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Remarks:
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(54) Technique for the growth of planar semi-polar gallium nitride

(57) A method for growing planar, semi-polar nitride film on a miscut spinel substrate, in which a large area of the planar, semi-polar nitride film is parallel to the substrate's surface. The planar films and substrates are: (1) {1011} gallium nitride (GaN) grown on a {100} spinel substrate miscut in specific directions, (2) {1013} gallium nitride (GaN) grown on a {110} spinel substrate, (3) {1122} gallium nitride (GaN) grown on a {1100} sapphire substrate, and (4) {1013} gallium nitride (GaN) grown on a {1100} sapphire substrate.

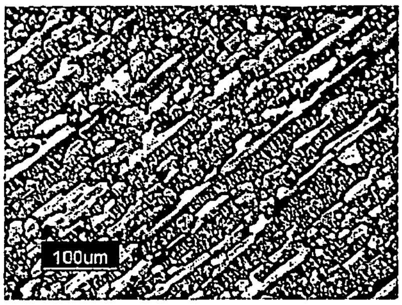

FIG. 1A

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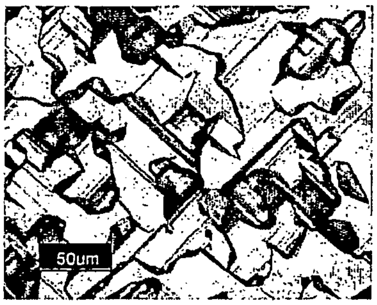

FIG. 1B

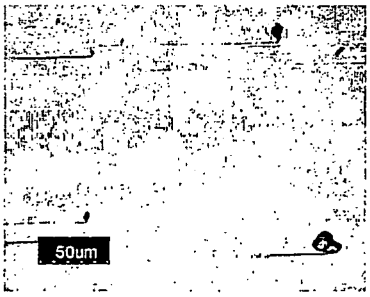

FIG. 1C

Description

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit under 35 U.S.C. Section 119(e) of the following co-pending and commonly-assigned U.S. patent application:

> United States Provisional Patent Application Serial No. 60/660,283, filed on March 10, 2005, by Troy J. Baker, Benjamin A. Haskell, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "TECHNIQUE FOR THE GROWTH OF PLANAR SEMI-POLAR GALLIUM NITRIDE," attorneys' docket no. 30794.128-US-P1;
> which application is incorporated by reference herein.

[0002] This application is related to the following co-pending and commonly-assigned applications:

> United States Provisional Patent Application Serial No. 60/686,244, filed on June 1, 2005, by Robert M. Farrell, Troy J. Baker, Arpan Chakraborty, Benjamin A. Haskell, P. Morgan Pattison, Rajat Sharma, Umesh K. Mishra, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "TECHNIQUE FOR THE GROWTH AND FABRICATION OF SEMIPOLAR (Ga,Al,In,B)N THIN FILMS, HETEROSTRUCTURES, AND DEVICES," attorneys' docket no. 30794,140-US-P1 (2005-668);
> United States Provisional Patent Application Serial No. 60/698,749, filed on July 13, 2005, by Troy J. Baker, Benjamin A. Haskell, James S. Speck, and Shuji Nakamura, entitled "LATERAL GROWTH METHOD FOR DEFECT REDUCTION OF SEMIPOLAR NITRIDE FILMS," attorneys' docket no. 30794.141-US-P1 (2005-672);
> United States Provisional Patent Application Serial No. 60/715,491, filed on September 9, 2005, by Michael Iza, Troy J. Baker, Benjamin A. Haskell, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR ENHANCING GROWTH OF SEMIPOLAR (Al, In,Ga,B)N VIA METALORGANIC CHEMICAL VAPOR DEPOSITION," attorneys' docket no. 30794.144-US-P1 (2005-722);
> United States Provisional Patent Application Serial No. 60/760,739, filed on January 20, 2006, by John F. Kaeding, Michael Iza, Troy J. Baker, Hitoshi Sato, Benjamin A. Haskell, James S. Speck, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR IMPROVED GROWTH OF SEMIPOLAR (Al, In,Ga,B)N," attorneys' docket no. 30794.150-US-P1 (2006-126);
> United States Provisional Patent Application Serial No. 60/760,628, filed on January 20, 2006, by Hitoshi Sato, John F. Keading, Michael Iza, Troy J. Baker, Benjamin A. Haskell, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR ENHANCING GROWTH OF SEMIPOLAR (Al,In,Ga,B)N VIA METALORGANIC CHEMICAL VAPOR DEPOSTTION," attorneys' docket no. 30794.159-US-P1 (2006-178);
> United States Provisional Patent Application Serial No. 60/772,184, filed on February 10, 2006, by John F. Kaeding, Hitoshi Sato, Michael Iza, Hirokuni Asamizu, Hong Zhong, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR CONDUCTIVITY CONTROL OF SEMIPOLAR (Al,In,Ga, B)N," attorneys' docket no. 30794.166-US-P1 (2006-285);
> United States Provisional Patent Application Serial No. 60/774,467, filed on February 17, 2006, by Hong Zhong, John F. Kaeding, Rajat Sharma, James S. Speck, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR GROWTH OF SEMIPOLAR (Al,In,Ga,B) N OPTOELECTRONICS DEVICES," attorneys' docket no. 30794.173-US-P1 (2006-422);
> United States Utility Patent Application Serial No. 10/537,644, filed June 6, 2005, by Benjamin A. Haskell, Michael D. Craven, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF REDUCED DISLOCATION DENSITY NON-POLAR GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPTTAXY," attorneys docket number 30794.93-US-WO (2003-224-2), which application claims the benefit under 35 U.S.C. Section 365(c) of International Patent Application No. PCT/US03/21918, filed July 15, 2003, by Benjamin A. Haskell, Michael D. Craven, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF REDUCED DISLOCATION DENSITY NON-POLAR GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys docket number 30794.93-WO-U1 (2003-224-2), which application claims the benefit under 35 U.S.C. Section 119(e) of United States Provisional Patent Application Serial No. 60/433,843, filed December 16, 2002, by Benjamin A. Haskell, Michael D. Craven, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF REDUCED DISLOCATION DENSITY NON-POLAR GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys docket number 30794.93-US-P1 (2003-224-1);
> United States Utility Patent Application Serial No. 10/537,385, filed June 3, 2005, by Benjamin A. Haskell, Paul T. Fini, Shigemasa Matsuda, Michael D. Craven, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF PLANAR, NON-POLAR A-PLANE GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys docket number 30794.94-US-WO.(2003-225-2), which application claims the benefit under 35 U.S.C. Section 365(c) of International Patent Application No. PCT/US03/21916, filed July 15, 2003, by Benjamin A. Haskell, Paul T. Fini, Shigemasa Matsuda,

