

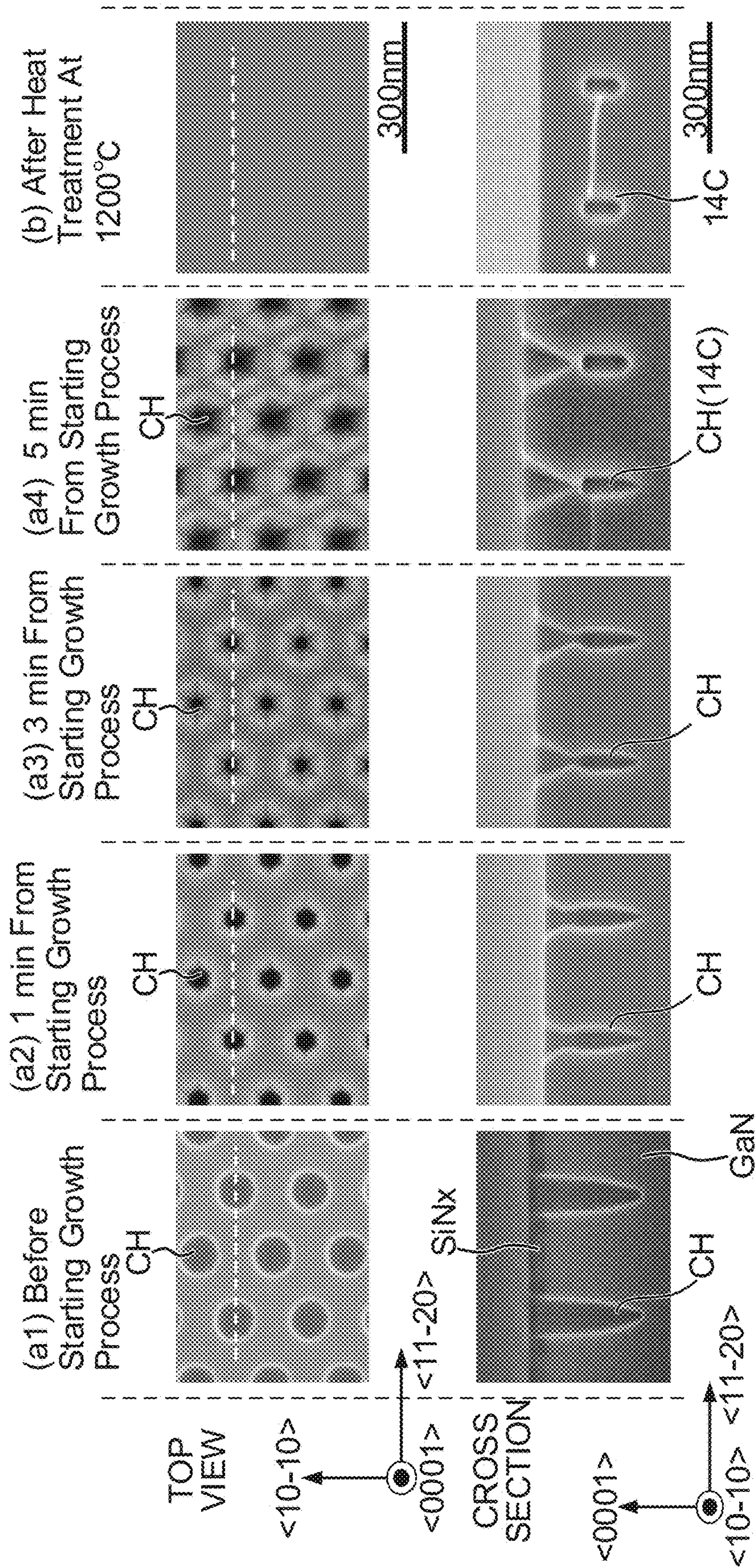


FIG.4

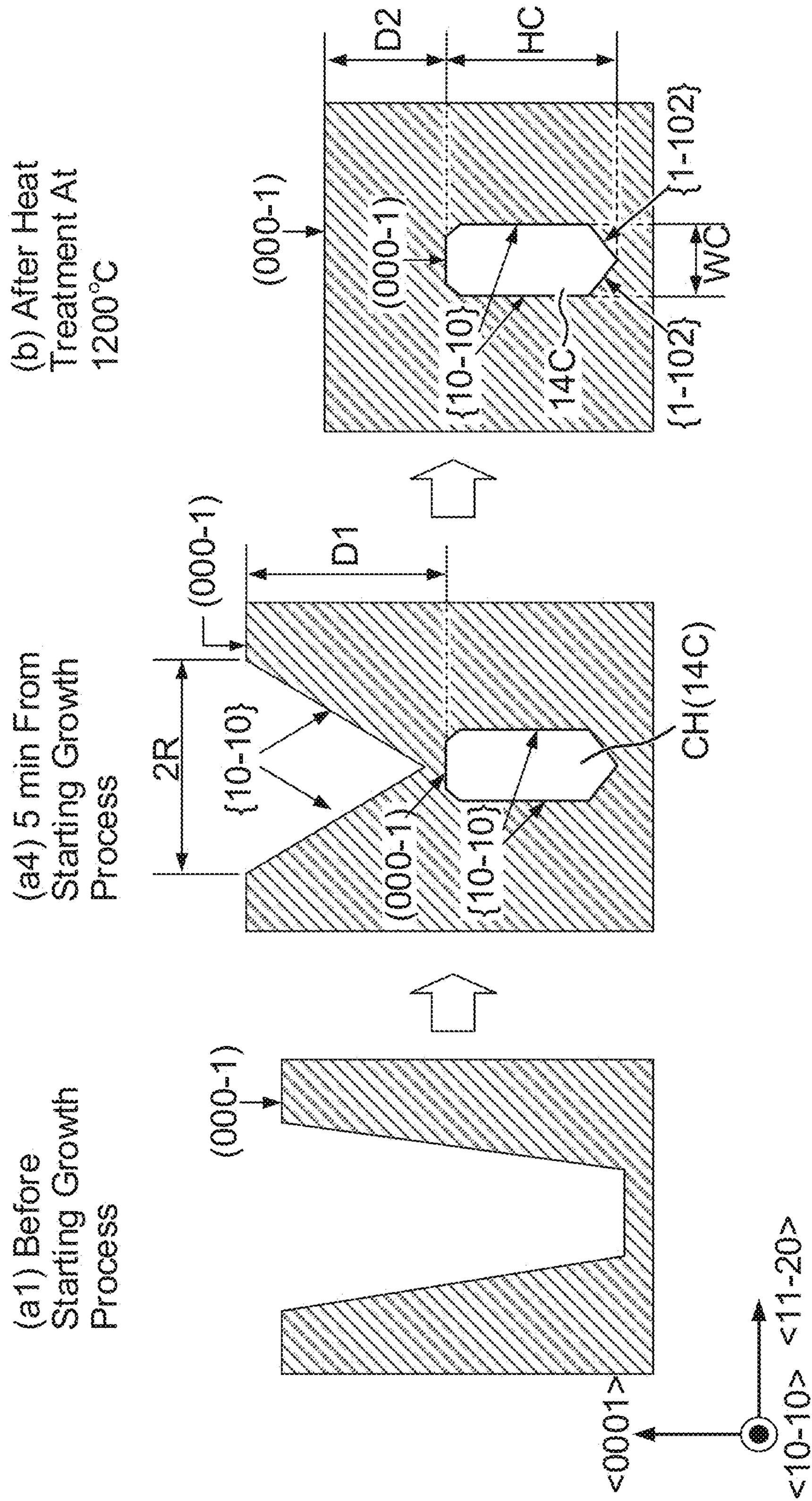


FIG.5

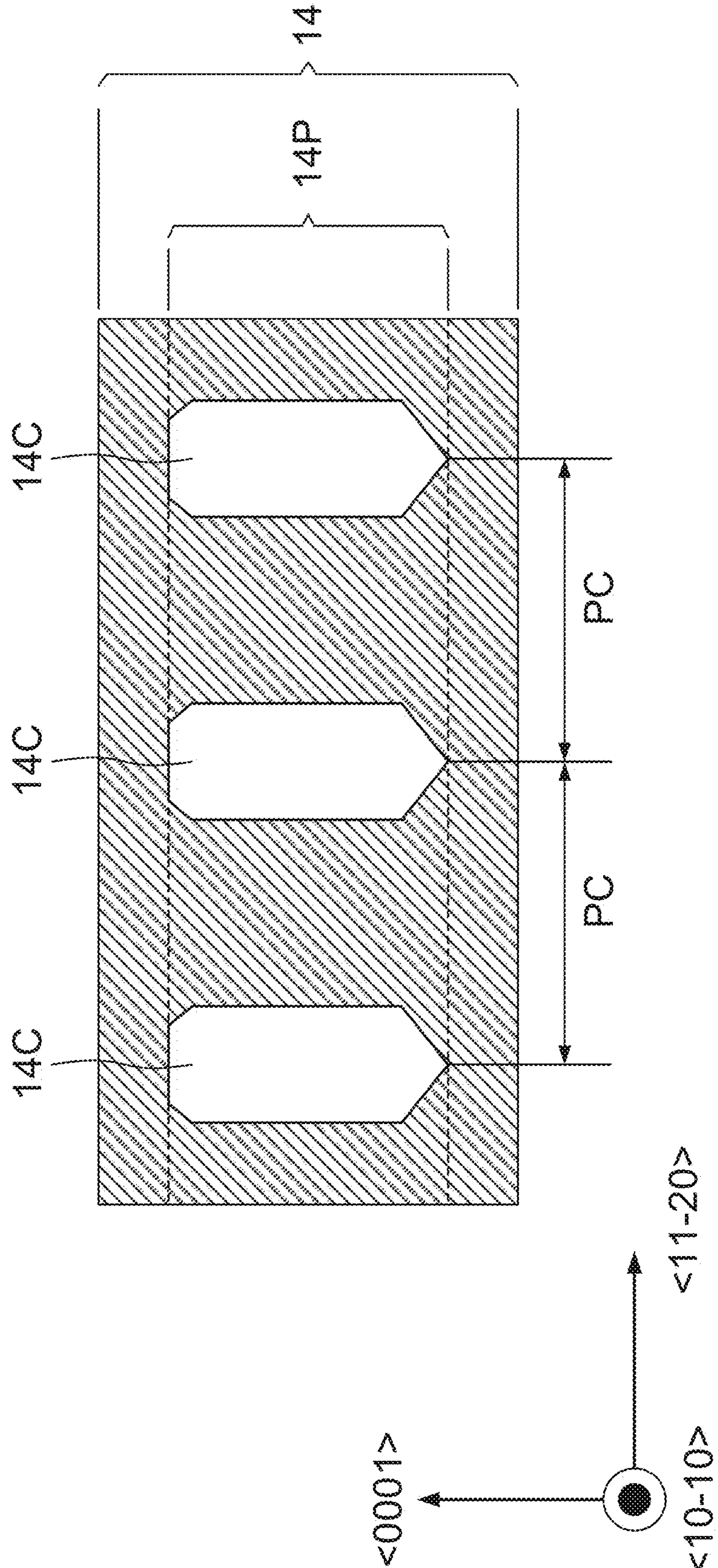


FIG.6

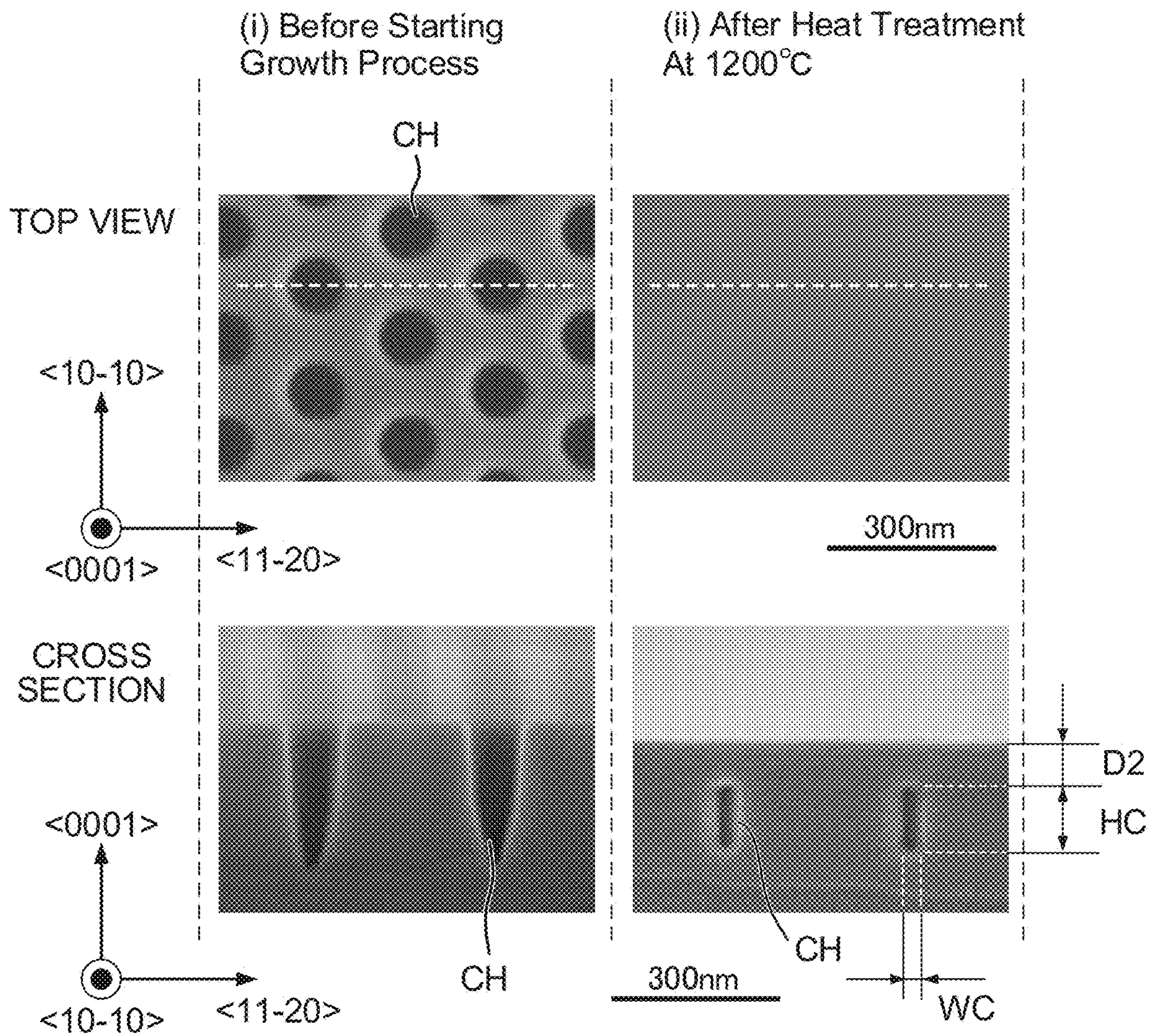


FIG.7

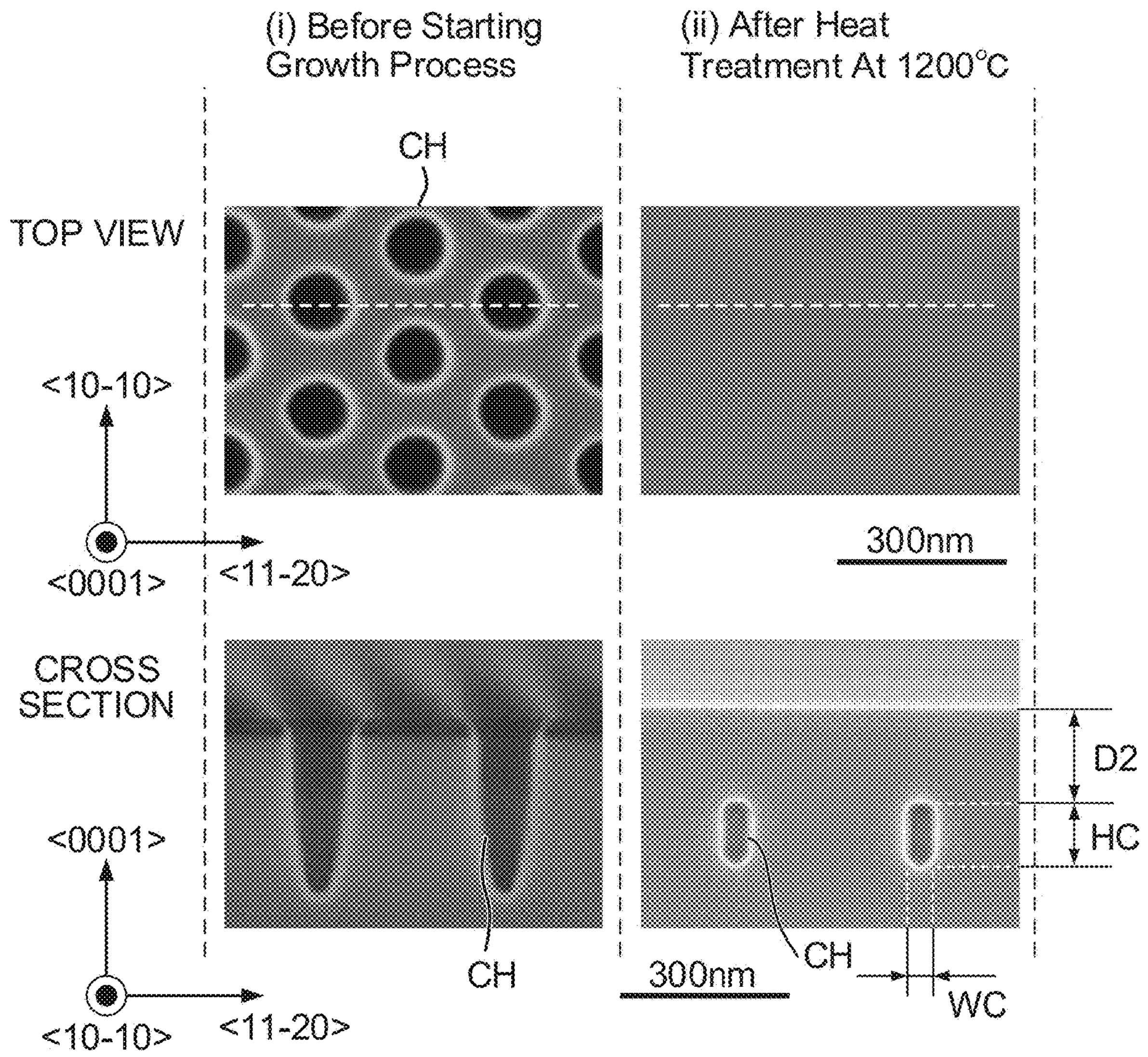


FIG.8

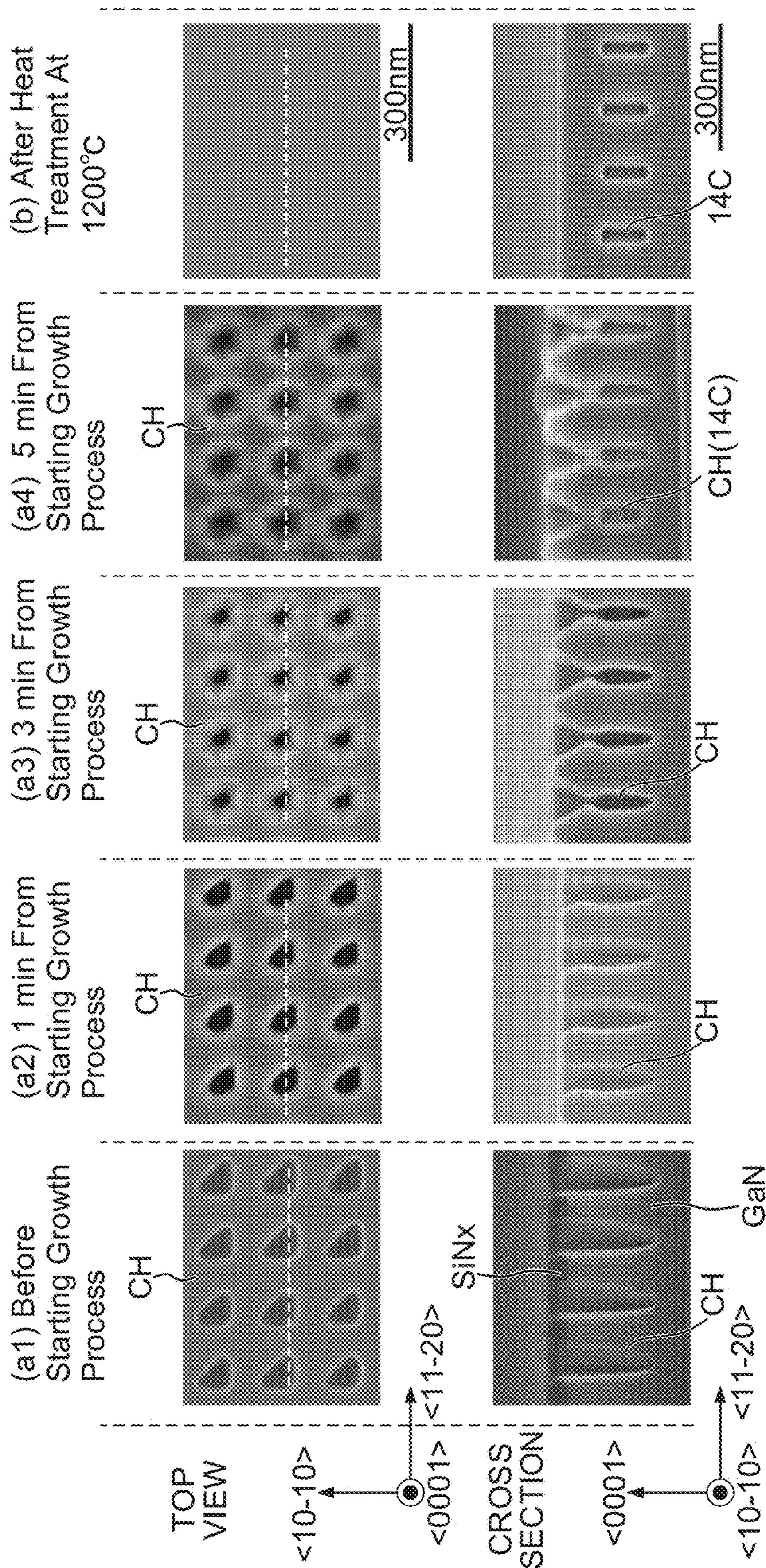


FIG.9

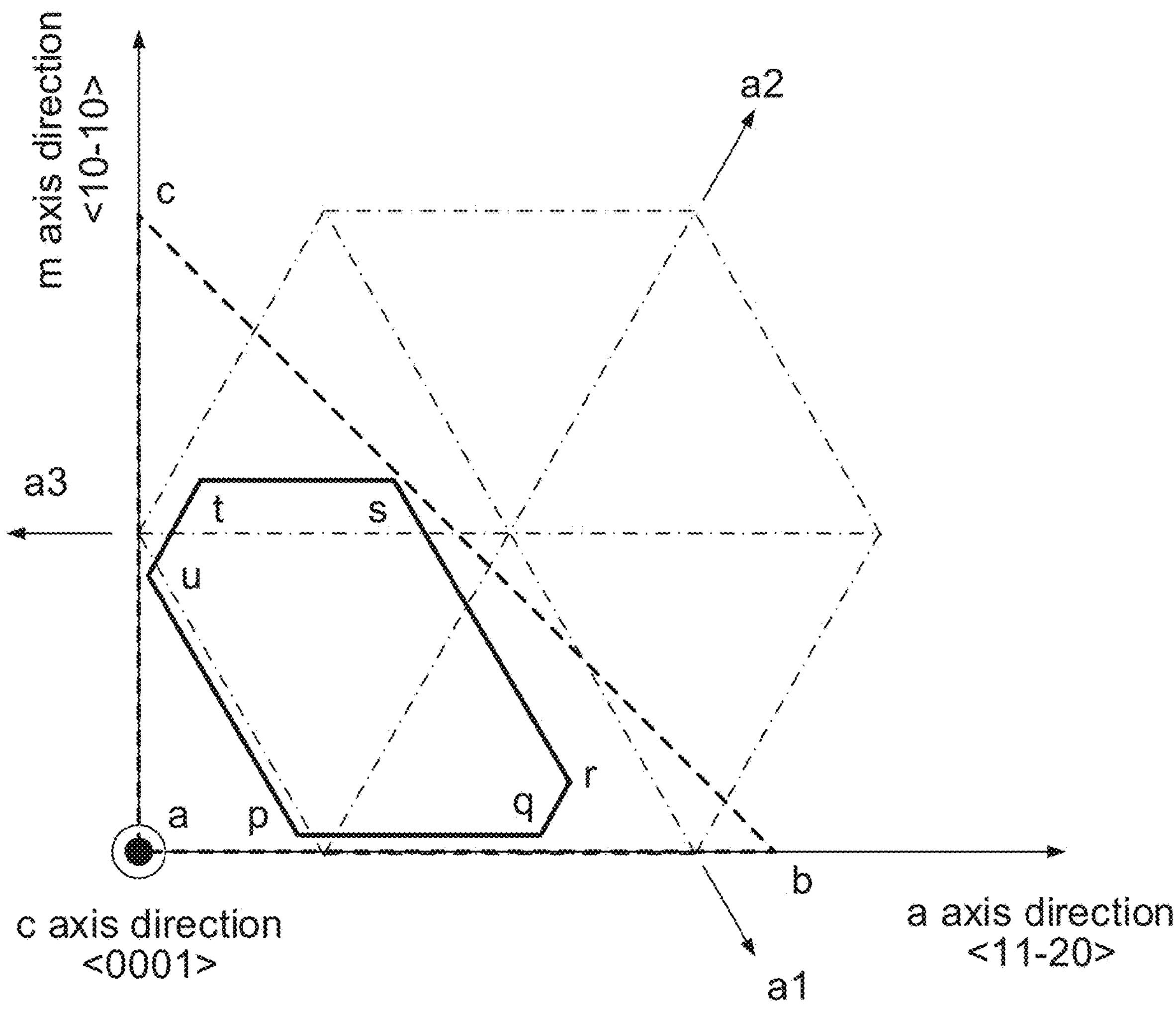


FIG.10

SURFACE-EMITTING LASER AND METHOD FOR MANUFACTURING SURFACE-EMITTING LASER

TECHNICAL FIELD

[0001] The present invention relates to a surface emitting laser and a method for manufacturing the surface emitting laser.

BACKGROUND ART

[0002] In recent years, surface emitting lasers using photonic crystals have been developed. For example, Patent Literature 1 discloses a semiconductor laser device intended for manufacturing without requiring fusion bonding.

[0003] Patent Literature 2 discloses a manufacturing method for producing a minute structure of a photonic crystal in a GaN-based semiconductor. Non-Patent Literature 1 discloses the manufacture of a photonic crystal by increasing a lateral growth rate by low pressure growth technique.

CITATION LIST

Patent Literature

[0004] Patent Literature 1: Japanese Patent No. 5082447

[0005] Patent Literature 2: Japanese Patent No. 4818464

Non-Patent Literature

[0006] Non-Patent Literature 1: H. Miyake et al.: Jpn. J. Appl. Phys. Vol. 38(1999) pp. L1000-L1002

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0007] In a surface emitting laser having a photonic crystal, in order to obtain a high resonance effect, it is required to increase a diffraction effect in a photonic crystal layer. Namely, in order to increase the diffraction effect, it is required to have a uniform two-dimensional refractive