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(54) **METHOD FOR GROWING BETA-GA2O3-BASED SINGLE CRYSTAL FILM, AND CRYSTALLINE LAYERED STRUCTURE**

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CPC *C30B 25/165* (2013.01); *C30B 29/16* (2013.01); *H01L 21/02565* (2013.01); *H01L 21/0259* (2013.01); *H01L 21/0262* (2013.01); *H01L 29/24* (2013.01); *H01L 21/02414* (2013.01); *H01L 21/02433* (2013.01); *H01L 29/04* (2013.01); *H01L 21/02634* (2013.01); *H01L 21/02598* (2013.01)

(57) **ABSTRACT**

As one embodiment, the present invention provides a method for growing a β-Ga_2O_3-based single crystal film by using HVPE method. The method includes a step of exposing a Ga_2O_3-based substrate to a gallium chloride-based gas and an oxygen-including gas, and growing a β-Ga_2O_3-based single crystal film on a principal surface of the Ga_2O_3-based substrate at a growth temperature of not lower than 900° C.
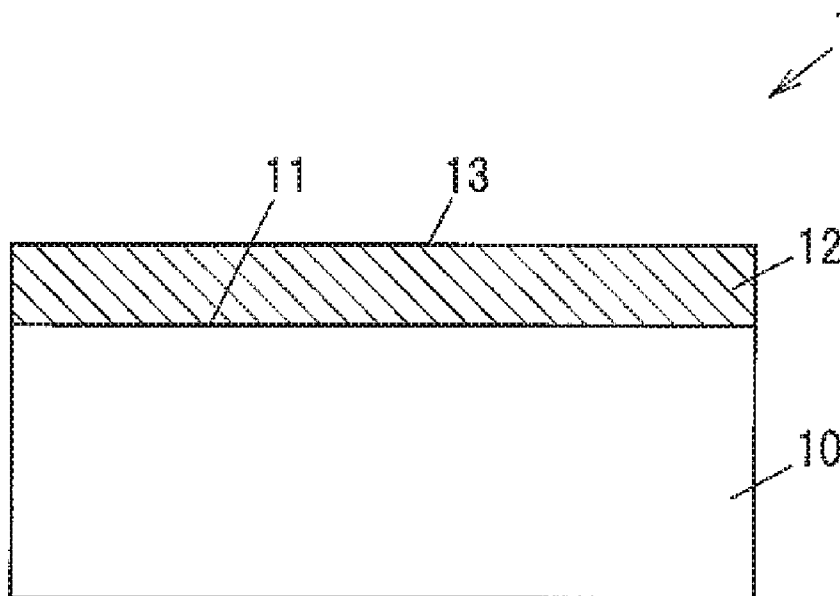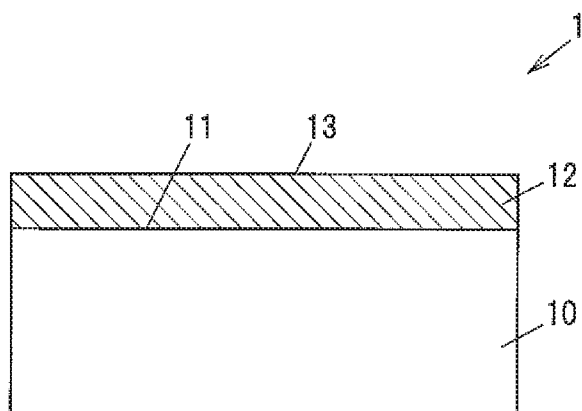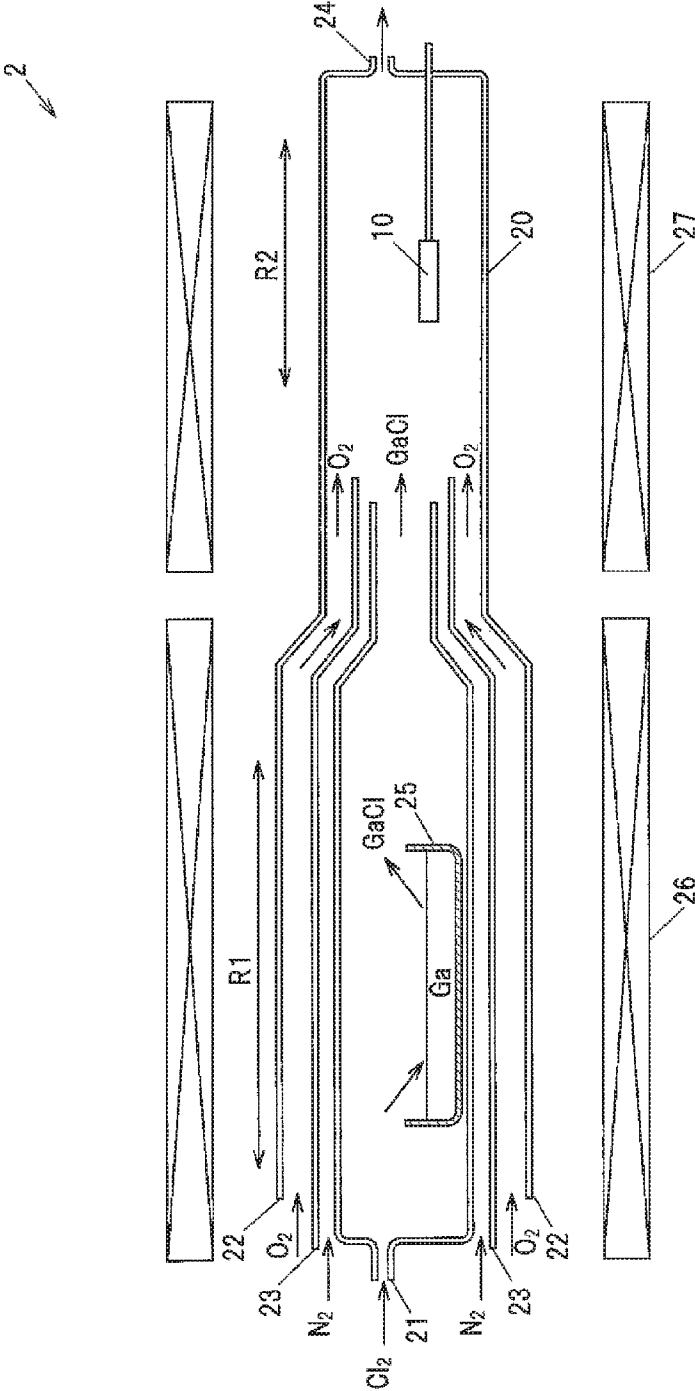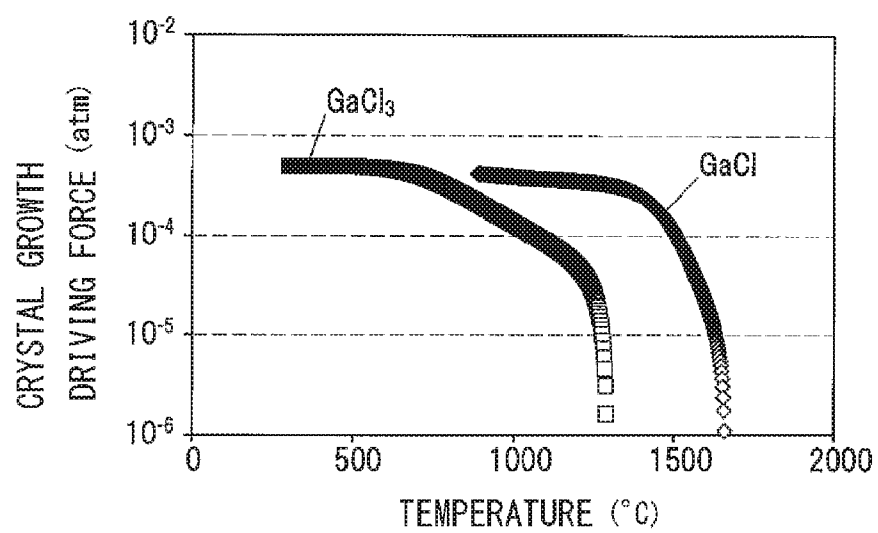
FIG. 1