Michael D. Craven, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF PLANAR, NON-POLAR A-PLANE GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys docket number 30794.94-WO-U1 (2003-225-2), which application claims the benefit under 35 U.S.C. Section 119(e) of United States Provisional Patent Application Serial No. 60/433,844, filed December 16, 2002, by Benjamin A. Haskell, Paul T. Fini, Shigemasa Matsuda, Michael D. Craven, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "TECHNIQUE FOR THE GROWTH OF PLANAR, NON-POLAR A-PLANE GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys docket number 30794.94-US-P1 (2003-225-1);

United States Utility Patent Application Serial No. 10/413,691, filed April 15, 2003, by Michael D. Craven and James S. Speck, entitled "NON-POLAR A-PLANE GALLIUM NITRIDE THIN FILMS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION," attorneys docket number 30794.100-US-U1 (2002-294-2), which application claims the benefit under 35 U.S.C. Section 119(e) of United States Provisional Patent Application Serial No. 60/372,909, filed April 15, 2002, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, entitled "NON-POLAR GALLIUM NITRIDE BASED THIN FILMS AND HETEROSTRUCTURE MATERIALS," attorneys docket number 30794.95-US-P1 (2002-294/301/303);

United States Utility Patent Application Serial Number 10/413,690, filed April 15, 2003, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, entitled "NON-POLAR (Al,B,In, Ga)N QUANTUM WELL AND HETEROSTRUCTURE MATERIALS AND DEVICES; attorneys docket number 30794.101-US-U1 (2002-301-2), which application claims the benefit under 35 U.S.C. Section 119(e) of United States Provisional Patent Application Serial No. 60/372,909, filed April 15, 2002, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, entitled "NON-POLAR GALLIUM NITRIDE BASED THIN FILMS AND HETEROSTRUCTURE MATERIALS," attorneys docket number 30794.95-US-P1 (2002-294/301/303);

United States Utility Patent Application Serial No. 10/413,913, filed April 15, 2003, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, entitled "DISLOCATION REDUCTION IN NON-POLAR GALLIUM NITRIDE THIN FILMS," attorneys docket number 30794.102-US-U1 (2002-303-2), which application claims the benefit under 35 U.S.C. Section 119(e) of United States Provisional Patent Application Serial No. 60/372,909, filed April 15, 2002, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, entitled "NON-POLAR GALLIUM NITRIDE BASED THIN FILMS AND HETEROSTRUCTURE MATERIALS," attorneys docket number 30794.95-US-P1;

International Patent Application No. PCT/US03/39355, filed December 11, 2003, by Michael D. Craven and Steven P. DenBaars, entitled "NONPOLAR (Al, B, In, Ga)N QUANTUM WELLS," attorneys docket number 30794.104-WO-01 (2003-529-1), which application is a continuation-in-part of the above-identified Patent Application Nos. PCT/US03/21918 (30794.93-WO-U1), PCT/US03/21916 (30794.94-WO-U1), 10/413,691 (30794.100-US-U1), 10/413,690 (30794.101-US-U1), 10/413,913 (30794.102-US-U1);

all of which applications are incorporated by reference herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention.

[0003] The present invention relates to a technique for the growth of planar semi-polar gallium nitride.

2. Description of the Related Art.

[0004] The usefulness of gallium nitride (GaN), and its ternary and quaternary compounds incorporating aluminum and indium (AlGaN, InGaN, AlInGaN), has been well established for fabrication of visible and ultraviolet optoelectronic devices and high-power electronic devices. These devices are typically grown epitaxially using growth techniques including molecular beam epitaxy (MBE), metalorganic chemical vapor deposition (MOCVD), and hydride vapor phase epitaxy (HVPE).

[0005] GaN and its alloys are most stable in the hexagonal würtzite crystal structure, in which the structure is described by two (or three) equivalent basal plane axes that are rotated 120° with respect to each other (the a-axes), all of which are perpendicular to a unique c-axis. Group III and nitrogen atoms occupy alternating c-planes along the crystal's c-axis. The symmetry elements included in the würtzite structure dictate that III-nitrides possess a bulk spontaneous polarization along this c-axis, and the würtzite structure exhibits piezoelectric polarization.

[0006] Current nitride technology for electronic and optoelectronic devices employs nitride films grown along the polar c-direction. However, conventional c-plane quantum well structures in III-nitride based optoelectronic and electronic devices suffer from the undesirable quantum-confined Stark effect (QCSE), due to the existence of strong piezoelectric and spontaneous polarizations. The strong built-in electric fields along the c-direction cause spatial separation of electrons and holes that in turn give rise to restricted carrier recombination efficiency, reduced oscillator strength, and red-shifted emission.

[0007] One approach to eliminating the spontaneous and piezoelectric polarization effects in GaN optoelectronic devices is to grow the devices on non-polar planes of the crystal. Such planes contain equal numbers of Ga and N atoms and are charge-neutral. Furthermore, subsequent non-polar layers are equivalent to one another so the bulk crystal will not be polarized along the growth direction. Two such families of symmetry-equivalent non-polar planes in GaN are the $\{11\bar{2}0\}$ family, known collectively as a-planes, and the $\{1\bar{1}00\}$ family, known collectively as m-planes. Unfortunately, despite advances made by researchers at the University of California, for example, as described in the applications cross-referenced above, growth of non-polar GaN remains challenging and has not yet been widely adopted in the III-nitride industry.