index period in the photonic crystal, to have a high occupation ratio (filling factor) of a different refractive index area to a base material in the photonic crystal, to have a high ratio (light confinement coefficient) of light intensity (light field) distributed in the photonic crystal and the like.

[0008] Considering the aforementioned items, the present invention aims at providing a surface emitting laser including a photonic crystal that has a uniform refractive index period and a high diffraction effect, and a manufacturing method thereof. The present invention also aims at providing a surface emitting laser including a photonic crystal that has a high filling factor and a high light confinement coefficient, and a manufacturing method thereof.

SOLUTION TO PROBLEM

[0009] The method for manufacturing a surface emitting laser made of a group-III nitride semiconductor by the MOVPE method according to the present invention comprises:

[0010] (a) a step of growing a first cladding layer of a first conductive type on a substrate;

[0011] (b) a step of growing a first optical guide layer of said first conductive type on said first cladding layer;

[0012] (c) a step of forming holes having a two-dimensional periodicity in a plane parallel to said first optical guide layer, in said first optical guide layer by etching;

[0013] (d) a step of supplying a gas containing a group-III material and a nitrogen source and performing growth to form recessed portions having a facet of a predetermined plane direction top of openings of said holes, thereby closing the openings of said holes; and

[0014] (e) a step of planarizing said recessed portions by mass transport, after said openings of said holes have been closed, wherein