FIG. 2

FIG. 3

FIG. 4

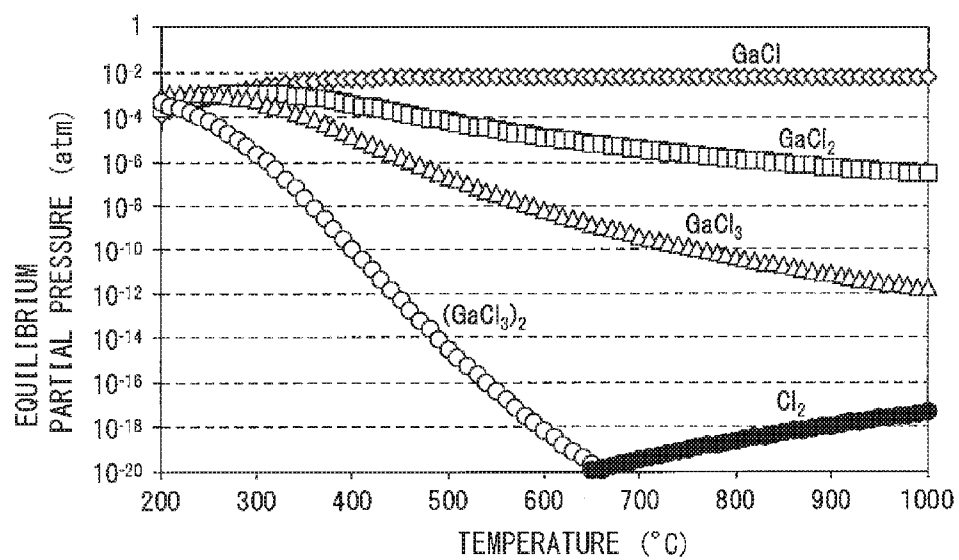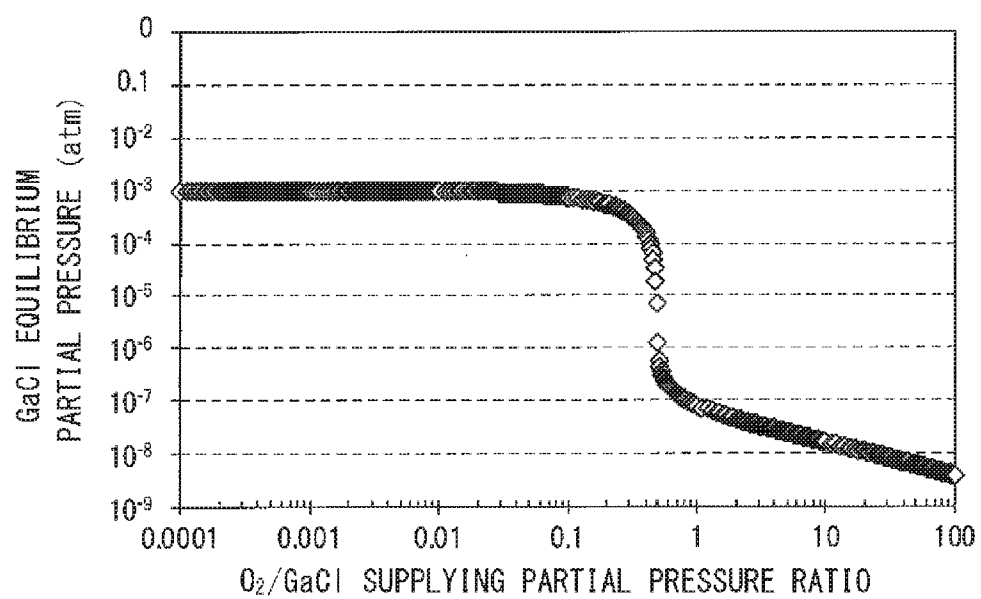EQUILIBRIUM PARTIAL PRESSURE (atm)

$GaCl$
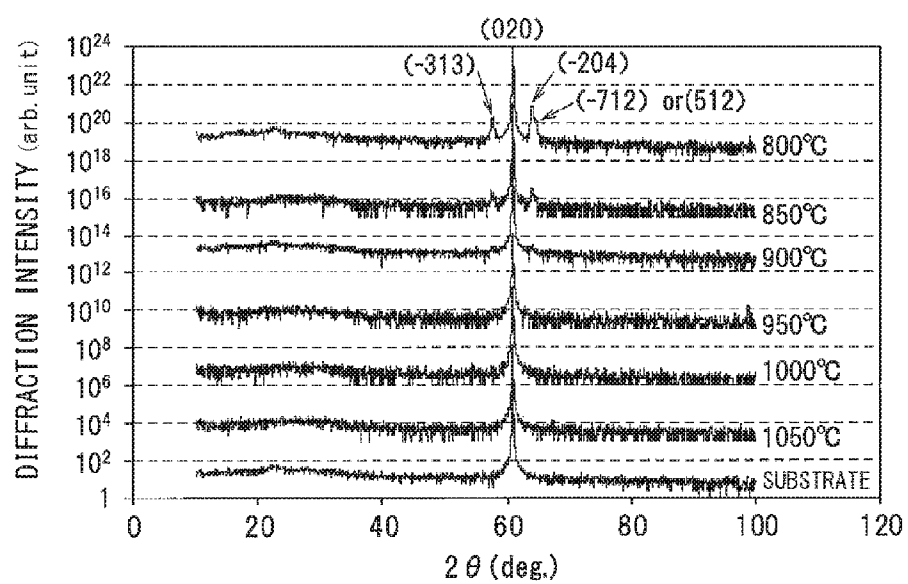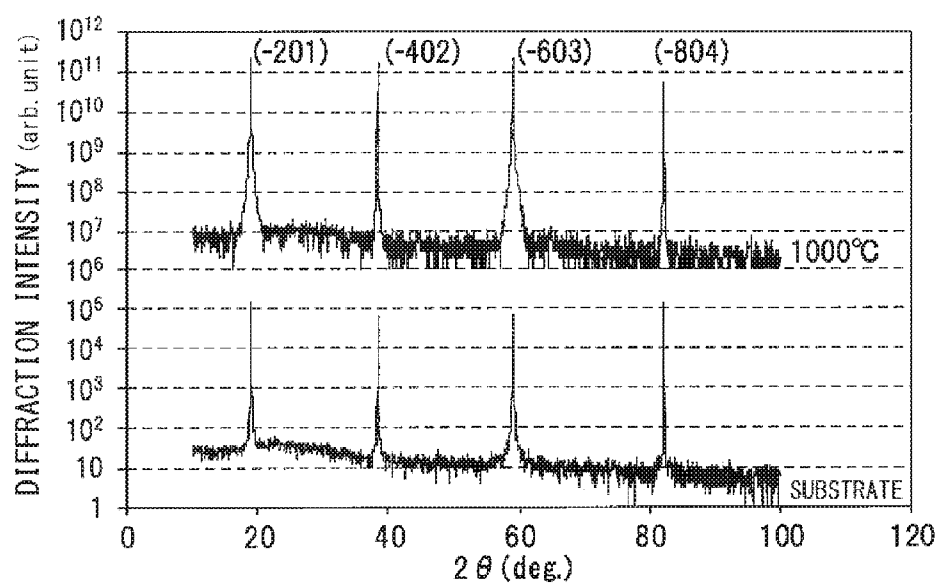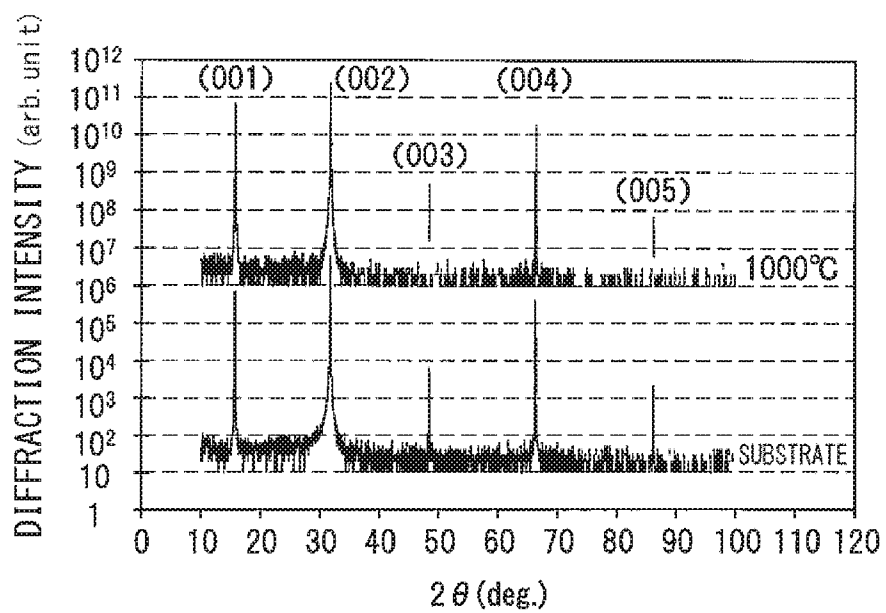
$GaCl_2$