[0008] Another approach to reducing or possibly eliminating the polarization effects in GaN optoelectronic devices is to grow the devices on semi-polar planes of the crystal. The term "semi-polar planes" can be used to refer to a wide variety of planes that possess both two nonzero h, i, or k Miller indices and a nonzero 1 Miller index. Some commonly observed examples of semi-polar planes in c-plane GaN heteroepitaxy include the $\{11\bar{2}2\}$, $\{10\bar{1}1\}$, and $\{10\bar{1}3\}$ planes, which are found in the facets of pits. These planes also happen to be the same planes that the inventors have grown in the form of planar films. Other examples of semi-polar planes in the würtzite crystal structure include, but are not limited to, $\{10\bar{1}2\}$, $\{20\bar{2}1\}$, and $\{10\bar{1}4\}$. The nitride crystal's polarization vector lies neither within such planes or normal to such planes, but rather lies at some angle inclined relative to the plane's surface normal. For example, the $\{10\bar{1}1\}$ and $\{10\bar{1}3\}$ planes are at 62.98° and 32.06° to the c-plane, respectively.

[0009] The other cause of polarization is piezoelectric polarization. This occurs when the material experiences a compressive or tensile strain, as can occur when (Al, In, Ga, B)N layers of dissimilar composition (and therefore different lattice constants) are grown in a nitride heterostructure. For example, a thin AlGaN layer on a GaN template will have in-plane tensile strain, and a thin InGaN layer on a GaN template will have in-plane compressive strain, both due to lattice matching to the GaN. Therefore, for an InGaN quantum well on GaN, the piezoelectric polarization will point in the opposite direction than that of the spontaneous polarization of the InGaN and GaN. For an AlGaN layer latticed matched to GaN, the piezoelectric polarization will point in the same direction as that of the spontaneous polarization of the AlGaN and GaN.

[0010] The advantage of using semi-polar planes over c-plane nitrides is that the total polarization will be reduced. There may even be zero polarization for specific alloy compositions on specific planes. Such scenarios will be discussed in detail in future scientific papers. The important point is that the polarization will be reduced compared to that of c-plane nitride structures.

[0011] Bulk crystals of GaN are not available, so it is not possible to simply cut a crystal to present a surface for subsequent device regrowth. Commonly, GaN films are initially grown heteroepitaxially, i.e. on foreign substrates that provide a reasonable lattice match to GaN.

[0012] Semi-polar GaN planes have been demonstrated on the sidewalls of patterned c-plane oriented stripes. Nishizuka et al. have grown $\{11\bar{2}2\}$ InGaN quantum wells by this technique. (See Nishizuka, K., Applied Physics Letters, Vol. 85, No. 15, 11 October 2004.) They have also demonstrated that the internal quantum efficiency of the semi-polar plane $\{11\bar{2}2\}$ is higher than that of the c-plane, which results from the reduced polarization.

[0013] However, this method of producing semi-polar planes is drastically different than that of the present invention; it is an artifact from epitaxial lateral overgrowth (ELO). ELO is used to reduce defects in GaN and other semiconductors. It involves patterning stripes of a mask material, often SiO_2 for GaN. The GaN is grown from open windows between the mask and then grown over the mask. To form a continuous film, the GaN is then coalesced by lateral growth. The facets of these stripes can be controlled by the growth parameters. If the growth is stopped before the stripes coalesce, then a small area of semi-polar plane can be exposed. The surface area may be 10 μm wide at best. Moreover, the semi-polar plane will be not parallel to the substrate surface. In addition, the surface area is too small to process into a semi-polar LED. Furthermore, forming device structures on inclined facets is significantly more difficult than forming those structures on normal planes.

[0014] The present invention describes a technique for the growth of planar films of semi-polar nitrides, in which a large area of (Al, In, Ga)N is parallel to the substrate surface. For example, samples are often grown on 10 mm x 10 mm or 2 inch diameter substrates compared to the few micrometer wide areas previously demonstrated for the growth of semi-polar nitrides.

SUMMARY OF THE INVENTION

[0015] The present invention describes a method for growing semi-polar nitrides as planar films, such as $\{10\bar{1}1\}$ $\{10\bar{1}3\}$, and $\{11\bar{2}2\}$ planar films of GaN. Growth of semi-polar nitride semiconductors offer a means of reducing polarization effects in würtzite-structure III-nitride device structures.

[0016] The present invention provides a method for growing a nitride film, comprising: growing a planar, semi-polar nitride film on a substrate, wherein the planar, semi-polar nitride film is grown parallel to the substrate's surface.

[0017] Preferably a surface area of the planar, semi-polar nitride film of at least 10 mm x 10 mm is parallel to the substrate's surface; or a surface area of the planar, semi- polar nitride film having at least a 2 inch diameter is parallel to the substrate's surface; or

the planar, semi-polar nitride film is $\{10\bar{1}1\}$ gallium nitride (GaN) grown on a {100} spinel substrate miscut in specific directions, in which case optionally the specific directions comprise <001>, <010> and <011>; or

the planar, semi-polar nitride film is $\{10\bar{1}1\}$ AlN, InN, AlGaN, InGaN, or AlInN grown on a (100) spinel substrate miscut in specific directions, in which case optionally the specific directions comprise <001>, <010> and <011>; or

the planar, semi-polar nitride film is $\{10\bar{1}3\}$ gallium nitride (GaN) grown on a {110} spinel substrate; or

the planar, semi-polar nitride film is $\{11\bar{2}2\}$ gallium nitride (GaN) grown on a {1100} sapphire substrate; or

the planar, semi-polar nitride film is $\{10\bar{1}3\}$ gallium nitride (GaN) grown on a {1100} sapphire substrate; or