[0015] after said planarizing step has been performed, at least one of side surfaces of said hole is a {10-10} facet.

[0016] The surface emitting laser made of a group-III nitride semiconductor according to the present invention comprises:

[0017] a first cladding layer of a first conductive type formed on a substrate;

[0018] a first optical guide layer of said first conductive type formed on said first cladding layer, the first optical guide layer having holes that are formed therein and arranged to have a two-dimensional periodicity in a plane parallel to said first optical guide layer;

[0019] a light emitting layer formed on said first optical guide layer;

[0020] a second optical guide layer of a second conductive type formed on said light emitting layer, the second conductive type being an opposite conductive type to said first conductive type; and

[0021] a second cladding layer of said second conductive type formed on said second optical guide layer, wherein

[0022] at least one of side surfaces of said hole is a {10-10} facet.

BRIEF DESCRIPTION OF DRAWINGS

[0023] FIG. **1** is a graph of the relationship between a filling factor (FF) and a radiation factor of a photonic crystal portion in an emission direction.

[0024] FIG. **2** is a cross-sectional view schematically illustrating a structure of a photonic crystal surface emitting laser according to a first embodiment.

[0025] FIG. **3** is a cross-sectional view schematically illustrating a hole CH forming process.

[0026] FIG. **4** shows SEM images of the surface and cross section of an optical guide layer in steps after the formation of holes CH.