$GaCl_3$

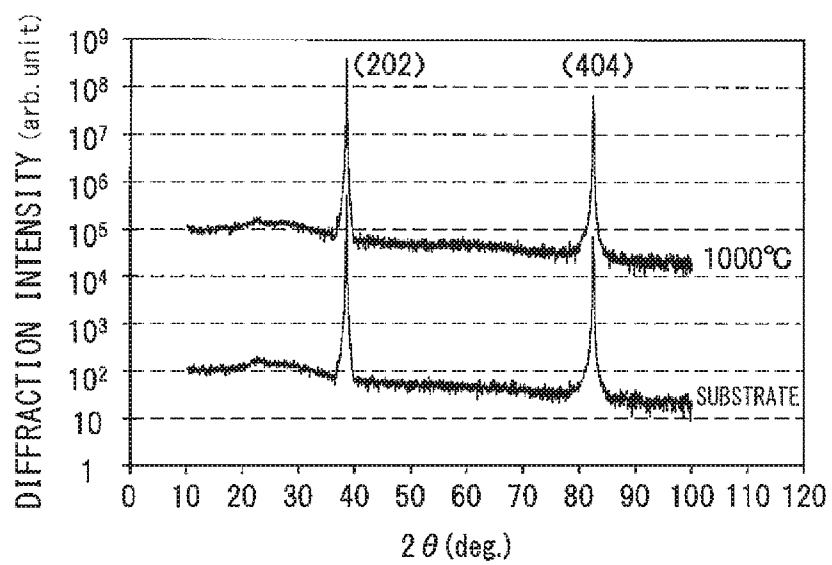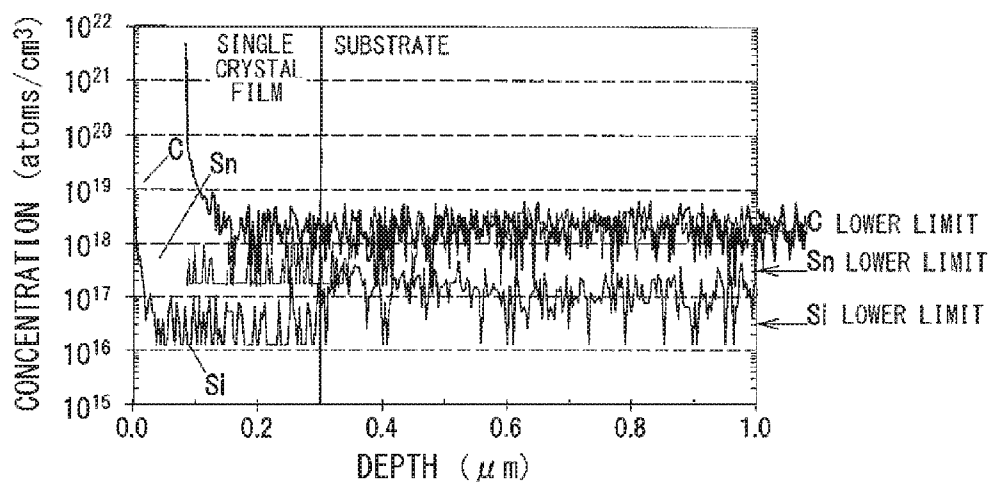$(GaCl_3)_2$

Cl_2

TEMPERATURE (°C)

FIG. 5

FIG. 6

FIG. 7

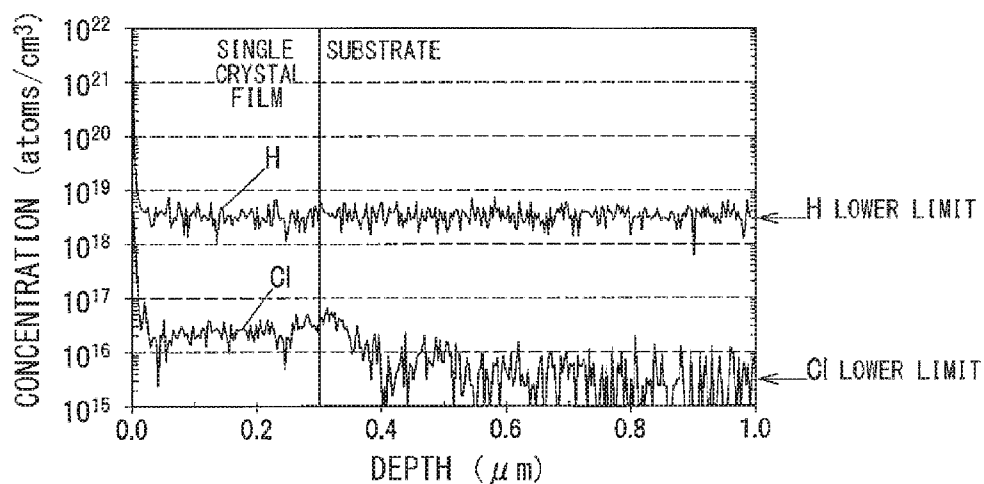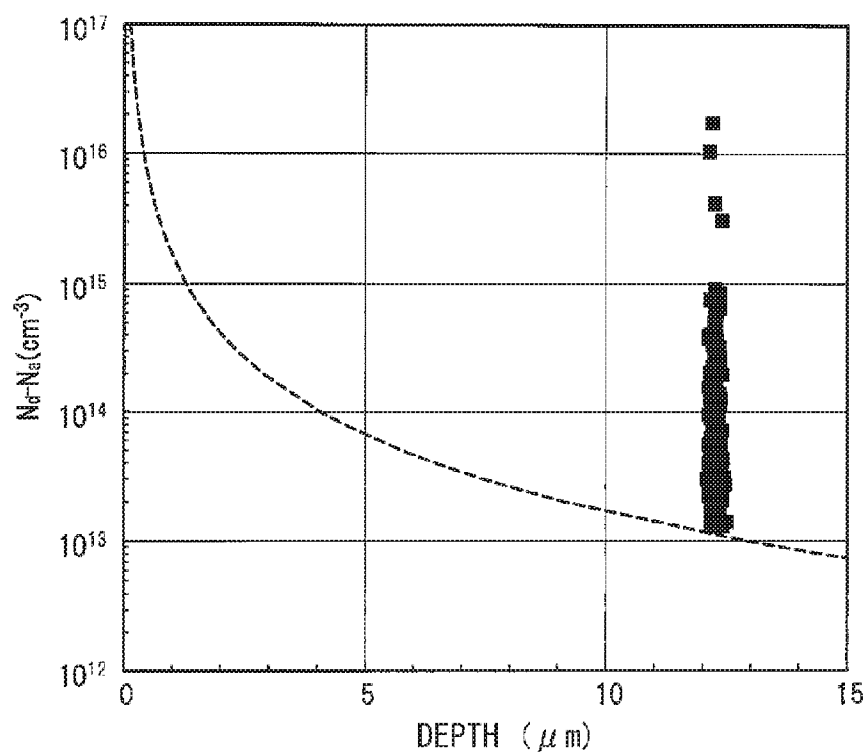# FIG. 8

FIG. 9

FIG. 10A

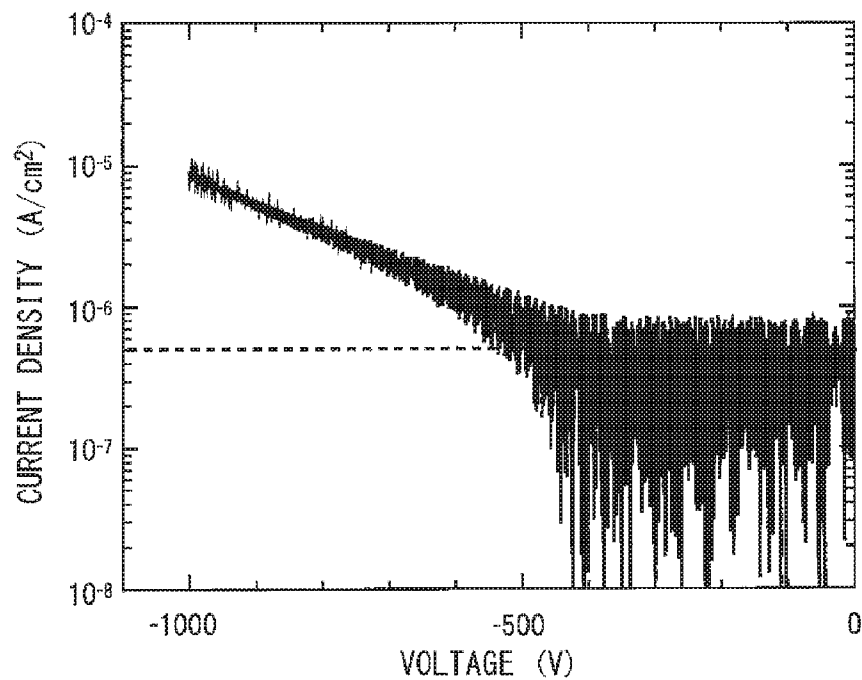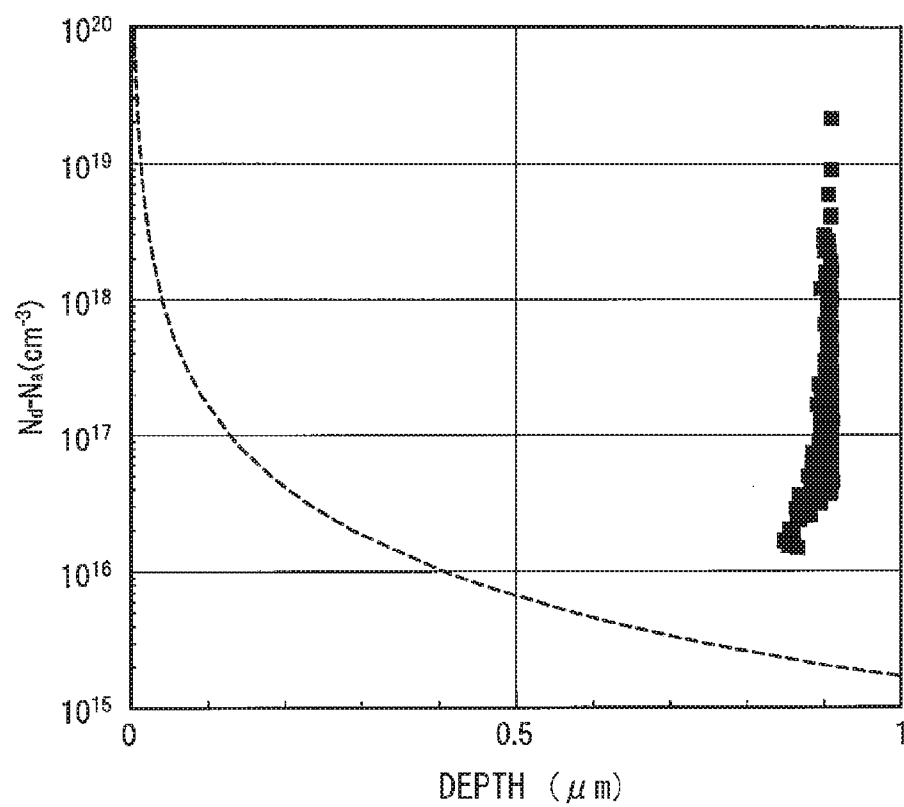FIG. 10B