further comprising the steps of: loading the substrate into a reactor, wherein the reactor is evacuated to remove oxygen, and then backfilled with nitrogen; turning on a furnace and ramping a temperature of the reactor under conditions that encourage nitridization of the substrate's surface; performing a gas flow of nitrogen, hydrogen, or ammonia over the substrate at atmospheric pressure; reducing the reactor's pressure when the furnace reaches a setpoint temperature; performing a gallium nitride (GaN) growth on the substrate, after the reactor's pressure is reduced, by flowing ammonia, and initiating a flow of hydrogen chloride (HCl) over gallium (Ga) to start the growth of the GaN; and cooling down the reactor after the growth of the GaN, wherein the HCl flow is stopped, and the reactor is cooled down while flowing ammonia to preserve the GaN; in which case optionally (a) the substrate is miscut before being loaded into the reactor, or (b) for growth of $\{11\bar{2}2\}$ GaN, ammonia is flowed while the furnace is ramping to the growth temperature, so that nitridation occurs at low temperature, or (c) for growth of $\{10\bar{1}3\}$ GaN, only hydrogen and nitrogen are flowed during the temperature ramping step, and the substrate is then subjected to a high temperature nitridation with ammonia flow at the growth temperature; or

further comprising, after the planar, semi-polar nitride film has been grown, growing one or more device layers on the on the planar, semi-polar nitride film, in which case optionally the step of growing the device layers on the planar, semi-polar nitride film includes doping the device layers with n-type and p-type dopants, and growing one or more quantum wells in a regrowth layer, in which case optionally further comprising fabricating a light emitting diode from the device layers.

[0018] The present invention provides a planar, semi-polar nitride film grown using the above method.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

FIGS. 1A, 1B and 1C are optical micrographs of GaN on (100) spinel with substrate miscuts of FIG. 1A (no miscut), FIG. 1B (miscut in <010>), and FIG. 1C (miscut in <011>).

FIG. 2 is a flowchart illustrating the process steps of the preferred embodiment of the present invention.

FIG. 3 is a photograph of an LED grown by MOCVD on a $\{10\bar{1}1\}$ GaN template grown by HVPE.

DETAILED DESCRIPTION OF THE INVENTION

[0020] In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

Overview

[0021] Growth of semi-polar nitride semiconductors, for example, $\{10\bar{1}1\}$, $\{10\bar{1}3\}$ and $\{11\bar{2}2\}$ planes of GaN, offer a means of reducing polarization effects in würtzite-structure III-nitride device structures. The semiconductor term nitrides refers to (Ga,Al,In,B)N and any alloy composition of these semiconductors. Current nitride devices are grown in the polar [0001] c-direction, which results in charge separation along the primary conduction direction in vertical devices. The resulting polarization fields are detrimental to the performance of current state of the art optoelectronic devices. Growth of these devices along a semi-polar direction could improve device performance significantly by reducing built-in electric fields along the conduction direction.

[0022] Until now, no means existed for growing large area, high quality films of semi-polar nitrides suitable for use as device layers, templates, or substrates in device growth. The novel feature of this invention is the establishment that semi-polar nitrides can be grown as planar films. As evidence, the inventors have grown $\{10\bar{1}1\}$, $\{10\bar{1}3\}$, and $\{11\bar{2}2\}$ planar films of GaN. However, the scope of this idea is not limited to solely these examples. This idea is relevant to all semi-polar planar films of nitrides.

Technical Description

[0023] The present invention comprises a method for growing planar nitride films in which a large area of the semi-polar nitrides is parallel to a substrate surface. Examples of this are $\{10\bar{1}1\}$ and $\{10\bar{1}3\}$ GaN films. In this particular embodiment, $MgAl_2O_4$ spinel substrates are used in the growth process. It is critically important that the spinel is miscut in the proper direction for growth of $\{10\bar{1}1\}$ GaN. $\{10\bar{1}1\}$ GaN grown on {100} spinel that is on-axis and that is miscut toward the <001> direction will have two domains at 90° to each other. This is apparent in the optical micrographs of GaN on (100) spinel shown in FIG. 1A (no miscut) and FIG. 1B (a miscut in <010>), respectively.

[0024] However, $\{10\bar{1}1\}$ single crystal GaN grows on {100} spinel that is miscut in the <011>, as shown in the optical micrograph of GaN on (100) spinel in FIG. 1C (a miscut in <011>) X-ray diffraction (XRD) was used to verify that the films grown on (100) spinel with miscut toward <011> direction are single crystal and that the films grown on-axis or miscut toward <010> direction have two domains.

[0025] $\{10\bar{1}3\}$ single crystal GaN was grown on nominally on-axis (lacking an intentional miscut) {110} spinel. XRD was used to verify that the $\{10\bar{1}3\}$ GaN is single crystal.

[0026] Also, planar films of $\{11\bar{2}2\}$ GaN and $\{10\bar{1}3\}$ GaN have been grown on m-plane sapphire, $\{1\bar{1}00\}$ Al_2O_3. It is uncommon in semiconductor growth for one substrate to be used for growth of two distinct planes of the same epitaxial material. However, the plane can be reproducibly selected by flowing ammonia at different temperatures before the GaN growth. Again, XRD was used to confirm the single crystal character of the films.

[0027] Thus, there has been experimentally proven four examples of planar semi-polar nitride films:

1) $\{10\bar{1}1\}$ GaN on {100} spinel miscut in specific directions (<001>, <010> and <011>),
2) $\{10\bar{1}3\}$ GaN on {110} spinel,
3) $\{11\bar{2}2\}$ GaN on $\{1\bar{1}00\}$ sapphire, and
4) $\{10\bar{1}3\}$ GaN on $\{1\bar{1}00\}$ sapphire.

[0028] These films were grown using an HVPE system in Shuji Nakamura's lab at the University of California, Santa Barbara. A general outline of growth parameters for both $\{10\bar{1}1\}$ and $\{10\bar{1}3\}$ is a pressure between 10 torr and 1000 torr, and a temperature between 900°C and 1200°C. This wide range of pressure shows that these planes are very stable when growing on the specified substrates. The epitaxial relationships should hold true regardless of the type of reactor. However, the reactor conditions for growing these planes will vary according to individual reactors and grow methods (HVPE, MOCVD, and MBE, for example).