[0027] FIG. **5** is a cross-sectional view that schematically explains the cross section of the optical guide layer substrate corresponding to (a**1**), (a**4**) and (b) of FIG. **4**.

[0028] FIG. **6** is a cross-sectional view schematically illustrating a photonic crystal layer **14**P and holes **14**C arranged in the photonic crystal layer **14**P.

[0029] FIG. **7** shows SEM images of the surface (upper row) and cross section (lower row) of holes CH before growth and after thermal treatment, according to a first comparative example.

[0030] FIG. **8** shows SEM images of the surface (upper row) and cross section (lower row) of holes CH before growth and after thermal treatment, according to a second comparative example.

[0031] FIG. **9** shows images of a photonic crystal layer **14**P forming process in a photonic crystal surface emitting laser according to a second embodiment.

[0032] FIG. **10** is a graph that schematically explains change in the shape of a hole **14**C in a growth plane according to the second embodiment.

DESCRIPTION OF EMBODIMENTS

[0033] Preferred embodiments of the present invention will be described below, and the embodiments may be appropriately modified or combined. In the following description and accompanying drawings, substantially the same or equivalent portions are denoted by the same reference signs, and a description will be given based on the reference signs.

[Resonance Effect of Photonic Crystal Surface Emitting Laser]

[0034] To obtain a resonance effect in a surface emitting laser having a photonic crystal portion (hereinafter sometimes simply referred to as a photonic crystal surface emitting laser), it is desired to have a high diffraction effect in the photonic crystal portion.