FIG. 11A

FIG. 11B

FIG. 12

METHOD FOR GROWING BETA-GA2O3-BASED SINGLE CRYSTAL FILM, AND CRYSTALLINE LAYERED STRUCTURE

TECHNICAL FIELD

[0001] The invention relates to a method for growing a β-Ga$_2$O$_3$-based single crystal film and a crystalline layered structure.

BACKGROUND ART

[0002] The MBE (Molecular Beam Epitaxy) method and the PLD (Pulsed Laser Deposition) method are known as a growth method of β-Ga$_2$O$_3$ single crystal film (see, e.g., PTL 1 and PTL 2). Other growth methods thereof, the sol-gel process, the MOCVD (Metal Organic Chemical Vapor Deposition) process and the mist CVD process are also known.

CITATION LIST

Patent Literature

[0003] [PTL 1]
[0004] JP-A-2013-56803
[0005] [PTL 2]
[0006] JP-B-4565062

SUMMARY OF INVENTION

Technical Problem

[0007] The MBE method is conducted, however, such that crystal is grown in a high vacuum chamber. Thus, it is difficult to increase the diameter of a β-Ga$_2$O$_3$ single crystal film. Although a high-quality film can be generally obtained by increasing the growth temperature, a sufficient film growth rate is not obtained due to an increase in re-evaporation of source gases and it is thus not suitable for mass production.
[0008] The PLD method is not suitable for growing a film with a large area since a source (a raw material supply source to a substrate) is a point source which causes a growth rate to be different between a portion immediately above the source and other portions and in-plane distribution of film thickness is likely to be non-uniform. In addition, it takes long time to form a thick film due to a low film growth rate, hence, not suitable for mass production.
[0009] In regard to the sol-gel method, the MOCVD method and the mist CVD method, it is relatively easy to increase a diameter but it is difficult to obtain single crystal films with high purity since impurities contained in the used materials are incorporated into the β-Ga$_2$O$_3$ single crystal film during epitaxial growth.
[0010] Thus, it is an object of the invention to provide a method for growing a β-Ga$_2$O$_3$-based single crystal film that allows a high-quality and large-diameter β-Ga$_2$O$_3$-based single crystal film to grow efficiently, as well as a crystalline layered structure having the β-Ga$_2$O$_3$-based single crystal film grown by the method.

Solution to Problem

[0011] According to an embodiment of the invention, in order to achieve the object, a growth method of a β-Ga$_2$O$_3$-based single crystal film defined by [1] to [8] below will be provided.

[0012] [1] A method for growing a β-Ga$_2$O$_3$-based single crystal film by HVPE method, comprising a step of exposing a Ga$_2$O$_3$-based substrate to a gallium chloride-based gas and an oxygen-including gas and growing a β-Ga$_2$O$_3$-based single crystal film on a principal surface of the Ga$_2$O$_3$-based substrate at a growth temperature of not lower than 900° C.
[0013] [2] The method for growing a β-Ga$_2$O$_3$-based single crystal film defined by [1], wherein the gallium chloride-based gas is produced by reacting a gallium source with a Cl-including gas comprising a Cl$_2$ gas or an HCl gas.
[0014] [3] The method for growing a β-Ga$_2$O$_3$-based single crystal film defined by [1] or [2], wherein in the gallium chloride-based gas a GaCl gas has a highest partial pressure ratio.
[0015] [4] The method for growing a β-Ga$_2$O$_3$-based single crystal film defined by [1] or [2], wherein the oxygen-including gas comprises an O$_2$ gas.
[0016] [5] The method for growing a β-Ga$_2$O$_3$-based single crystal film defined by [2], wherein the Cl-including gas comprises a Cl$_2$ gas.
[0017] [6] The method for growing a β-Ga$_2$O$_3$-based single crystal film defined by [1] or [2], wherein a ratio of a supplied partial pressure of the oxygen-including gas to a supplied partial pressure of the gallium chloride-based gas when growing the β-Ga$_2$O$_3$-based single crystal film is not more than 0.5.
[0018] [7] The method for growing a β-Ga$_2$O$_3$-based single crystal film defined by [1] or [2], wherein the principal surface of the Ga$_2$O$_3$-based substrate has a plane orientation of (010), (−201), (001) or (101).
[0019] [8] The method for growing a β-Ga$_2$O$_3$-based single crystal film defined by [1] or [2], wherein the gallium chloride-based gas is produced at an atmosphere temperature of not less than 300° C.
[0020] According to another embodiment of the invention, in order to achieve the object, a crystalline layered structure defined by [9] to [12] below will be provided.
[0021] [9] A crystalline layered structure, comprising:
[0022] a Ga$_2$O$_3$-based substrate; and
[0023] a β-Ga$_2$O$_3$-based single crystal film that is formed on a principal surface of the Ga$_2$O$_3$-based substrate by epitaxial crystal growth and includes Cl.
[0024] [10] The crystalline layered structure defined by [9], wherein a Cl concentration in the β-Ga$_2$O$_3$-based single crystal film is not more than 5×10^{16} atoms/cm^3.
[0025] [11] The crystalline layered structure defined by [9] or [10], wherein the β-Ga$_2$O$_3$-based single crystal film comprises a β-Ga$_2$O$_3$ crystal film.
[0026] The crystalline layered structure defined by [11], wherein a residual carrier concentration in the β-Ga$_2$O$_3$-based single crystal film is not more than 3×10^{35} atoms/cm^3.

Advantageous effects of Invention

[0027] According to the invention, a method for growing a β-Ga$_2$O$_3$-based single crystal film can be provided that allows a high-quality and large-diameter β-Ga$_2$O$_3$-based single crystal film to grow efficiently, as well as a crystalline layered structure having the β-Ga$_2$O$_3$-based single crystal film grown by the method.

BRIEF DESCRIPTION OF DRAWINGS

[0028] FIG. 1 is a vertical cross-sectional view showing a crystalline layered structure in an embodiment.

[0029] FIG. 2 is a vertical cross-sectional view showing a vapor phase deposition system in the embodiment.

[0030] FIG. 3 is a graph showing a relation, based on calculation of thermal equilibrium, between a driving force for growth and a growth temperature of Ga_2O_3 crystal in the case that a gallium chloride gas is only of a GaCl gas and a $GaCl_3$ gas, respectively.

[0031] FIG. 4 is a graph showing a relation, based on calculation of thermal equilibrium, between an atmosphere temperature and equilibrium partial pressures of GaCl gas, $GaCl_2$ gas, $GaCl_3$ gas and $(GaCl_3)_2$ gas which are obtained by reaction of Ga with Cl_2.

[0032] FIG. 5 is a graph showing a relation, based on calculation of thermal equilibrium, between equilibrium partial pressure of GaCl and an O_2/GaCl supplied partial pressure ratio when the atmosphere temperature during Ga_2O_3 crystal growth is 1000° C.