Process Steps

[0029] FIG. 2 is a flowchart illustrating the process steps of the preferred embodiment of the present invention. Specifically, these process steps comprise a method for growing planar, semi-polar nitride films in which a large area of the planar, semi-polar nitride film is parallel to the substrate's surface.

[0030] Block 10 represents the optional step of preparing the substrate. For example, the preparation may involve performing a miscut of the substrate. For the growth of $\{10\bar{1}1\}$ GaN, a (100) spinel substrate is used with a miscut in the <011> direction (which includes <010> and <011>). For the growth of $\{10\bar{1}3\}$ GaN, an on-axis (110) spinel substrate is used. The (110) spinel may or may not have a miscut in any direction, but a miscut is not necessary as it is to grow $\{10\bar{1}1\}$ GaN on (100) spinel.

[0031] Block 12 represents the step of loading the substrate into an HVPE reactor. The reactor is evacuated to at least 9E-2 torr to remove oxygen, then it is backfilled with nitrogen.

[0032] Block 14 represents the step of turning on the furnace and ramping the temperate of the reactor under conditions to encourage nitridization of the surface of the substrate.

[0033] Block 16 represents the step of performing a gas flow. The process generally flows nitrogen, hydrogen, and/or ammonia over the substrate at atmospheric pressure.

[0034] Block 18 represents the step of reducing the pressure in the reactor. The furnace setpoint is 1000°C, and when it reaches this temperature, the pressure of the reactor is reduced to 62.5 torr.

[0035] Block 20 represents the step of performing a GaN growth. After the pressure is reduced, the ammonia flow is set to 1.0 slpm (standard liters per minute), and HCl (hydrogen chloride) flow over Ga (gallium) of 75 sccm (standard cubic centimeters per minute) is initiated to start the growth of GaN.

[0036] Block 22 represents the step of cooling down the reactor. After 20 to 60 minutes of GaN growth time, the HCl flow is stopped, and the reactor is cooled down while flowing ammonia to preserve the GaN film.

[0037] The end result of these steps comprises a planar, semi-polar nitride film in which a large surface area (at least 10 mm x 10 mm or a 2 inch diameter) of the planar, semi-polar nitride film is parallel to the substrate's surface.

[0038] Although the process steps are described in conjunction with a spinel substrate, m-plane sapphire can be used to grow either $\{11\bar{2}2\}$ GaN or $\{10\bar{1}3\}$ GaN. The process is the same as described above, with one exception. For growth of $\{11\bar{2}2\}$ GaN, ammonia is flowed while the furnace is ramping to the growth temperature, thus the nitridation occurs at low temperature. To select for $\{10\bar{1}3\}$ GaN, only hydrogen and nitrogen can be flowed during the ramp temperature step. The substrate should then be subjected to a high temperature nitridation with ammonia flow at the growth temperature.

[0039] After the semi-polar film has been grown using the HVPE system, Block 22 represents the step of growing device layers on the substrate using MOCVD or MBE. This step usually involves doping the nitride layers with n-type and p-type, and growing one or several quantum wells in the regrowth layer. An LED can be made in this step using standard LED processing methods in a cleanroom.

[0040] FIG. 3 is a photograph of a green LED grown by MOCVD on a $\{10\bar{1}1\}$ GaN template grown by HVPE. Specifically, the template was grown by the previously described HVPE growth process, and the LED structure was grown by MOCVD. This is the first $\{10\bar{1}1\}$ GaN LED.

Possible Modifications and Variations

[0041] The scope of this invention covers more than just the particular examples cited. This idea is pertinent to all nitrides on any semi-polar plane. For example, one could grow $\{10\bar{1}1\}$ AlN, InN, AlGaN, InGaN, or AlInN on a miscut (100) spinel substrate. Another example is that one could grow $\{10\bar{1}2\}$ nitrides, if the proper substrate is found. These examples and other possibilities still incur all of the benefits of planar semi-polar films.

[0042] The research that was performed in Shuji Nakamura's Lab at University of California, Santa Barbara, was done using HVPE; however, direct grow of semi-polar planes of nitrides should be possible using MOCVD and MBE as well. The epitaxial relations should be the same for most growth method, although it can vary as seen in the example of GaN on m-plane sapphire. For example, an MOCVD grown $\{10\bar{1}1\}$ GaN LED could be grown directly on miscut (100) spinel without an HVPE template. This idea covers any growth technique that generates a planar semi-polar nitride film.

[0043] The reactor conditions will vary by reactor type and design. The growth described here is only a description of one set of conditions that has been found to be useful conditions for the growth of semi-polar GaN. It was also discovered that these films will grow under a wide parameter space of pressure, temperature, gas flows, etc., all of which will generate planar semi-polar nitride film.

[0044] There are other steps that could vary in the growth process. A nucleation layer has been found unnecessary for our reactor conditions; however, it may or may not be necessary to use a nucleation layer for other reactors, which is common practice in the growth of GaN films. It has also been found that nitridizing the substrate improves surface morphology for some films, and determines the actual plane grown for other films. However, this may or may not be necessary for any particular growth technique.

Advantages and Improvements

[0045] The existing practice is to grow GaN with the c-plane normal to the surface. This plane has a spontaneous polarization and piezoelectric polarization which are detrimental to device performance. The advantage of semi-polar over c-plane nitride films is the reduction in polarization and the associated increase in internal quantum efficiency for certain devices.

[0046] Non-polar planes could be used to completely eliminate polarization effects in devices. However, these planes are quite difficult to grow, thus non-polar nitride devices are not currently in production. The advantage of semi-polar over non-polar nitride films is the ease of growth. It has been found that semi-polar planes have a large parameter space in which they will grow. For example, non-polar planes will not grow at atmospheric pressure, but semi-polar planes have been experimentally demonstrated to grow from 62.5 torr to 760 torr, but probably have an even wider range than that. $\{1\bar{1}00\}$ GaN is grown at low pressure, but when the pressure is increased to 760 torr, all other things being equal, c-plane GaN will result. This is probably related to the outline of the unit cell for the two planes. A further difficulty of {1120} GaN is In incorporation for InGaN devices. Results have found In incorporation to be quite favorable for {1011} GaN.