[0035] More specifically, to increase the diffraction effect in the photonic crystal surface emitting laser, it is desired that

[0036] (1) when λ represents an oscillation wavelength and n_{eff} represents the effective refractive index of the photonic crystal portion, the two-dimensional refractive index period P in the photonic crystal portion satisfies $P=m\lambda/n_{eff}$ (m is a natural number) in the case of a square-lattice two-dimensional photonic crystal, and satisfies $P=m\lambda\times 2/(3^{1/2}\times n_{eff})$ (m is a natural number) in the case of a triangular-lattice two-dimensional photonic crystal.

[0037] (2) the occupation ratio (FF: filling factor) of a different refractive index area to a base material in the photonic crystal portion is sufficiently high.

[0038] (3) the ratio Γ_{PC}: optical confinement factor) of optical power distribution in the photonic crystal portion of optical power distribution in the photonic crystal surface emitting laser is sufficiently high.

[0039] To satisfy the aforementioned (1), a lattice constant is required to be set appropriately in accordance with the oscillation wavelength of the photonic crystal laser. For example, in the case of oscillating at a wavelength of 405 nm using a gallium nitride-based material, n_{eff} is of the order of 2.5, and so in the case of using a square-lattice two-dimensional photonic crystal, a lattice constant may be of the order of 162 nm.

[0040] As to the aforementioned (2), FIG. **1** shows the relationship between a filling factor (FF) and a radiation constant of a photonic crystal portion in an emission direction, in a square-lattice two-dimensional photonic crystal having, for example, a period of 161 nm and a distance between an active layer and the photonic crystal portion of 80 nm.

[0041] The radiation constant of the photonic crystal portion is the ratio of light radiating in the perpendicular direction (emission direction) to a photonic crystal surface by diffraction, while waves are guided through a unit length, out of light existing in the photonic crystal as a waveguide mode. In the photonic crystal portion, a loss is desired to be lower for better laser oscillation, but when the FF is less than 5%, the radiation factor becomes approximately 0 and it becomes difficult to extract light to the outside. In other words, to allow the function of a photonic crystal surface emitting laser, the filling factor (FF) is preferably 5% or more.

[0042] To satisfy the aforementioned (3), the distance between the photonic crystal portion and the active layer, and more specifically the distance between a top surface of the photonic crystal portion on the side of the active layer and a bottom surface of the first barrier layer of an MQW active layer on the side of the photonic crystal portion is required to be short. An increase in the thickness of the photonic crystal portion can increase Γ_{PC}, but the optical power distribution in the typical laser is generally sharp with respect to the vicinity of the active layer, to increase the optical confinement factor Γ_{MQW} of the active layer. Therefore, there is a limit to improvement of Γ_{PC} (the optical confinement factor of the photonic crystal portion), even if the thickness of the photonic crystal portion is increased. An increase in the thickness of the photonic crystal portion decreases the refractive index of a optical guide layer, so that Γ_{MQW} becomes small and not preferable. Therefore, to obtain sufficient Γ_{PC}, it is desired to make the aforementioned distance short to bring the photonic crystal portion and the active layer close to each other.

[0043] Considering these matters, conventional techniques have the following problems. For example, in the technology of Patent Literature 1 described above, a thermal treatment is performed in a gas atmosphere containing a nitrogen source, without being supplied with group-III atoms, and thereafter another thermal treatment is performed at a higher temperature than the preceding step to fill narrow holes. However, when the holes are embedded in this manner, the holes are narrowed in the first heating step, and a sufficient FF cannot be obtained. Even if the first heating step is eliminated, the holes are narrowed during an increase in temperature and cannot be embedded in a sufficient FF state.

[0044] For example, in the technology of Patent Literature 2 described above, group-III atoms and a nitrogen source are supplied to a depressurized atmosphere, and the growth of a group-III nitride in a lateral direction is promoted to close narrow holes. This method enables embedding the narrow holes, while relatively maintaining the diameter of the holes. However, with reference to Non-Patent Literature 1, even if the lateral growth rate is increased by decompression, the lateral growth rate can be increased up to the order of 0.7 times faster than a vertical growth rate. In other words, even if the diameter of the embedded holes is maintained, the distance between the photonic crystal portion and the active layer becomes long, and therefore a sufficiently high Fpc cannot be obtained.

[0045] A method in which a material having a low refractive index material such as SiO_2 or MgF is laid on the bottoms of the holes and the holes are embedded using these materials as a mask is also described. However, in this case, a shape processed by dry etching or the like remains as is, as the shape of the embedded holes. When holes are formed by dry etching or the like, it is difficult to etch the holes perfectly perpendicularly with respect to an in-plane direction of the optical guide layer, thus causing variations in the diameter of each hole in a depth direction. In other words, it is difficult to obtain a single periodical structure.

First Embodiment

[0046] FIG. **2** is a schematic cross-sectional view of a structure of a surface emitting laser (hereinafter sometimes simply referred to as photonic crystal surface emitting laser) **10** including a photonic crystal layer according to a first embodiment. As shown in FIG. **2**, a semiconductor structure layer **11** is formed on a substrate **12**. More specifically, an n-cladding layer **13**, an n-optical guide layer **14**, an active layer **15**, a optical guide layer **16**, an electron blocking layer **17**, and a p-cladding layer **18** are sequentially formed in this order on the substrate **12**. In other words, the semiconductor structure layer **11** is constituted of the semiconductor layers **13**, **14**, **15**, **16**, **17**, and **18**. The n-optical guide layer **14** contains a photonic crystal layer **14**P.

[0047] An n-electrode **19**A is formed on the n-cladding layer **12** (bottom surface), and a p-electrode **19**B is formed on the p-cladding layer **18** (top surface).

[0048] Light from the surface emitting laser **10** is extracted in a direction perpendicular to the active layer **15** from a top surface of the semiconductor structure layer **11** (i.e., a front surface of the p-cladding layer **18**) to the outside.

[0049] [Growth of Cladding Layers and Optical Guide Layers]

[0050] A manufacturing process of the semiconductor structure layer **11** will be described below in detail. The MOVPE (metalorganic vapor phase epitaxy) method was used as a crystal growth method, so that the semiconductor structure layer **11** was grown on the growth substrate **12** by normal-pressure (atmospheric pressure) growth.

[0051] As the growth substrate of the semiconductor structure layer **11**, the n-type GaN substrate **12** whose growth face was a +c-plane was used. On the substrate **12**, n-type AlGaN (a layer thickness of 2 μm) having an Al (aluminum) composition of 4% was grown as the n-cladding layer **13**. Trimethylgallium (TMG) and trimethylaluminum (TMA) were used as a group-III MO (organic metal) material, and ammonia (NH_3) was used as a group-V material. Disilane (Si_2H_6) was supplied as a doping material. A carrier concentration at room temperature was approximately 5×10^{18} cm^{-3}.

[0052] Subsequently, n-type GaN (a layer thickness of 300 nm) was grown as the n-optical guide layer **14** by the supply of TMG and NH_3. Disilane (Si_2H_6) was supplied and doped, while being grown. The carrier concentration was approximately 5×10^{18} cm^{-3}.

[0053] [Formation of Holes in Optical Guide Layer]

[0054] The substrate after the growth of the n-optical guide layer **14**, in other words, the substrate having the optical guide layer (hereinafter referred to as optical guide layer substrate) was taken out of the MOVPE apparatus to form minute holes in the n-optical guide layer **14**. Referring to FIGS. **3** and **4**, the formation of the holes will be described below in detail. FIG. **3** is a cross-sectional view schematically illustrating a hole CH forming process. FIG. **4** shows SEM (scanning electron microscope) images of the surface and cross section of the optical guide layer substrate in steps after the formation of holes CH. In FIG. **4**, the surface SEM images of the optical guide layer substrate are shown in the upper row, and the cross section SEM images, which are taken along broken lines (white) of the surface SEM images, are shown in the lower row.

[0055] The optical guide layer substrate in which the n-cladding layer **13** and the n-optical guide layer **14** had been grown on the substrate **12** was cleaned to obtain a clean surface (FIG. **3**, (i)). After that, a silicon nitride film (SiNx) SN was laminated (a film thickness of 120 nm) by plasma CVD (FIG. **3**, (ii)).

