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(54) **NON-POLAR (AL,B,IN,GA)N QUANTUM WELL AND HETEROSTRUCTURE MATERIALS AND DEVICES**

(75) Inventors: **Michael D. Craven**, San Jose, CA (US); **Stacia Keller**, Santa Barbara, CA (US); **Steven P. DenBaars**, Goleta, CA (US); **Tal Margalith**, Pleasanton, CA (US); **James Stephen Speck**, Goleta, CA (US); **Shuji Nakamura**, Santa Barbara, CA (US); **Umesh K. Mishra**, Montecito, CA (US)

(73) Assignee: **THE REGENTS OF THE UNIVERSITY OF CALIFORNIA**, Oakland, CA (US)

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Related U.S. Application Data

(60) Continuation of application No. 13/099,834, filed on May 3, 2011, now Pat. No. 8,188,458, which is a

(57) **ABSTRACT**

A method for forming non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices. Non-polar (11$\overline{2}$0) a-plane GaN layers are grown on an r-plane (1$\overline{1}$02) sapphire substrate using MOCVD. These non-polar (11$\overline{2}$0) a-plane GaN layers comprise templates for producing non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices.

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          │      LOAD       │
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          │    SAPPHIRE     │⟍___ 102
          │    SUBSTRATE    │
          └─────────────────┘
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          │      LAYER      │
          └─────────────────┘
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          │ GALLIUM NITRIDE │⟍___ 106
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          └─────────────────┘
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                   ▼
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          │   COOL UNDER    │
          │    NITROGEN     │⟍___ 108
          │  OVERPRESSURE   │
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          │     LAYERS      │
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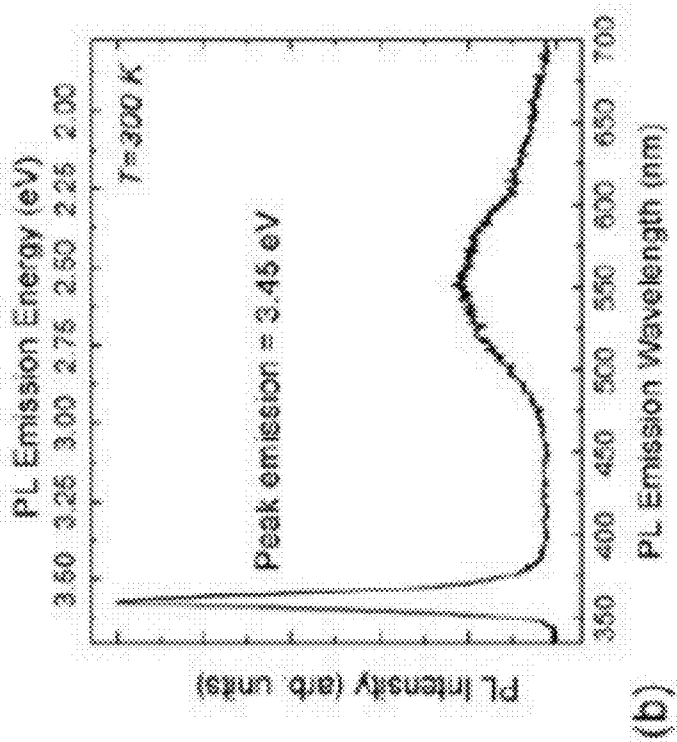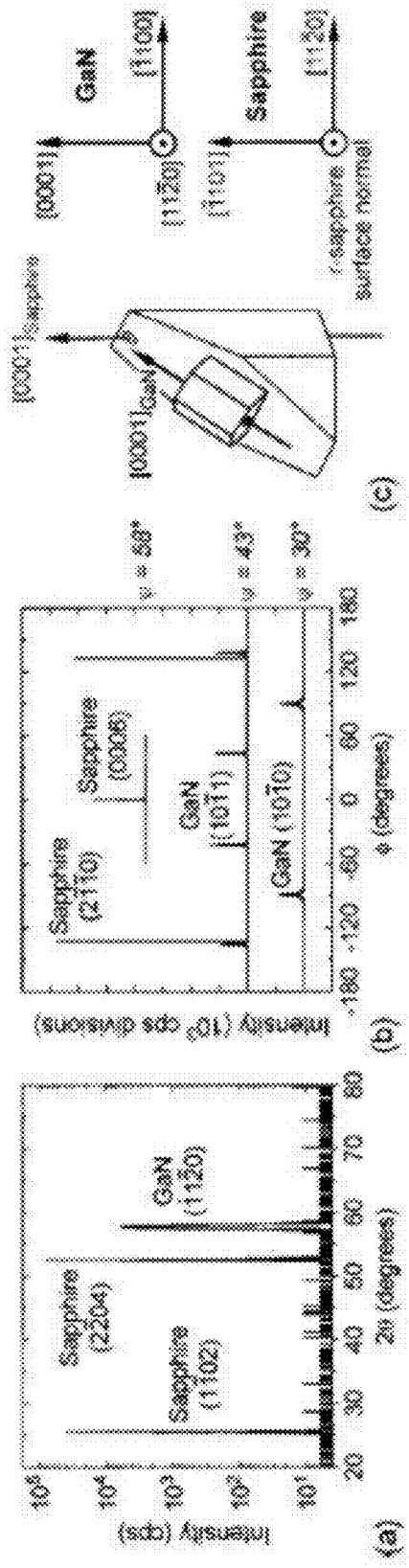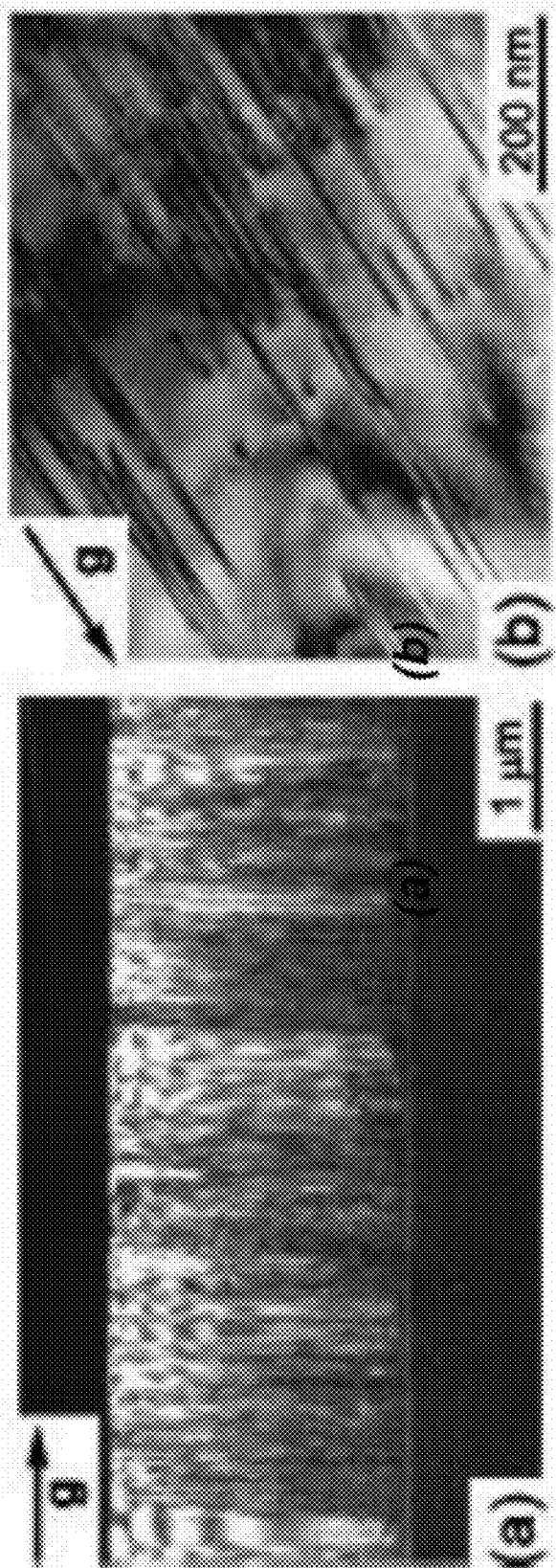
FIG. 1