[0047] The advantage of planar semi-polar films over ELO sidewall is the large surface area that can be processed into an LED or other device. Another advantage is that the growth surface is parallel to the substrate surface, unlike that of ELO sidewall semi-polar planes.

[0048] In summary, the present invention establishes that planar semi-polar films of nitrides can be grown. This has been experimentally confirmed for four separate cases. The previously discussed advantages will be pertinent to all planar semi-polar films.

References

[0049] The following references are incorporated by reference herein:

[1] Takeuchi, Tetsuya, Japanese Journal of Applied Physics, Vol. 39, (2000), pp. 413-416. This paper is a theoretical study of the polarity of semi-polar GaN films.

[2] Nishizuka, K., Applied Physics Letters, Vol. 85 No. 15, 11 October 2004. This paper is a study of $\{11\bar{2}2\}$ GaN sidewalls of ELO material.

[3] T. J. Baker, B. A. Haskell, F. Wu, J. S. Speck, and S. Nakamura, "Characterization of Planar Semipolar Gallium Nitride Films on Spinel Substrates," Japanese Journal of Applied Physics, Vol. 44, No. 29, (2005), L920.

[4] A. Chakraborty, T. J. Baker, B. A. Haskell, F. Wu, J. S. Speck, S. P. Denbaars, S. Nakamura, and U. K. Mishra, "Milliwatt Power Blue InGaN/GaN Light-Emitting Diodes on Semipolar GaN Templates," Japanese Journal of Applied Physics, Vol. 44, No. 30 (2005), L945.

[5] R. Sharma, P. M. Pattison, H. Masui, R. M. Farrell, T. J. Baker, B. A. Haskell, F. Wu, S. P. Denbaars, J. S. Speck, and S. Nakamura, "Demonstration of a Semipolar (10-1-3) InGaN/GaN Green Light Emitting Diode," Appl. Phys. Lett. 87, 231110 (2005).

[6] T. J. Baker, B. A. Haskell, F. Wu, J. S. Speck, and S. Nakamura, "Characterization of Planar Semipolar Gallium Nitride Films on Sapphire Substrates," Japanese Journal of Applied Physics, Vol. 45, No. 6, (2006), L154.

Conclusion

[0050] This concludes the description of the preferred embodiment of the present invention. The foregoing description of one or more embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

Claims

1. A III-nitride film, comprising:

a semi-polar III-nitride film grown on a substrate, such that a surface of the semi-polar III-nitride film is planar and parallel to a surface of the substrate; and
one or more III-nitride device layers on the semi-polar III-nitride film, wherein at least one of the device layers is lattice mismatched to the semi-polar III-nitride film.

2. The film of claim 1, wherein the semi-polar film reduces polarization in the at least one device layers grown on the semi-polar film as compared to a device layer grown on a c-plane polar nitride film, the polarization resulting from the device layer and the film having dissimilar compositions and therefore different lattice constants.

3. The film of claim 1, wherein the semi-polar nitride film is a {10-11} nitride, {10-13} nitride, {10-14} nitride, {11-22} nitride, or {20-21} nitride.

4. The film of claim 1, wherein the substrate is a {100} substrate miscut in specific directions to create the surface of the substrate.

5. The film of claim 4, wherein the specific directions comprise <001>, <010> or <011>.

6. The film of claim 1, wherein the semi-polar nitride film is a {10-11} nitride grown on a (100) spinel substrate miscut in specific directions.

7. The film of claim 6, wherein the specific directions comprise <001>, <010> and <011>.

8. A method for growing a III-nitride film, comprising:

growing a semi-polar III-nitride film on a substrate, such that a surface of the semi-polar III-nitride film is planar and parallel to a surface of the substrate; and
growing one or more III-nitride device layers on the semi-polar III-nitride film, wherein at least one of the device layers is lattice mismatched to the semi-polar III-nitride film.

9. The method of claim 8, wherein the semi-polar film reduces polarization in the at least one device layers grown on the semi-polar film as compared to a device layer grown on a c-plane polar nitride film, the polarization resulting from the device layer and the film having dissimilar compositions and therefore different lattice constants.

10. The method of claim 8, wherein the semi-polar nitride film is a {10-11} nitride, {10-13} nitride, {10-14} nitride, {11-22} nitride, or {20-21} nitride.

11. The method of claim 8, wherein the substrate is a {100} substrate miscut in specific directions to create the surface of the substrate.

12. The method of claim 11, wherein the specific directions comprise <001>, <010> or <011>.

13. The method of claim 8, wherein the semi-polar nitride film is a {10-11} nitride grown on a (100) spinel substrate miscut in specific directions.