[0056] Next, an EB (electron beam) drawing resist RZ was applied to the SiNx film SN with a thickness of the order of 300 nm by spin coating, and a pattern having a two-dimensional periodical structure was formed on a surface of the optical guide layer substrate by an electron beam drawing apparatus (FIG. **3**, (iii)). More specifically, patterning was performed, so that circular dots having a diameter (ϕ) of 100 nm were arranged in a plane of the resist RZ in two dimensions into a regular triangular lattice with a period PC of 186 nm.

[0057] After the patterned resist RZ was developed, the SiNx film SN was selectively dry etched by an ICP-RIE (inductive coupled plasma-reactive ion etching) apparatus (FIG. **3**, (iv)). Therefore, through holes having a diameter (ϕ) of approximately 100 nm that were arranged in two dimensions into a regular triangular lattice with an in-plane period PC of 186 nm were formed in the SiNx film SN.

[0058] Subsequently, the resist RZ was removed, and holes CH that extend from a surface of the n-optical guide layer **14** (GaN) to the inside were formed, using the patterned SiNx film SN as a hard mask. More specifically, the holes CH that were arranged in two dimensions in the n-optical guide layer **14** were formed by dry etching using a chlorine-based gas in the ICP-RIE apparatus (FIG. **3**, (v)).

[0059] FIG. **4** shows a surface SEM image (upper row) and a cross section SEM image (lower row) of the holes CH formed in the n-optical guide layer **14** at this time (FIG. **4** (a**1**)). As shown in the surface SEM image, a plurality of holes CH that were arranged in two dimensions into a regular triangular lattice (in other words, the vertexes and center of a regular hexagon) with intervals (period) PC between the holes of 186 nm were formed. As shown in the cross section SEM image, the depth of the holes CH formed in the n-optical guide layer **14** was approximately 250 nm, and the diameter of the holes CH was approximately 100 nm. In other words, the hole CH is an opening (hole) whose top surface is open, and is in an approximately cylindrical shape except for its bottom portion.

[0060] [Closure of Holes]

[0061] The SiNx film SN of the optical guide layer substrate in which the holes CH having two-dimensional periodicity were formed in the n-optical guide layer **14** was removed using a hydrofluoric acid (HF) (FIG. **3** (vi)), and a clear surface was obtained by degreasing. Then, the optical guide layer substrate was introduced again into the MOVPE apparatus.

[0062] In the MOVPE apparatus, the optical guide layer substrate was heated to 1100° C. (growth temperature), and was grown so as to have recessed portions having {10-11} facets (facets of a predetermined plane direction) by supply of a group-III material gas (TMG) and a group-V material gas (NH_3), to close the openings of the holes CH. Note that, the growth temperature is preferably in a range of 900 to 1150° C.

[0063] FIGS. **4** ((a**2**) to (a**4**) in the drawing) shows variations in the shape of the holes CH at this time with respect to a growth time. FIG. **5** is a cross-sectional view that schematically explains the cross section of the optical guide layer substrate corresponding to (a**1**), (a**4**) and (b) of FIG. **4**.

[0064] As shown in FIG. **4**, the {10-11} facets are preferentially grown with a lapse of the growth time (1 minute, 3 minutes and 5 minutes). After 5 minutes from the start of growth, the {10-11} facets that are grown from opposite planes to each other are brought into contact with each other to close the hole CH (FIG. **4**, (a**4**)). A (000-1) plane appears in a surface (top surface) of the embedded hole CH on the side of the active layer **15**, and {10-10} planes appears in side surfaces of the hole CH. A {1-102} facet appears in a bottom portion of the hole CH on the side of the substrate **12**.

[0065] At this time, the distance D**1** between the (000-1) plane, which was the top surface of the embedded hole CH, and a (0001) plane, which was an outermost surface of the n-optical guide layer **14**, was approximately 140 nm (FIG. **5**, (a**4**)). The opening radius R of the {10-11} facet was approximately 82 nm (FIG. **5**, (a**4**)).

[0066] [Planarization of Surface]

[0067] After the holes CH were closed by the {10-11} facets, the supply of the group-III material gas was stopped. While the group-V material gas (NH_3) was supplied, the temperature was increased to 1200° C. at a temperature increase rate of 100° C./min and maintained. After being maintained (thermal treatment) for **1** minute at 1200° C., the surfaces of the holes were changed as shown in FIG. **4** (FIG. **4**(*b*)). The {10-11} facets formed in the surface of the n-optical guide layer **14** disappeared, and the surface became a flat (0001) plane. The surface was planarized by mass transport, and the surface of the n-optical guide layer **14** was changed into the (0001) plane.

[0068] At this time, the distance D**2** between a plane (top surface, (000-1) plane) of the embedded hole (cavity) **14**C on the side of the active layer **15** and a front surface (i.e., (0001) plane) of the n-optical guide layer **14** was approximately 105 nm (FIG. **5**, (b)). The height HC of the hole **14**C was approximately 110 nm, and the diameter (width in cross section) WC of the hole CH was approximately 60 nm.

[0069] FIG. **6** is a cross-sectional view schematically illustrating the photonic crystal layer **14**P and the holes **14**C arranged in the photonic crystal layer **14**P, formed by the above process. As shown in FIG. **6**, the photonic crystal layer **14**P in which the holes **14**C arranged in two dimensions into a regular triangular lattice with a period PC in a plane parallel to the n-optical guide layer **14** were embedded was formed. As shown in FIG. **5**, the top surface of the hole **14**C is constituted of the (000-1) plane, and the side surfaces thereof are constituted of the {10-10} planes. The bottom portion of the hole **14**C on the side of the substrate **12** has the shape of a polygonal pyramid constituted of {1-102} facets. Note that the hole **14**C preferably has the shape of a polygonal columnar shape, except for the bottom portion, and at least one of the side surfaces of the hole **14**C is preferably the {10-10} plane (facet).

[0070] In other words, the photonic crystal layer **14**P having the holes **14**C arranged in two dimensions with the constant period (PC) was formed in a state of being embedded in the n-optical guide layer **14**. Since the respective holes **14**C in the photonic crystal layer **14**P are arranged to have approximately the same depth (the depth from the top surface was D**2**) in the n-optical guide layer **14**, the top surfaces of the holes **14**C formed in the photonic crystal layer **14**P forms the top surface of the photonic crystal layer **14**P. The holes **14**C in the photonic crystal layer **14**P have approximately the same height HC. In other words, the photonic crystal layer **14**P is formed so as to have a layer thickness HC. The n-optical guide layer **14** has a flat front surface.

[0071] Since it is conceivable that the total volume of a GaN layer formed on the holes **14**C does not change between before and after the deformation by mass transport, when D and d represent the distance between the top surface (i.e., (000-1) plane) of the hole **14**C and the surface (i.e., (0001) plane) of the n-optical guide layer **14** before and after the deformation respectively (here, D=D**1**, d=D**2**), r represents an opening radius of the {10-11} facet before the deformation (here, r=R, diameter is 2R), and p represents the period of the holes **14**C of the photonic crystal (here, p=PC), the distance d can be estimated from:

[Equation 1]

$$d=D(1-(r/p)^2) \tag{1}$$

[0072] The distance d estimated from the equation (1) was 110 nm, which was almost the same distance as a measured value. Therefore, it was understood that the surface was deformed from the {10-11} facet into the (0001) plane by the diffusion of Ga in the vicinity of the surface.

[0073] The holes **14**C were thereby embedded in the n-optical guide layer **14** whose surface was the flat (0001) plane, so that the photonic crystal layer **14**P could be formed in the n-optical guide layer **14**.

[0074] At this time, the filling factor (FF), which was the ratio of the different refractive index area (holes **14**C) to the base material (GaN) in the photonic crystal layer, was 10.4%. Therefore, the photonic crystal layer having a high diffractive effect to the oscillation wavelength X could be obtained.

[0075] The embodiment describes a case where the temperature of mass transport is 1200° C., but the temperature of mass transport is preferably 1100° C. or higher.

[0076] [Growth of Active Layer and p-Type Semiconductor Layer]

[0077] Subsequently, multiple quantum well (MQW) layers including five layers of quantum well layers were grown as the active layer **15**. A barrier layer and a well layer of the multiple quantum well were made of GaN and InGaN respectively, and had layer thicknesses of 5.0 nm and 3.5 nm respectively. In the present embodiment, the center wavelength of PL emission from the active layer was 405 nm.