FIG. 2

FIG. 3
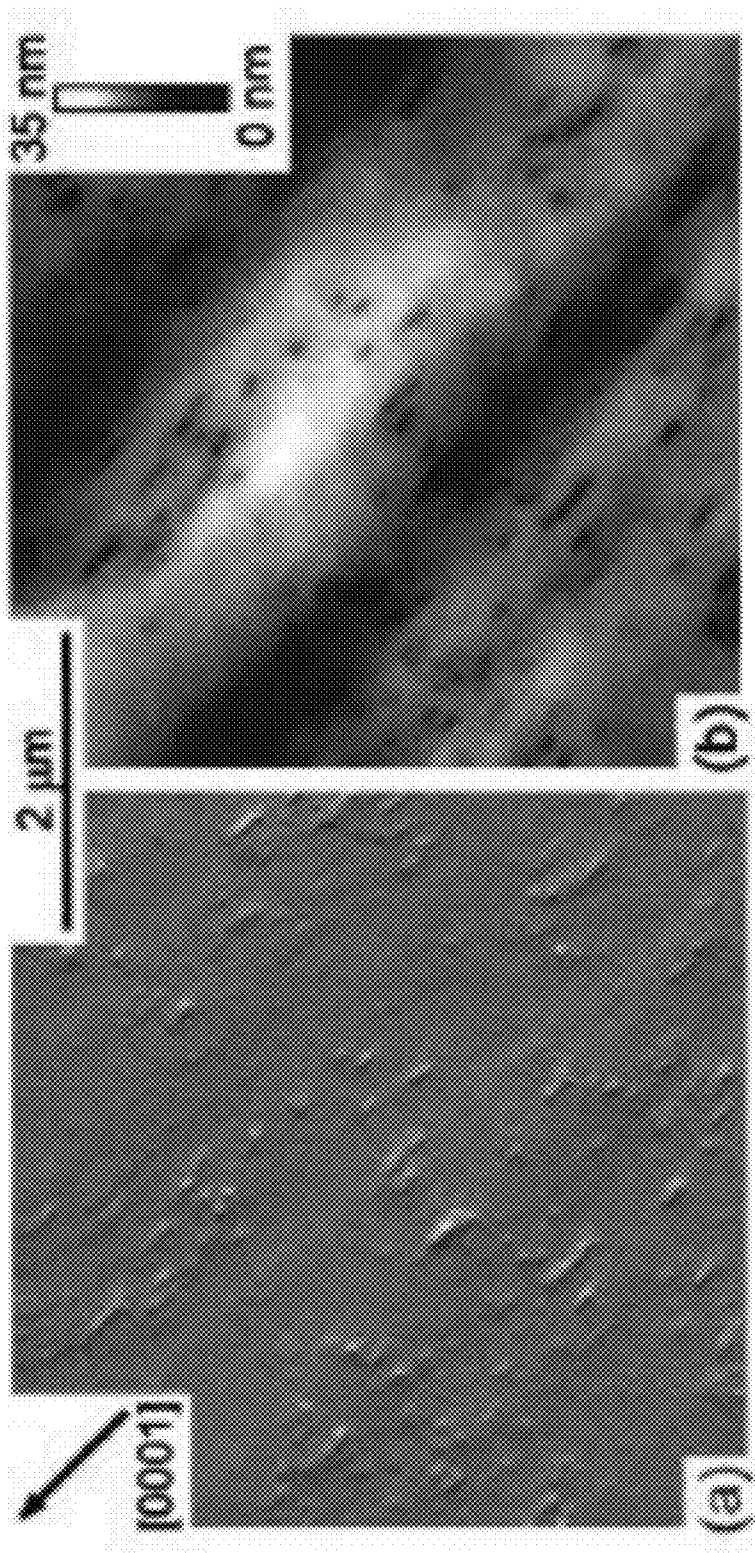
FIG. 4

FIG. 5

FIG. 6

FIG. 7

NON-POLAR (AL,B,IN,GA)N QUANTUM WELL AND HETEROSTRUCTURE MATERIALS AND DEVICES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation under 35 U.S.C. §120 of co-pending and commonly-assigned U.S. Utility patent application Ser. No. 13/099,834, filed on May 3, 2011, 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 no. 30794.101-US-C1 (2002-301-5), which application is a continuation under 35 U.S.C. §120 of co-pending and commonly-assigned U.S. Utility patent application Ser. No. 11/472,033, filed on Jun. 21, 2006, 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 no. 30794.101-US-D1 (2002-301-3), now U.S. Pat. No. 7,982,208, issued Jul. 19, 2011, which application is a divisional application claiming the benefit under 35 U.S.C. §§120 and 121 of U.S. Utility patent application Ser. No. 10/413,690, filed on Apr. 15, 2003, now U.S. Pat. No. 7,091,514, issued Aug. 15, 2006, 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 no. 30794.101-US-U1 (2002-301-2), which application claims the benefit under 35 U.S.C. §119(e) of the following co-pending and commonly-assigned U.S. Provisional patent application Ser. No. 60/372,909, entitled "NON-POLAR GALLIUM NITRIDE BASED THIN FILMS AND HETEROSTRUCTURE MATERIALS," filed on Apr. 15, 2002, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, attorneys docket number 30794.95-US-P1, all of which applications are incorporated by reference herein.

[0002] This application is related to the following co-pending and commonly-assigned United States Utility Patent Applications:

[0003] Ser. No. 10/413,691, entitled "NON-POLAR A-PLANE GALLIUM NITRIDE THIN FILMS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION," filed Apr. 15, 2003, by Michael D. Craven and James S. Speck, attorneys docket number 30794.100-US-U1; and

[0004] Ser. No. 10/413,913, entitled "DISLOCATION REDUCTION IN NON-POLAR GALLIUM NITRIDE THIN FILMS," Apr. 15, 2003, now issued U.S. Pat. No. 6,900,070 issued May 31, 2005, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, attorneys docket number 30794.102-US-U1;

[0005] both of which applications are incorporated by reference herein.

FIELD OF THE INVENTION

[0006] The invention is related to semiconductor materials, methods, and devices, and more particularly, to non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices.

DESCRIPTION OF THE RELATED ART