14. The method of claim 13, wherein the specific directions comprise <001>, <010> and <011>.

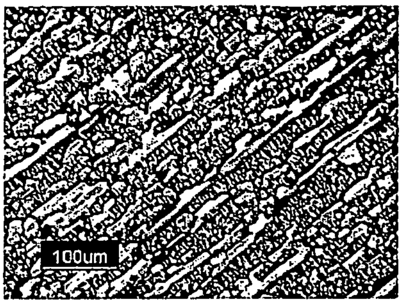

FIG. 1A

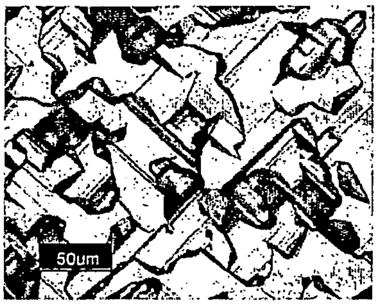

FIG. 1B

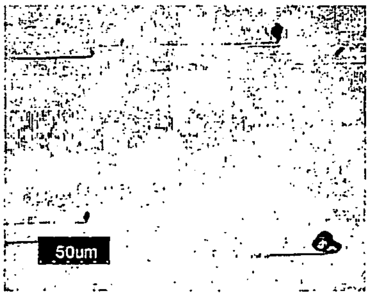

FIG. 1C

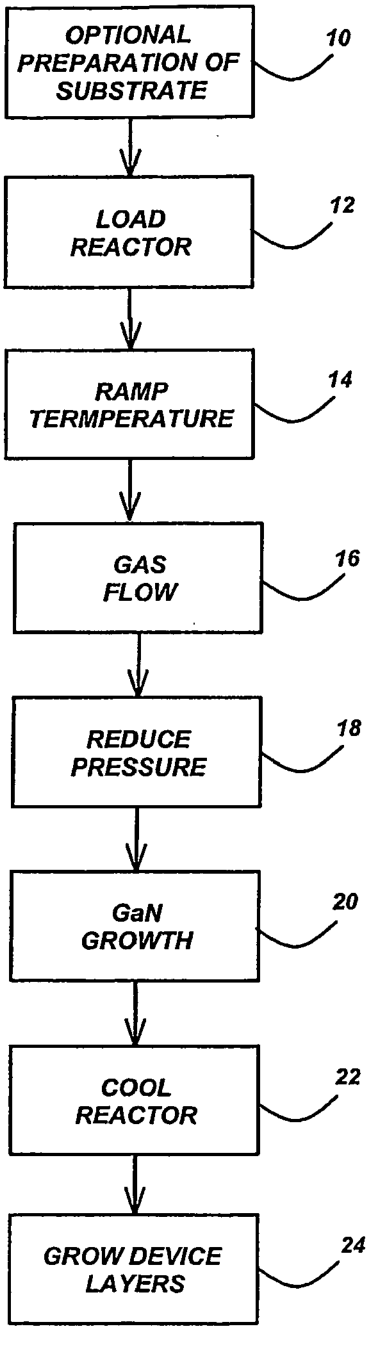
OPTIONAL PREPARATION OF SUBSTRATE
10
LOAD REACTOR
12
RAMP TERMPERATURE
14
GAS FLOW
16
REDUCE PRESSURE
18
GaN GROWTH
20
COOL REACTOR
22
GROW DEVICE LAYERS
24

FIG. 2

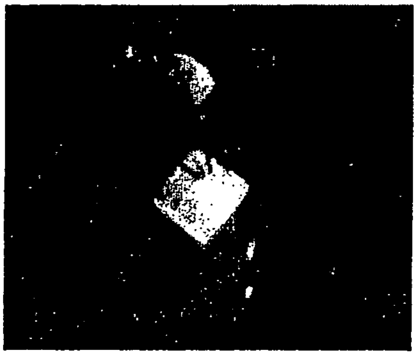

FIG. 3

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EUROPEAN SEARCH REPORT

Application Number
EP 10 01 4011

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
Y	A. TEMPEL, W. SEIFERT, J. HAMMER, E. BUTTER: "Zur epitaxie von Galliumnitrid auf nichtstöchiometrischem Spinell im system GaCl/NH3/He", KRISTALL UND TECHNIK, vol. 10, 1975, pages 747-758, XP002509066, * abstract; table 1 * * page 751, paragraph 2 * * page 752, paragraphs 1,4 * * page 757, paragraph 4-9 * * page 752, paragraph 3 * -----	6,7,13, 14	INV. H01L29/04
X	JIN SOO HWANG, ALEXANDER V. KUZNETSOV, SUN SOOK LEE, HYANG SOOK KIM, JOONG GILL CHOI, PAUL JOE CHONG: "Heteroepitaxy of gallium nitride on (0001), (-1012) and (10-10) sapphire surfaces", JOURNAL OF CRYSTAL GROWTH, vol. 142, 1 September 1994 (1994-09-01), pages 5-14, XP002509067, * abstract; table 1 * * page 5, column 1, paragraph 1; figure 4 * -----	1-3,8-10	TECHNICAL FIELDS SEARCHED (IPC)
X	EP 0 383 215 A (NIPPON TELEGRAPH & TELEPHONE [JP]) 22 August 1990 (1990-08-22) * abstract; claims 1-7; table 1 * * embodiment 1.1 * -----	1-3,8-10	C30B H01L
A	J. BAUER, L. BISTE, D. BOLZE: "Optical properties of aluminium nitride prepared by chemical and plasmachemical vapour deposition", PHYSICA STATUS SOLIDI (A), vol. 39, 16 January 1977 (1977-01-16), pages 173-181, XP002509068, * page 176, paragraph 3.1 * ----- -/--	6,7	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	14 March 2011	Lemoisson, Fabienne

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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Application Number
EP 10 01 4011

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	US 6 218 280 B1 (KRYLIOUK OLGA [US] ET AL) 17 April 2001 (2001-04-17) * abstract; claims 1,2,5,6 * * column 8, lines 15-18 * -----	1	
Y	NISHIZUKA K ET AL: "Efficient radiative recombination from<1122> -oriented InxGa1-xN multiple quantum wells fabricated by the regrowth technique", APPLIED PHYSICS LETTERS, AIP, AMERICAN INSTITUTE OF PHYSICS, MELVILLE, NY, US, vol. 85, no. 15, 11 October 2004 (2004-10-11), pages 3122-3124, XP008134126, ISSN: 0003-6951, DOI: DOI:10.1063/1.1806266 * abstract * -----	6,7,13, 14	
X	US 2002/074561 A1 (SAWAKI NOBUHIKO [JP] ET AL) 20 June 2002 (2002-06-20) * fifth embodiment; paragraphs [0018], [0023], [0026], [0044], [0045], [0056], [0058], [0 81]; figure 7d * -----	1-5,8-12	TECHNICAL FIELDS SEARCHED (IPC)
X	US 2003/178702 A1 (SAWAKI NOBUHIKO [JP] ET AL) 25 September 2003 (2003-09-25) * third embodiment; paragraphs [0006], [0007], [1236], [0086] - [0101]; figure 9 * ----- -/--	1-5,8-12	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	14 March 2011	Lemoisson, Fabienne