[0078] The barrier layer was grown with the supply of triethylgallium (TEG) and NH_3 after decrease the growth temperature to 850° C. The well layer was grown at the same temperature as that for the barrier layer with the supply of TEG, trimethylindium (TMI), and NH**3**.

[0079] After the growth of the active layer **15**, the temperature of the substrate was increased to 1100° C., and the optical guide layer **16** (layer thickness of 100 nm), which was a p-side optical guide layer, was grown. As the optical guide layer **16**, an undoped GaN layer was grown without being doped with a dopant.

[0080] While the growth temperature was maintained at 1100° C., the electron blocking layer (EBL) **17** and the p-cladding layer **18** were grown on the optical guide layer **16**. The electron blocking layer **17** and the p-cladding layer **18** were grown with the supply of TMG, TMA and NH_3.

[0081] The electron blocking layer **17** was an AlGaN layer (layer thickness of 20 nm) having an Al composition of 18%, and the p-cladding layer **18** was an AlGaN layer (layer thickness of 600 nm) having an Al composition of 6%.

While the electron blocking layer **17** and the p-cladding layer **18** were grown, CP2Mg (bis-cyclopentadienyl magnesium) was supplied and a carrier concentration was 4×10^{17} cm^{-3}.

[0082] The laminated structure of the surface emitting laser including the photonic crystal was obtained by the above-described method.

[0083] [Investigation 1] Closure of Holes

[0084] In the first embodiment described above, the holes CH were closed by growing the {10-11} facets. The (000-1) plane appears in the top surface of the closed hole CH, and the {10-10} planes appear in the side surfaces thereof.

[0085] In other words, a lot of N (nitrogen) atoms are present in the vicinity of the surface, and an N-pole surface tends to selectively grow. Therefore, {10-11} that can have N polarity is formed as an oblique facet. It is conceivable that the reason why the {10-11} appears instead of {11-22}, which is also an oblique facet having N polarity, is that dangling bond density is low, that is, surface energy is low. The {10-11} facet grows preferentially with a lapse of the growth time, and closes the holes by being brought into contact with the {10-11} facet that has grown from the opposite side.

[0086] When the hole CH was closed, the most stable plane is formed as each surface of the hole CH. The (000-1) plane having the highest N polarity and the lowest dangling bond density is formed as a top surface, and the {1-102} facet having the N polarity is formed as a bottom surface. Since the group-III nitride has no polarity in a direction parallel to the growth direction, the {10-10} plane having the lowest dangling bond density in the same plane appears in the side surface.

[0087] [Investigation 2] Planarization of Surface

[0088] To planarize the surface, the {10-11} facets present at above the top surfaces of the embedded holes CH are planarized by mass transport, and the surface of the optical guide layer is changed into the (0001) plane.

[0089] As described above, after the holes CH were closed by the {10-11} facets, the supply of the group-III atoms is stopped, and the substrate temperature is increased by heating while suppling a nitrogen source.

[0090] In other words, when the temperature is increased to a level at which the elimination of N atoms attached to the surface of the n-optical guide layer **14** is increased, the N-polarity plane does not always stable. A stable surface is a plane having low surface energy, in other words, having the lowest dangling bond density. In the group-III nitride, the (0001) plane having the lowest dangling bond density appears. At this time, the supply of the group-III atoms is stopped, the group-III atoms are diffused in the surface plane. Atoms in crests of the {10-11} facets having the most unstable energy are diffused and adhered to troughs of the {10-11} facets having the most stable energy, to form the (0001) plane.

[0091] The distance between the (000-1) plane of the embedded hole **14**C and the (0001) plane of the outermost surface of the n-optical guide layer **14** thereby becomes short, so the distance between the photonic crystal layer **14**P and the active layer **15** is made close. If the group-III nitride constituting the n-optical guide layer **14** does not sublimate, the total volume does not change between before and after the deformation, and the distance between the (000-1) plane of the embedded hole **14**C and the (0001) plane of the outermost surface of the n-optical guide layer **14** becomes close by a volume for embedding the recessed portions formed of the {10-11} facets of the outermost surface of the n-optical guide layer **14**. Therefore, the holes **14**C having the two-dimensional period were embedded in the n-optical guide layer **14** whose top surface was the flat (0001) plane without increasing a distance between the photonic crystal layer **14**P and the active layer **15**.

[0092] [Investigation 3] Comparison with Comparative Examples

[0093] As a first comparative example, holes CH were embedded only by the same process as the planarizing process (mass transport) of the first embodiment. More specifically, the supply of the group-III material was stopped, and the holes CH were embedded by only the process in which temperature was increased by heating while suppling the nitrogen source.

[0094] The process will be described below with reference to FIG. **7**. In the same process as that of the first embodiment, holes CH were formed in two dimensions into a regular triangular lattice with a period PC of 186 nm using an SiNx as a hard mask. After that, the SiNx was removed by HF, and degreasing was performed to obtain a optical guide layer substrate having a clean surface. FIG. **7** (i) shows a surface SEM image (upper row) and a cross section SEM image (lower row) of the holes CH at this time.

[0095] The optical guide layer substrate was put in the MOVPE apparatus, and temperature was increased to 1200° C. at a temperature increase rate of 100° C./min, while NH_3 was supplied, and maintained in that state. After the temperature was maintained at 1200° C. for 1 minute, the surfaces of the holes CH were changed as shown in FIG. **7** (ii), so that the surface of the optical guide layer became a flat (0001) plane.

[0096] At this time, the distance D**2** between a (000-1) plane, which was a plane of the embedded hole CH on the side of the active layer, and a (0001) plane, which was the outermost surface of the optical guide layer, was 83 nm. The height HC of the hole CH was 113 nm, and the diameter (width in cross section) WC of the hole CH became 38 nm, very narrow. At this time, the FF of the hole was 4.2%, and a radiation constant became almost 0, and so light could not be extracted in an emission direction.

[0097] As a second comparative example, holes CH were embedded only by the same process as the hole closing process according to the first embodiment. The process will be described below with reference to FIG. **8**.

[0098] In the same process as that of the first embodiment, holes CH were formed in two dimensions into a regular triangular lattice with a period of 186 nm. FIG. **8** (i) shows a surface SEM image (upper row) and a cross section SEM image (lower row) of the holes CH at this time.

[0099] The optical guide layer substrate was put in the MOVPE apparatus, and temperature was increased to 1100° C. at a temperature increase rate of 100° C./min, while TMG and NH_3 were supplied, to close the holes CH. FIG. **8** (ii) shows a surface image and a cross section image, when the growth time is 10 minutes.

[0100] About FF, the holes CH having almost the same size as the first embodiment could be embedded. However, the distance D**2** between a (000-1) plane, which was a plane of the embedded hole CH on the side of the active layer, and a (0001) plane, which was the outermost surface of the

optical guide layer, was 164 nm. Note that the dimeter WC of the hole CH was 61 nm, and the height HC thereof was 113 nm.

[0101] When the growth time was 8 minutes, an oblique facet was left in the surface of the optical guide layer, and a flat (0001) plane could not be obtained. Therefore, when the holes are embedded only by the process of supplying a group-III material and NH_3, the distance between the (000-1) plane of the hole and the (0001) plane, which is the surface of the optical guide layer, becomes long, thus Γ_{PV} can not be increased.

[0102] According to the results of the first and second comparative examples, it was difficult to have a sufficiently high FF of the holes of the photonic crystal portion, while the distance between the (000-1) plane of the top plane of the embedded hole and the (0001) plane of the top surface of the optical guide layer on the side of the active layer is shortened.

Second Embodiment

[0103] FIG. **9** is a drawing showing the formation of a photonic crystal layer **14**P in a photonic crystal surface emitting laser **10** according to a second embodiment. More specifically, FIG. **9** shows surface SEM images (upper row) and cross section SEM images (lower row) of holes CH formed in a n-optical guide layer **14**. Note that the structure of a photonic crystal surface emitting laser **10** is the same as that of the first embodiment (FIG. **2**).