[0033] FIG. 6 is a graph showing X-ray diffraction spectra obtained by 2θ-ω scan on crystalline layered structure in each of which a Ga_2O_3 single crystal film is epitaxially grown on a (010)-oriented principal surface of a Ga_2O_3 substrate.

[0034] FIG. 7 is a graph showing an X-ray diffraction spectrum obtained by 2θ-ω scan on a crystalline layered structure in which a Ga_2O_3 single crystal film is epitaxially grown on a (−201)-oriented principal surface of a Ga_2O_3 substrate at 1000° C.

[0035] FIG. 8 is a graph showing an X-ray diffraction spectrum obtained by 2θ-ω scan on a crystalline layered structure in which a Ga_2O_3 single crystal film is epitaxially grown on a (001)-oriented principal surface of a $β$-Ga_2O_3 substrate.

[0036] FIG. 9 is a graph showing an X-ray diffraction spectrum obtained by 2θ-ω scan on a crystalline layered structure in which a Ga_2O_3 single crystal film is epitaxially grown on a (101)-oriented principal surface of a $β$-Ga_2O_3 substrate.

[0037] FIG. 10A is a graph showing the concentration of impurities in the crystalline layered structure measured by secondary ion mass spectrometry (SIMS).

[0038] FIG. 10B is a graph showing the concentration of impurities in the crystalline layered structure measured by secondary ion mass spectrometry (SIMS).

[0039] FIG. 11A is a graph showing the carrier concentration profile in a depth direction of the crystalline layered structure in which a $β$-Ga_2O_3 crystal film is epitaxially grown on a (001)-oriented principal surface of a $β$-Ga_2O_3 substrate.

[0040] FIG. 11B is a graph showing the voltage endurance characteristics of the crystalline layered structure in which a $β$-Ga_2O_3 crystal film is epitaxially grown on a (001)-oriented principal surface of a $β$-Ga_2O_3 substrate.

[0041] FIG. 12 is a graph showing a carrier concentration profile in a depth direction of the crystalline layered structure in which a $β$-Ga_2O_3 crystal film is epitaxially grown on a (010)-oriented principal surface of a $β$-Ga_2O_3 substrate.

DESCRIPTION OF EMBODIMENT

Embodiment

(Configuration of Crystalline Layered Structure)

[0042] FIG. 1 is a vertical cross-sectional view showing a crystalline layered structure 1 in an embodiment. The crystalline layered structure 1 has a Ga_2O_3-based substrate 10 and a $β$-Ga_2O_3-based single crystal film 12 formed on a principal surface 11 of the Ga_2O_3-based substrate 10 by epitaxial crystal growth.

[0043] The Ga_2O_3-based substrate 10 is a substrate formed of a Ga_2O_3-based single crystal with a $β$-crystal structure. The Ga_2O_3-based single crystal here means a Ga_2O_3 single crystal or is a Ga_2O_3 single crystal doped with an element such as Al or In, and may be, e.g., a $(Ga_xAl_yIn_{(1-x-y)})_2O_3$ $(0<x≤1, 0≤y≤1, 0<x+y≤1)$ single crystal which is a Ga_2O_3 single crystal doped with Al and In. The band gap is widened by adding Al and is narrowed by adding In. In addition, the Ga_2O_3-based substrate 10 may contain a conductive impurity such as Si.

[0044] The plane orientation of the principal surface 11 of the Ga_2O_3-based substrate 10 is, e.g., (010), (−201), (001) or (101).

[0045] To form the Ga_2O_3-based substrate 10, for example, a bulk crystal of a Ga_2O_3-based single crystal grown by, e.g., a melt-growth technique such as the FZ (Floating Zone) method or the EFG (Edge Defined Film Fed Growth) method is sliced and the surface thereof is then polished.

[0046] The $β$-Ga_2O_3-based single crystal film 12 is formed of a Ga_2O_3-based single crystal with a $β$-crystal structure in the same manner as the Ga_2O_3-based substrate 10. In addition, the $β$-Ga_2O_3-based single crystal film 12 may contain a conductive impurity such as Si.

(Structure of Vapor Phase Deposition System)

[0047] A structure of a vapor phase deposition system used for growing the $β$-Ga_2O_3-based single crystal film 12 in the present embodiment will be described below as an example.

[0048] FIG. 2 is a vertical cross-sectional view showing a vapor phase deposition system 2 in the embodiment. The vapor phase deposition system 2 is a vapor phase deposition system using HVPE (Halide Vapor Phase Epitaxy) technique, and has a reaction chamber 20 having a first gas introducing port 21, a second gas introducing port 22, a third gas introducing port 23 and an exhaust port 24, and a first heating means 26 and a second heating means 27 which are placed around the reaction chamber 20 to heat predetermined regions in the reaction chamber 20.

[0049] The growth rate when using the HVPE technique is higher than that in the PLD method, etc. In addition, in-plane distribution of film thickness is highly uniform and it is possible to grow a large-diameter film. Therefore, it is suitable for mass production of crystal.

[0050] The reaction chamber 20 has a source reaction region R1 in which a reaction container 25 containing a Ga source is placed and a gallium source gas is produced, and a crystal growth region R2 in which the Ga_2O_3-based substrate 10 is placed and the $β$-Ga_2O_3-based single crystal film 12 is grown thereon. The reaction chamber 20 is formed of, e.g., quartz glass.

[0051] Here, the reaction container 25 is formed of, e.g., quartz glass and the Ga source contained in the reaction container 25 is metal gallium.

[0052] The first heating means 26 and the second heating means 27 are capable of respectively heating the source reaction region R1 and the crystal growth region R2 of the reaction chamber 20. The first heating means 26 and the second heating means 27 are, e.g., resistive heaters or radiation heaters.

[0053] The first gas introducing port 21 is a port for introducing a Cl-containing gas (Cl_2 gas or HCl gas) into the source reaction region R1 of the reaction chamber 20 using an inert carrier gas (N_2 gas, Ar gas or He gas). The second gas introducing port 22 is a port for introducing an oxygen-con-

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taining gas (O_2 gas or H_2O gas, etc.) as an oxygen source gas and a chloride gas (e.g., silicon tetrachloride, etc.) used to add a dopant such as Si to the β-Ga_2O_3-based single crystal film **12**, into the crystal growth region R**2** of the reaction chamber **20** using an inert carrier gas (N_2 gas, Ar gas or He gas). The third gas introducing port **23** is a port for introducing an inert carrier gas (N_2 gas, Ar gas or He gas) into the crystal growth region R**2** of the reaction chamber **20**.

(Growth of β-Ga_2O_3-Based Single Crystal Film)

[0054] A process of growing the β-Ga_2O_3-based single crystal film **12** in the present embodiment will be described below as an example.

[0055] Firstly, the source reaction region R**1** of the reaction chamber **20** is heated by the first heating means **26** and an atmosphere temperature in the source reaction region R**1** is then maintained at a predetermined temperature.

[0056] Next, in the source reaction region R**1**, a Cl-containing gas introduced through the first gas introducing port **21** using a carrier gas is reacted with the metal gallium in the reaction container **25** at the above-mentioned atmosphere temperature, thereby producing a gallium chloride gas.

[0057] The atmosphere temperature in the source reaction region R**1** here is preferably a temperature at which GaCl gas has the highest partial pressure among component gases of the gallium chloride gas produced by the reaction of the metal gallium in the reaction container **25** with the Cl-containing gas. The gallium chloride gas here contains GaCl gas, $GaCl_2$ gas, $GaCl_3$ gas and $(GaCl_3)_2$ gas, etc.

[0058] The temperature at which a driving force for growth of Ga_2O_3 crystal is maintained is the highest with the GaCl gas among the gases contained in the gallium chloride gas. Growth at a high temperature is effective to obtain a high-quality Ga_2O_3 crystal with high purity. Therefore, for growing the β-Ga_2O_3-based single crystal film **12**, it is preferable to produce a gallium chloride gas in which a partial pressure of GaCl gas having a high driving force for growth at a high temperature is high.

[0059] FIG. **3** is a graph showing a relation, based on calculation of thermal equilibrium, between a driving force for growth and a growth temperature of Ga_2O_3 crystal respectively when a gallium chloride gas consists of only a GaCl gas and consists of only a $GaCl_3$ gas. The calculation conditions are as follows: a carrier gas is, e.g., an inert gas such as N_2, a furnace pressure is 1 atom, the supplied partial pressures of GaCl gas and $GaCl_3$ gas are both 1×10^{-3} atom, and an O_2/GaCl partial pressure ratio is 10.

[0060] In FIG. **3**, the horizontal axis indicates a growth temperature (° C.) of Ga_2O_3 crystal and the vertical axis indicates a driving force for crystal growth. The Ga_2O_3 crystal grows more efficiently with a larger driving force for crystal growth.

[0061] FIG. **3** shows that the maximum temperature at which the driving force for growth is maintained is higher when using the GaCl gas as a Ga source gas than when using the $GaCl_3$ gas.