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EUROPEAN SEARCH REPORT

Application Number
EP 10 01 4011

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	TAKEUCHI T ET AL: "Theoretical study of orientation dependence of piezoelectric effects in wurtzite strained GaInN/GaN heterostructures and quantum wells", JAPANESE JOURNAL OF APPLIED PHYSICS, JAPAN SOCIETY OF APPLIED PHYSICS, JP, vol. 39, no. 2A, 1 February 2000 (2000-02-01), pages 413-416, XP002426936, ISSN: 0021-4922, DOI: DOI:10.1143/JJAP.39.413 * figure 2 * -----	1	
A	PARK SEOUNG-HWAN: "Crystal orientation effects on electronic properties of wurtzite InGaN/GaN quantum wells", JOURNAL OF APPLIED PHYSICS, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, US, vol. 91, no. 12, 15 June 2002 (2002-06-15), pages 9904-9908, XP012055516, ISSN: 0021-8979, DOI: DOI:10.1063/1.1480465 -----	1	TECHNICAL FIELDS SEARCHED (IPC)
A	M. ILEGEMS: "vapor epitaxy of gallium nitride", JOURNAL OF CRYSTAL GROWTH, vol. 13/14, 1 May 1972 (1972-05-01), pages 360-364, XP002509751, -----	1	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	14 March 2011	Lemoisson, Fabienne

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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EP 10 01 4011

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0383215 A	22-08-1990	DE 69009216 D1	07-07-1994
		DE 69009216 T2	02-03-1995
		JP 2211620 A	22-08-1990
		JP 2704181 B2	26-01-1998
		US 5006908 A	09-04-1991
US 6218280 B1	17-04-2001	US 2003024475 A1	06-02-2003
		US 2001006845 A1	05-07-2001
US 2002074561 A1	20-06-2002	NONE	
US 2003178702 A1	25-09-2003	JP 4307113 B2	05-08-2009
		JP 2003347585 A	05-12-2003

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 60660283 B, Troy J. Baker, Benjamin A. Haskell, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0001]**
- US 60686244 B, Robert M. Farrell, Troy J. Baker, Arpan Chakraborty, Benjamin A. Haskell, P. Morgan Pattison, Rajat Sharma, Umesh K. Mishra, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0002]**
- US 60698749 B, Troy J. Baker, Benjamin A. Haskell, James S. Speck, and Shuji Nakamura **[0002]**
- US 60715491 B, Michael Iza, Troy J. Baker, Benjamin A. Haskell, Steven P. DenBaars, and Shuji Nakamura **[0002]**
- US 60760739 B, John F. Kaeding, Michael Iza, Troy J. Baker, Hitoshi Sato, Benjamin A. Haskell, James S. Speck, Steven P. DenBaars, and Shuji Nakamura **[0002]**
- US 60760628 B, Hitoshi Sato, John F. Keading, Michael Iza, Troy J. Baker, Benjamin A. Haskell, Steven P. DenBaars, and Shuji Nakamura **[0002]**
- US 60772184 B, John F. Kaeding, Hitoshi Sato, Michael Iza, Hirokuni Asamizu, Hong Zhong, Steven P. DenBaars, and Shuji Nakamura **[0002]**
- US 60774467 B, Hong Zhong, John F. Kaeding, Rajat Sharma, James S. Speck, Steven P. DenBaars, and Shuji Nakamura **[0002]**
- US 10537644 B, Benjamin A. Haskell, Michael D. Craven, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0002]**
- US 0321918 W, Benjamin A. Haskell, Michael D. Craven, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0002]**
- US 60433843 B, Benjamin A. Haskell, Michael D. Craven, Paul T. Fini, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0002]**
- US 10537385 B, Benjamin A. Haskell, Paul T. Fini, Shigemasa Matsuda, Michael D. Craven, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0002]**
- US 0321916 W, Benjamin A. Haskell, Paul T. Fini, Shigemasa Matsuda, Michael D. Craven, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0002]**
- US 60433844 B, Benjamin A. Haskell, Paul T. Fini, Shigemasa Matsuda, Michael D. Craven, Steven P. DenBaars, James S. Speck, and Shuji Nakamura **[0002]**
- US 10413691 B, Michael D. Craven and James S. Speck **[0002]**
- US 60372909 B, Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra **[0002]**
- US 10413690 B, Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra **[0002]**
- US 10413913 B, Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra **[0002]**
- US 0339355 W, Michael D. Craven and Steven P. DenBaars **[0002]**

Non-patent literature cited in the description

- **Nishizuka, K.** *Applied Physics Letters,* October 2004, vol. 85 (15), 11 **[0012]**
- **Takeuchi ; Tetsuya.** *Japanese Journal of Applied Physics,* 2000, vol. 39, 413-416 **[0049]**
- **Nishizuka, K.** *Applied Physics Letters,* 11 October 2004, vol. 85 (15 **[0049]**
- **T. J. Baker ; B. A. Haskell ; F. Wu ; J. S. Speck ; S. Nakamura.** Characterization of Planar Semipolar Gallium Nitride Films on Spinel Substrates. *Japanese Journal of Applied Physics,* 2005, vol. 44 (29), L920 **[0049]**
- **A. Chakraborty ; T. J. Baker ; B. A. Haskell ; F. Wu ; J. S. Speck ; S. P. Denbaars ; S. Nakamura ; U. K. Mishra.** Milliwatt Power Blue InGaN/GaN Light-Emitting Diodes on Semipolar GaN Templates. *Japanese Journal of Applied Physics,* 2005, vol. 44 (30), L945 **[0049]**
- **R. Sharma ; P. M. Pattison ; H. Masui ; R. M. Farrell ; T. J. Baker ; B. A. Haskell ; F. Wu ; S. P. Denbaars ; J. S. Speck ; S. Nakamura.** Demonstration of a Semipolar (10-1-3) InGaN/GaN Green Light Emitting Diode. *Appl. Phys. Lett.,* 2005, vol. 87, 231110 **[0049]**

- **T. J. Baker ; B. A. Haskell ; F. Wu ; J. S. Speck ; S. Nakamura.** Characterization of Planar Semipolar Gallium Nitride Films on Sapphire Substrates. *Japanese Journal of Applied Physics,* 2006, vol. 45 (6), L154 **[0049]**