[0104] As shown in FIG. **9**, an SiNx film SN was formed on a surface of the optical guide layer substrate in the same process as that of the first embodiment. Next, the SiNx film SN was selectively dry etched by an ICP-RIE apparatus, to form through holes that were arranged in two dimensions into a square lattice with an in-plane period PC of 161 nm on the SiNx film SN. In other words, the through holes in the shape of an right-angled isosceles triangle having a short side length of 100 nm were formed so as to penetrate the SiNx film SN.

[0105] Subsequently, holes CH were formed from a surface of the n-optical guide layer **14** (GaN) using the patterned SiNx film SN as a hard mask. More specifically, the holes CH that had a depth of approximately 230 nm and a shape of an right-angled isosceles right triangle having a short side length of 100 nm were formed in the n-optical-guide layer **14** so as to be arranged in a plane in two dimensions into a square lattice with a period PC of 161 nm (FIG. **9**, (a**1**)).

[0106] Next, as in the case of the first embodiment, in the MOVPE apparatus, the optical guide layer substrate was heated to 1100° C., and a group-III material gas (TMG) and a group-V material gas (NH_3) were supplied to form {10-11} facets and close openings of the holes CH. FIGS. **9** ((a**2**) to (a**4**) in the drawing) shows variations in the shape of the holes CH at this time, with respect to a growth time.

[0107] As shown in FIG. **9**, as in the case of the first embodiment, the {10-11} facets are grown preferentially with a lapse of the growth time (1 minute, 3 minutes and 5 minutes), and the {10-11} facet that is grown from opposite sides to each other are brought into contact with each other in 5 minutes after the start of growth so as to close the hole CH (FIG. **9**, (a**4**)). At this time, the distance D**1** between a (000-1) plane, which was a top surface of the embedded hole **14**C, and a (0001) plane, which was a surface of the n-optical guide layer **14**, was approximately 140 nm (FIG. **9**, (a**4**)).

[0108] Note that, in this case, the shape of a gap formed in a growth face by the {10-11} facets in the surface of the n-optical guide layer **14** is a regular hexagon in the first embodiment, but is an irregular hexagon whose sides have various lengths in the second embodiment (FIG. **9**, upper images of (a**3**) and (a**4**)). Since the cross sectional shape of the embedded hole has a similar figure thereof, it is possible to form a photonic crystal layer **14**P in which the holes **14**C of an irregular shape are embedded by adjusting the initial shape of patterning.

[0109] After the holes CH were closed by the {10-11} facets, as in the case of the first embodiment, the supply of the group-III material gas was stopped. While the group-V material gas (NH_3) was supplied, the temperature was increased to 1200° C. at a temperature increase rate of 100° C./min and maintained. After being maintained (thermal treatment) for 1 minute at 1200° C., the surfaces of the holes were changed as shown in FIG. **9** (FIG. **9**(*b*)). The {10-11} facets formed in the surface of the n-optical guide layer **14** disappeared, and the surface became a flat (0001) plane. The surface was planarized by mass transport, and the surface of the n-optical guide layer **14** was changed into the (0001) plane.

[0110] At this time, the distance D**2** between a plane (i.e., (000-1) plane) of the formed hole **14**C on the side of an active layer **15** and the surface of the n-optical guide layer **14** (i.e., (0001) plane) was approximately 94 nm (FIG. **9**, (b)). The height HC of the hole **14**C was approximately 136 nm, and the width WC of the hole CH in cross section was approximately 58 nm.

[0111] Note that, as described above, in the second embodiment, the shape of the hole **14**C in the growth face is an irregular hexagon whose sides have various lengths. FIG. **10** is a graph that schematically explains variations in the shape of the hole **14**C in the growth plane.

[0112] More specifically, the shape of the hole CH formed in the n-optical guide layer **14** is an isosceles right triangle abc. The shape of the hole CH changes by planarizing growth and mass transport. After the planarizing growth and mass transport, the hole **14**C has {10-10} planes (m planes) as side surfaces, and has a shape of an irregular hexagon pqrstu in the growth plane. In other words, the hole **14**C has the shape of a polygonal column having the {10-10} planes as the side surfaces, and an asymmetrical shape with respect to diagonal lines (for example, diagonal lines ps, qt and the like) in a plane parallel to the n-optical guide layer **14**.

[0113] Note that, in the above embodiments, the various values and the like are just examples. The values can be appropriately changed without departing from the scope of the present invention.

[0114] The above-described embodiments describe cases in which the semiconductor structure layer **11** has the electron blocking layer **17**, but may not have the electron blocking layer **17**. Alternatively, the semiconductor structure layer **11** may have a contact layer, a current diffusion layer or another semiconductor layer.

[0115] The present specification describes, as an example, a case in which the first conductive type semiconductor (n-type semiconductor), the active layer and the second conductive type semiconductor (p-type semiconductor, which is the opposite conductive type to the first conductive

type) are grown in this order, but the first conductive type may be a p-type and the second conductive type may be an n-type.

[0116] As described above, according to the present invention, it is possible to provide the surface emitting laser including the photonic crystal that has a uniform refractive index period and a high diffraction effect, and the manufacturing method thereof. It is also possible to provide the surface emitting laser including the photonic crystal that has a high filling factor and a high optical confinement factor, and the manufacturing method thereof.

REFERENCE SIGNS LIST

[0117] **10** photonic crystal surface emitting laser
[0118] **12** substrate
[0119] **13** n-cladding layer
[0120] **14** n-optical guide layer
[0121] **14**P photonic crystal layer
[0122] **14**C hole
[0123] **15** active layer
[0124] **16** optical guide layer
[0125] **18** p-cladding layer

1. A method for manufacturing a surface emitting laser made of a group-III nitride semiconductor by an MOVPE method, comprising:

(a) a step of growing a first cladding layer of a first conductive type on a substrate;

(b) a step of growing a first optical guide layer of said first conductive type on said first cladding layer;

(c) a step of forming holes having a two-dimensional periodicity in a plane parallel to said first optical guide layer, in said first optical guide layer by etching;

(d) a step of supplying a gas containing a group-III material and a nitrogen source and performing growth to form recessed portions having a facet of a predetermined plane direction top of above openings of said holes, thereby closing the openings of said holes; and

(e) a step of planarizing said recessed portions by mass transport, after said openings of said holes have been closed,

wherein after said planarizing step has been performed, at least a part of a side of said holes is a {10-10} facet.

2. The manufacturing method according to claim **1**, wherein a growth plane of said first optical guide layer is a (0001) plane, and a plane of said holes on a side of said light emitting layer, after said step (e), is a (000-1) plane.

3. The manufacturing method according to claim **1**, wherein a plane of said holes on a side of said first cladding layer, after said step (e), includes a {1-102} facet.

4. The manufacturing method according to claim **1**, wherein in said step (d), the facet of said predetermined plane direction includes a {10-11} facet.

5. The manufacturing method according to claim **1**, wherein a growth temperature in said step (d) is 900° C. or higher and 1100° C. or lower.

6. The manufacturing method according to claim **1**, wherein a temperature of said mass transport in said step (e) is 1100° C. or higher.

7. A surface emitting laser made of a group-III nitride semiconductor comprising:

a first cladding layer of a first conductive type formed on a substrate;

a first optical guide layer of said first conductive type formed on said first cladding layer, the first optical guide layer having holes that are formed therein and arranged to have a two-dimensional periodicity in a plane parallel to said first optical guide layer;

a light emitting layer formed on said first optical guide layer;

a second optical guide layer of a second conductive type formed on said light emitting layer, the second conductive type being an opposite conductive type to said first conductive type; and

a second cladding layer of said second conductive type formed on said second optical guide layer,

wherein at least one of side surfaces of said hole holes is a {10-10} facet.

8. The surface emitting laser according to claim **7**, wherein a surface of said first optical guide layer being in contact with the light emitting layer is a (0001) plane, and a plane of said holes on a side of said light emitting layer is a (000-1) plane.

9. The surface emitting laser according to claim **7**, wherein said holes have a polygonal columnar shape, and at least one of the side planes of said holes is a {10-10} facet.

10. The surface emitting laser according to claim **7**, wherein said holes have a polygonal columnar shape, and have an asymmetrical cross section with respect to a diagonal line in a cross section parallel to said first optical guide layer.

* * * * *