[0062] If hydrogen is contained in an atmosphere for growing the β-Ga_2O_3-based single crystal film **12**, surface flatness and a driving force for growth of the β-Ga_2O_3-based single crystal film **12** decrease. Therefore, it is preferable that a Cl_2 gas not containing hydrogen be used as the Cl-containing gas.

[0063] FIG. **4** is a graph showing a relation, based on calculation of thermal equilibrium, between an atmosphere temperature during reaction and equilibrium partial pressures of GaCl gas, $GaCl_2$ gas, $GaCl_3$ gas and $(GaCl_3)_2$ gas which are

obtained by reaction of Ga with Cl_2. The other calculation conditions are as follows: a carrier gas is, e.g., an inert gas such as N_2, a furnace pressure is 1 atom and the supplied partial pressure of Cl_2 gas is 3×10^{-3} atom.

[0064] In FIG. **4**, the horizontal axis indicates an atmosphere temperature (° C.) and the vertical axis indicates an equilibrium partial pressure (atm). It is shown that more gas is produced at a higher equilibrium partial pressure.

[0065] FIG. **4** shows that when reacting the metal gallium chloride with the Cl-containing gas at an atmosphere temperature of about not less than 300° C., the equilibrium partial pressure of GaCl gas particularly capable of increasing a driving force for growth of Ga_2O_3 crystal is increased, i.e., a partial pressure ratio of the GaCl gas with respect to the gallium chloride gas becomes higher. Based on this, it is preferable that the metal gallium in the reaction container **25** be reacted with the Cl-containing gas in a state that the atmosphere temperature in the source reaction region R**1** is maintained at not less than 300° C. by using the first heating means **26**.

[0066] Also, at the atmosphere temperature of, e.g., 850° C., the partial pressure ratio of the GaCl gas is predominantly high (the equilibrium partial pressure of the GaCl gas is four orders of magnitude greater than the $GaCl_2$ gas and is eight orders of magnitude greater than the $GaCl_3$ gas) and the gases other than GaCl gas hardly contribute to the growth of Ga_2O_3 crystal.

[0067] Meanwhile, in consideration of the lifetime of the first heating means **26** and heat resistance of the reaction chamber **20** formed of quartz glass, etc., it is preferable that the metal gallium in the reaction container **25** be reacted with the Cl-containing gas in a state that the atmosphere temperature in the source reaction region R**1** is maintained at not more than 1000° C.

[0068] Next, in the crystal growth region R**2**, the gallium chloride gas produced in the source reaction region R**1** is mixed with the oxygen-containing gas introduced through the second gas introducing port **22** and the Ga_2O_3-based substrate **10** is exposed to the mixed gas, thereby epitaxially growing the β-Ga_2O_3-based single crystal film **12** on the Ga_2O_3-based substrate **10**. At this time, in a furnace housing the reaction chamber **20**, pressure in the crystal growth region R**2** is maintained at, e.g., 1 atm.

[0069] When forming the β-Ga_2O_3-based single crystal film **12** containing an additive element such as Si or Al, a source gas of the additive element (e.g., a chloride gas such as silicon tetrachloride ($SiCl_4$)) is introduced, together with the gallium chloride gas and the oxygen-containing gas, into the crystal growth region R**2** through the gas introducing port **22**.

[0070] If hydrogen is contained in an atmosphere for growing the β-Ga_2O_3-based single crystal film **12**, surface flatness and a driving force for growth of the β-Ga_2O_3-based single crystal film **12** decrease. Therefore, it is preferable that an O_2 gas not containing hydrogen be used as the oxygen-containing gas.

[0071] FIG. **5** is a graph showing a relation, based on calculation of thermal equilibrium, between an equilibrium partial pressure of GaCl and an O_2/GaCl supplied partial pressure ratio when the atmosphere temperature during Ga_2O_3 crystal growth is 1000° C. Here, a ratio of the supplied partial pressure of the O_2 gas to the supplied partial pressure of the GaCl gas is referred to as "O_2/GaCl supplied partial pressure ratio". It is calculated using the supplied partial pressure value of the GaCl gas fixed to 1×10^{-3} atom, a furnace pressure

of 1 atom adjusted by using, e.g., an inert gas such as N_2 as a carrier gas, and various values of the O_2 gas supplied partial pressure.

[0072] In FIG. 5, the horizontal axis indicates the O_2/GaCl supplied partial pressure ratio and the vertical axis indicates an equilibrium partial pressure (atm) of the GaCl gas. It is shown that the smaller the supplied partial pressure of the GaCl gas, the more the GaCl gas is consumed for growth of Ga_2O_3 crystal, i.e., the Ga_2O_3 crystal grows efficiently.

[0073] FIG. 5 shows that the equilibrium partial pressure of the GaCl gas sharply falls at the O_2/GaCl supplied partial pressure ratio of not less than 0.5.

[0074] Based on this, to efficiently grow the β-Ga_2O_3-based single crystal film 12, the β-Ga_2O_3-based single crystal film 12 is preferably grown in a state that a ratio of the supplied partial pressure of the O_2 gas to the supplied partial pressure of the GaCl gas in the crystal growth region R2 is not less than 0.5.

[0075] FIG. 6 is a graph showing X-ray diffraction spectra obtained by 2θ-ω scan on crystalline layered structures in each of which a Ga_2O_3 single crystal film is epitaxially grown on a (010)-oriented principal surface of a β-Ga_2O_3 substrate. The growth conditions are as follows: a furnace pressure is 1 atom, a carrier gas is N_2 gas, the GaCl supplied partial pressure is 5×10^{-4} atom, and the O_2/GaCl supplied partial pressure ratio is 5.

[0076] In FIG. 6, the horizontal axis indicates an angle 2θ (degrees) formed between the incident direction and the reflected direction of X-ray and the vertical axis indicates diffraction intensity (arbitrary unit) of the X-ray.

[0077] FIG. 6 shows a spectrum from a β-Ga_2O_3 substrate (without β-Ga_2O_3 crystal film) and spectra from crystalline layered structures having β-Ga_2O_3 crystal films respectively epitaxially grown at 800° C., 850° C., 900° C., 950° C., 1000° C. and 1050° C. The β-$Ga2O_3$ crystal films of these crystalline layered structures have a thickness of about 300 to 1000 nm.

[0078] Diffraction peaks from a (−313) plane, a (−204) plane and a (−712) plane or a (512) plane resulting from the presence of non-oriented grains, which are observed in the spectra from the crystalline layered structures having the β-Ga_2O_3 crystal films grown at growth temperatures of 800° C. and 850° C., disappear in the spectra from the crystalline layered structures having the β-Ga_2O_3 crystal films grown at growth temperatures of not less than 900° C. This shows that a β-Ga_2O_3 single crystal film is obtained when a Ga_2O_3 single crystal film is grown at a growth temperature of not less than 900° C.

[0079] Also in case that the principal surface of the β-Ga_2O_3 substrate has a plane orientation of (−201), (001) or (101), a β-Ga_2O_3 single crystal film is obtained when a β-Ga_2O_3 crystal film is grown at a growth temperature of not less than 900° C. In addition, also in case that another Ga_2O_3-based substrate is used in place of the Ga_2O_3 substrate or another Ga_2O_3-based crystal film is formed instead of the Ga_2O_3 crystal film, evaluation results similar to those described above are obtained. In other words, when the plane orientation of the principal surface of the Ga_2O_3-based substrate 10 is (010), (−201), (001) or (101), the β-Ga_2O_3-based single crystal film 12 is obtained by growing at a growth temperature of not less than 900° C.

[0080] FIG. 7 is a graph showing an X-ray diffraction spectrum obtained by 2θ-ω scan on a crystalline layered structure in which a β-Ga_2O_3 single crystal film is epitaxially grown on

a (−201)-oriented principal surface of a β-Ga_2O_3 substrate. The growth conditions for this β-Ga_2O_3 single crystal film are as follows: a furnace pressure is 1 atom, a carrier gas is N_2 gas, the GaCl supplied partial pressure is 5×10^{-4} atom, the O_2/GaCl supplied partial pressure ratio is 5 and the growth temperature is 1000° C.

[0081] FIG. 7 shows a spectrum from a β-Ga_2O_3 substrate (without β-Ga_2O_3 crystal film) having a (−201)-oriented principal surface and a spectrum from a crystalline layered structure having a β-Ga_2O_3 crystal film epitaxially grown on the β-Ga_2O_3 substrate at 1000° C. The β-Ga_2O_3 crystal film of this crystalline layered structure has a thickness of about 300 nm.

[0082] FIG. 8 is a graph showing an X-ray diffraction spectrum obtained by 2θ-ω scan on a crystalline layered structure in which a Ga_2O_3 single crystal film is epitaxially grown on a (001)-oriented principal surface of a β-Ga_2O_3 substrate. The growth conditions for this β-Ga_2O_3 single crystal film are as follows: a furnace pressure is 1 atom, a carrier gas is N_2 gas, the GaCl supplied partial pressure is 5×10^{-4} atom, the O_2/GaCl supplied partial pressure ratio is 5 and the growth temperature is 1000° C.

[0083] FIG. 8 shows a spectrum from a β-Ga_2O_3 substrate (without β-Ga_2O_3 crystal film) having a (001)-oriented principal surface and a spectrum from a crystalline layered structure having a β-Ga_2O_3 crystal film epitaxially grown on the β-Ga_2O_3 substrate at 1000° C. The β-Ga_2O_3 crystal film of this crystalline layered structure has a thickness of about 6 μm.

[0084] FIG. 9 is a graph showing an X-ray diffraction spectrum obtained by 2θ-ω scan on a crystalline layered structure in which a Ga_2O_3 single crystal film is epitaxially grown on a (101)-oriented principal surface of a β-Ga_2O_3 substrate. The growth conditions for this β-Ga_2O_3 single crystal film are as follows: a furnace pressure is 1 atom, a carrier gas is N_2 gas, the GaCl supplied partial pressure is 5×10^{-4} atom, the O_2/GaCl supplied partial pressure ratio is 5 and the growth temperature is 1000° C.

[0085] FIG. 9 shows a spectrum from a β-Ga_2O_3 substrate (without β-Ga_2O_3 crystal film) having a (101)-oriented principal surface and a spectrum from a crystalline layered structure having a β-Ga_2O_3 crystal film epitaxially grown on the β-Ga_2O_3 substrate at 1000° C. The β-Ga_2O_3 crystal film of this crystalline layered structure has a thickness of about 4 μm.

[0086] In FIGS. 7, 8 and 9, the horizontal axis indicates an angle 2θ (degrees) formed between the incident direction and the reflected direction of X-ray and the vertical axis indicates diffraction intensity (arbitrary unit) of the X-ray.

[0087] In FIGS. 7, 8 and 9, diffraction peaks of the spectrum from the crystalline layered structure having the β-Ga_2O_3 crystal film grown at a growth temperature of 1000° C. are coincident with the diffraction peaks of the spectrum from the β-Ga_2O_3 substrate. This result shows that a β-Ga_2O_3 single crystal film is obtained when the β-Ga_2O_3 crystal film is grown on the principal surface of the β-Ga_2O_3 substrate having a plane orientation of (010), (−201), (001) or (101) at a growth temperature of 1000° C.

[0088] FIGS. 10A and 10B are graphs showing concentrations of impurities in the crystalline layered structure measured by secondary ion mass spectrometry (SIMS).

[0089] In FIGS. 10A and 10B, the horizontal axis indicates a depth (μm) of the crystalline layered structure from a principal surface 13 of the β-Ga_2O_3 single crystal film and the

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vertical axis indicates concentration (atoms/cm³) of each impurity. Here, an interface between the β-Ga₂O₃ substrate and the β-Ga₂O₃ single crystal film is located at a depth of about 0.3 μm in the crystalline layered structure. In addition, horizontal arrows on the right side in FIGS. **10A** and **10B** indicate the respective measurable lower limits of concentrations of the impurity elements.

[0090] The β-Ga₂O₃ single crystal film of the crystalline layered structure used for the measurement is a film which is grown on the (010)-oriented principal surface of the β-Ga₂O₃ substrate at a growth temperature of 1000° C.

[0091] FIG. **10A** shows the concentrations of C, Sn, and Si in the crystalline layered structure and FIG. **10B** shows the concentrations of H and Cl in the crystalline layered structure. According to FIGS. **10A** and **10B**, the concentration of each impurity element in the β-Ga₂O₃ single crystal film is close to the measurable lower limit and is almost unchanged from the concentration in the Ga₂O₃ substrate. This shows that the β-Ga₂O₃ single crystal film is a highly pure film.

[0092] Similar evaluation results are obtained also in case that the principal surface of the β-Ga₂O₃ substrate has a plane orientation of (−201), (101) or (001). In addition, also in case that another Ga₂O₃-based substrate is used in place of the β-Ga₂O₃ substrate or another Ga₂O₃-based single crystal film is formed instead of the β-Ga₂O₃ single crystal film, evaluation results similar to those described above are obtained.

[0093] According to FIG. **10B**, not more than about 5×10^{16} (atoms/cm³) of Cl is contained in the β-Ga₂O₃ single crystal film. This results from that the Ga₂O₃ single crystal film is formed by the HVPE method using Cl-containing gas. Generally, Cl-containing gas is not used to form a Ga₂O₃ single crystal film when using a method other than the HVPE method, and the Ga₂O₃ single crystal film does not contain Cl, or at least does not contain 1×10^{16} (atoms/cm³) or more of Cl.

[0094] FIG. **11A** is a graph showing a carrier concentration profile in a depth direction of the crystalline layered structure in which a β-Ga₂O₃ crystal film is epitaxially grown on a (001)-oriented principal surface of a β-Ga₂O₃ substrate.

[0095] In FIG. **11A**, the horizontal axis indicates a depth (μm) from the surface of the β-Ga₂O₃ crystal film and the vertical axis indicates a carrier concentration, i.e., a difference (cm⁻³) between a donor concentration N_d as a net donor concentration and an acceptor concentration N_a. Then, a dotted curved line in the drawing is a theoretical curve showing a relation between the donor concentration and depletion layer thickness when relative permittivity of β-Ga₂O₃ is 10 and built-in potential of β-Ga₂O₃ in contact with Pt is 1.5V.

[0096] The procedure used to obtain the data shown in FIG. **11A** is as follows. Firstly, an undoped β-Ga₂O₃ crystal film having a thickness of about 15 μm is epitaxially grown on an Sn-doped n-type β-Ga₂O₃ substrate having a (001)-oriented principal surface by the HVPE method. "Undoped" here means that intentional doping is not carried out, and it does not deny the presence of unintentional impurities.

[0097] The β-Ga₂O₃ substrate is a 10 mm-square substrate having a thickness of 600 μm and has a carrier concentration of about 6×10^{18} cm⁻³. The growth conditions for this β-Ga₂O₃ single crystal film are as follows: a furnace pressure is 1 atom, a carrier gas is N₂ gas, the GaCl supplied partial pressure is 5×10^{-4} atom, the O₂/GaCl supplied partial pressure ratio is 5 and the growth temperature is 1000° C.

[0098] Next, the surface of the undoped β-Ga₂O₃ crystal film is polished 3 μm by CMP to flatten the surface.

[0099] Next, a Schottky electrode is formed on the β-Ga₂O₃ crystal film and an ohmic electrode on the β-Ga₂O₃ substrate, and C-V measurement is conducted while changing bias voltage in a range of +0 to −10V. Then, a carrier concentration profile in a depth direction is calculated based on the C-V measurement result.

[0100] The Schottky electrode here is an 800 μm-diameter circular electrode having a laminated structure in which a 15 nm-thick Pt film, a 5 nm-thick Ti film and a 250 nm-thick Au film are laminated in this order. Also, the ohmic electrode is a 10 mm-square electrode having a laminated structure in which a 50 nm-thick Ti film and a 300 nm-thick Au film are laminated in this order.

[0101] In FIG. **11A**, no measurement point is present in a region shallower than 12 μm which is equal to the thickness of the β-Ga₂O₃ crystal film, and all measurement points are 12 μm on the horizontal axis. This shows that the entire region of the β-Ga₂O₃ crystal film is depleted in the bias voltage range of +0 to −10V.

[0102] Therefore, the entire region of the β-Ga₂O₃ crystal film is naturally depleted at the bias voltage of 0. It is predicted that the residual carrier concentration in the β-Ga₂O₃ crystal film is as very small as not more than 1×10^{13} cm⁻³ since the donor concentration is about 1×10^{13} cm⁻³ when the depletion layer thickness is 12 μm, based on the theoretical curve.

[0103] Since the residual carrier concentration in the β-Ga₂O₃ crystal film is not more than 1×10^{13} cm⁻³, for example, it is possible to control the carrier concentration in the β-Ga₂O₃ crystal film in a range of 1×10^{13} to 1×10^{20} cm⁻³ by doping a IV group element.

[0104] FIG. **11B** is a graph showing voltage endurance characteristics of the above-mentioned crystalline layered structure.

[0105] In FIG. **11B**, the horizontal axis indicates applied voltage (V) and the vertical axis indicates current density (A/cm²). In addition, a dotted straight line in the drawing indicates the measurable lower limit value.

[0106] The procedure used to obtain the data shown in FIG. **11B** is as follows. Firstly, the above-mentioned crystalline layered structure composed of a β-Ga₂O₃ substrate and a β-Ga₂O₃ crystal film is prepared.

[0107] Next, a Schottky electrode is formed on the β-Ga₂O₃ crystal film and an ohmic electrode on the β-Ga₂O₃ substrate, and current density at an applied voltage of 1000V is measured.

[0108] The Schottky electrode here is a 200 μm-diameter circular electrode having a laminated structure in which a 15 nm-thick Pt film, a 5 nm-thick Ti film and a 250 nm-thick Au film are laminated in this order. Also, the ohmic electrode is a 10 mm-square electrode having a laminated structure in which a 50 nm-thick Ti film and a 300 nm-thick Au film are laminated in this order.

[0109] FIG. **11B** shows that, even when voltage of 1000V is applied to the crystalline layered structure, leakage current is as very small as about 1×10^{-5} A/cm² and insulation breakdown does not occur. This result is considered to be due to that the β-Ga₂O₃ crystal film is a high-quality crystal film with only few crystal defects and the donor concentration is low.

[0110] FIG. **12** is a graph showing a carrier concentration profile in a depth direction of the crystalline layered structure in which a β-Ga₂O₃ crystal film is epitaxially grown on a (010)-oriented principal surface of a β-Ga₂O₃ substrate.

[0111] In FIG. **12**, the horizontal axis indicates a depth (µm) from the surface of the β-Ga$_2$O$_3$ crystal film and the vertical axis indicates a carrier concentration, i.e., a difference (cm^{-3}) between a donor concentration N$_d$ as a net donor concentration and an acceptor concentration N$_a$. Then, a dotted curved line in the drawing is a theoretical curve showing a relation between the donor concentration and depletion layer thickness when relative permittivity of β-Ga$_2$O$_3$ is 10 and built-in potential of β-Ga$_2$O$_3$ in contact with Pt is 1.5V.

[0112] The procedure used to obtain the data shown in FIG. **12** is as follows. Firstly, an undoped β-Ga$_2$O$_3$ crystal film having a thickness of about 0.9 µm is epitaxially grown on an Sn-doped n-type β-Ga$_2$O$_3$ substrate having a (010)-oriented principal surface by the HVPE method.

[0113] The β-Ga$_2$O$_3$ substrate is a 10 mm-square substrate having a thickness of 600 µm and has a carrier concentration of about 6×10^{18} cm^{-3}. The growth conditions for this β-Ga$_2$O$_3$ single crystal film are as follows: a furnace pressure is 1 atom, a carrier gas is N$_2$ gas, the GaCl supplied partial pressure is 5×10^{-4} atom, the O$_2$/GaCl supplied partial pressure ratio is 5 and the growth temperature is 1000° C.

[0114] Next, a Schottky electrode is formed on the undoped β-Ga$_2$O$_3$ crystal film and an ohmic electrode on the β-Ga$_2$O$_3$ substrate, and C-V measurement is conducted while changing bias voltage in a range of +0 to −10V. Then, a carrier concentration profile in a depth direction is calculated based on the C-V measurement result.

[0115] The Schottky electrode here is a 400 µm-diameter circular electrode having a laminated structure in which a 15 nm-thick Pt film, a 5 nm-thick Ti film and a 250 nm-thick Au film are laminated in this order. Also, the ohmic electrode is a 10 mm-square electrode having a laminated structure in which a 50 nm-thick Ti film and a 300 nm-thick Au film are laminated in this order.

[0116] In FIG. **12**, measurement points at a bias voltage of 0 are 0.85 µm on the horizontal axis (measurement points in a region deeper than 0.85 µm are measurement points when the bias voltage is close to 10V). It is predicted that the residual carrier concentration in the β-Ga$_2$O$_3$ crystal film is as very small as not more than 3×10^{15} cm^{-3} since the donor concentration is about 2.3×10^{15} cm^{-3} when the depletion layer thickness is 0.85 µm, based on the theoretical curve.

(Effects of the Embodiment)

[0117] According to the embodiment, by controlling the conditions of producing the gallium source gas and the growth conditions for the β-Ga$_2$O$_3$-based single crystal film in the HVPE method, it is possible to efficiently grow a high-quality and large-diameter β-Ga$_2$O$_3$-based single crystal film. In addition, since the β-Ga$_2$O$_3$-based single crystal film has excellent crystal quality, it is possible to grow a good-quality crystal film on the β-Ga$_2$O$_3$-based single crystal film. Thus, a high-quality semiconductor device can be manufactured by using the crystalline layered structure including the β-Ga$_2$O$_3$-based single crystal film in the present embodiment.

[0118] Although the embodiment of the invention has been described, the invention is not intended to be limited to the embodiment, and the various kinds of modifications can be implemented without departing from the gist of the invention.

[0119] In addition, the invention according to claims is not to be limited to the embodiment described above. Further, it should be noted that all combinations of the features described in the embodiment are not necessary to solve the problem of the invention.

INDUSTRIAL APPLICABILITY

[0120] Provided are a method for efficiently growing a high-quality, large diameter β-Ga$_2$O$_3$-based single crystal film, and a crystalline layered structure having a β-Ga$_2$O$_3$-based single crystal film grown using this growing method.

REFERENCE SIGNS LIST

[0121] **1**: CRYSTALLINE LAYERED STRUCTURE
[0122] **10**: Ga$_2$O$_3$-BASED SUBSTRATE
[0123] **11**: PRINCIPAL SURFACE
[0124] **12**: β-Ga$_2$O$_3$-BASED SINGLE CRYSTAL FILM

1. A method for growing a β-Ga$_2$O$_3$-based single crystal film by HYPE method, comprising a step of exposing a Ga$_2$O$_3$-based substrate to a gallium chloride-based gas and an oxygen-including gas and growing a β-Ga$_2$O$_3$-based single crystal film on a principal surface of the Ga$_2$O$_3$-based substrate at a growth temperature of not lower than 900° C.

2. The method for growing a β-Ga$_2$O$_3$-based single crystal film according to claim **1**, wherein the gallium chloride-based gas is produced by reacting a gallium source with a Cl-including gas comprising a Cl$_2$ gas or an HCl gas.

3. The method for growing a β-Ga$_2$O$_3$-based single crystal film according to claim **1**, wherein in the gallium chloride-based gas a GaCl gas has a highest partial pressure ratio.

4. The method for growing a β-Ga$_2$O$_3$-based single crystal film according to claim **1**, wherein the oxygen-including gas comprises an O$_2$ gas.

5. The method for growing a β-Ga$_2$O$_3$-based single crystal film according to claim **2**, wherein the Cl-including gas comprises a Cl$_2$ gas.

6. The method for growing a β-Ga$_2$O$_3$-based single crystal film according to claim **1**, wherein a ratio of a supplied partial pressure of the oxygen-including gas to a supplied partial pressure of the gallium chloride-based gas when growing the β-Ga$_2$O$_3$-based single crystal film is not more than 0.5.

7. The method for growing a β-Ga$_2$O$_3$-based single crystal film according to claim **1**, wherein the principal surface of the Ga$_2$O$_3$-based substrate has a plane orientation of (010), (−01), (001) or (101).

8. The method for growing a β-Ga$_2$O$_3$-based single crystal film according to claim **1**, wherein the gallium chloride-based gas is produced at an atmosphere temperature of not less than 300° C.

9. A crystalline layered structure, comprising:
a Ga$_2$O$_3$-based substrate; and
a β-Ga$_2$O$_3$-based single crystal film that is formed on a principal surface of the Ga$_2$O$_3$-based substrate by epitaxial crystal growth and includes Cl.

10. The crystalline layered structure according to claim **9**, wherein a Cl concentration in the β-Ga$_2$O$_3$-based single crystal film is not more than 5×10^{16} atoms/cm^3.

11. The crystalline layered structure according to claim **9**, wherein the β-Ga$_2$O$_3$-based single crystal film comprises a β-Ga$_2$O$_3$ crystal film.

12. The crystalline layered structure according to claim **11**, wherein a residual carrier concentration in the β-Ga$_2$O$_3$-based single crystal film is not more than 3×10^{15} atoms/cm^3.

13. The method for growing a β-Ga_2O_3-based single crystal film according to claim **2**, wherein in the gallium chloride-based gas a GaCl gas has a highest partial pressure ratio.

14. The method for growing a β-Ga_2O_3-based single crystal film according to claim **2**, wherein the oxygen-including gas comprises an O_2 gas.

15. The method for growing a β-Ga_2O_3-based single crystal film according to claim **2**, wherein a ratio of a supplied partial pressure of the oxygen-including gas to a supplied partial pressure of the gallium chloride-based gas when growing the β-Ga_2O_3-based single crystal film is not more than 0.5.

16. The method for growing a β-Ga_2O_3-based single crystal film according to claim **2**, wherein the principal surface of the Ga_2O_3-based substrate has a plane orientation of (010), (−201), (001) or (101).

17. The method for growing a β-Ga_2O_3-based single crystal film according to claim **2**, wherein the gallium chloride-based gas is produced at an atmosphere temperature of not less than 300° C.

18. The crystalline layered structure according to claim **10**, wherein the β-Ga_2O_3-based single crystal film comprises a β-Ga_2O_3 crystal film.

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