[0007] (Note: This application references a number of different patents, applications and/or publications as indicated throughout the specification by one or more reference numbers. A list of these different publications ordered according to these reference numbers can be found below in the section entitled "References." Each of these publications is incorporated by reference herein.)

[0008] Current state of the art (Al,B,In,Ga)N heterostructures and quantum well structures employ c-plane (0001) layers. The total polarization of a III-N film consists of spontaneous and piezoelectric polarization contributions, which both originate from the single polar [001] axis of the wurtzite nitride crystal structure. Polarization discontinuities which exist at surfaces and interfaces within nitride heterostructures are associated with fixed sheet charges, which in turn produce electric fields. Since the alignment of these internal electric fields coincides with the growth direction of the c-plane (0001) layers, the fields affect the energy bands of device structures.

[0009] In quantum wells, the "tilted" energy bands spatially separate electrons and hole wave functions, which reduces the oscillator strength of radiative transitions and red-shifts the emission wavelength. These effects are manifestations of the quantum confined Stark effect (QCSE) and have been thoroughly analyzed for GaN/(Al,Ga)N quantum wells. See References 1-8. Additionally, the large polarization-induced fields are partially screened by dopants and impurities, so the emission characteristics can be difficult to engineer accurately.

[0010] The internal fields are also responsible for large mobile sheet charge densities in nitride-based transistor heterostructures. Although these large 2D electron gases (2DEGs) are attractive and useful for devices, the polarization-induced fields, and the 2DEG itself, are difficult to control accurately.

[0011] Non-polar growth is a promising means of circumventing the strong polarization-induced electric fields that exist in wurtzite nitride semiconductors. Polarization-induced electric fields do not affect wurtzite nitride semiconductors grown in non-polar directions (i.e., perpendicular to the [0001] axis) due to the absence of polarization discontinuities along non-polar growth directions.

[0012] Recently, two groups have grown non-polar GaN/(Al,Ga)N multiple quantum wells (MQWs) via molecular beam epitaxy (MBE) without the presence of polarization-induced electric fields along non-polar growth directions. Waltereit et al. grew m-plane GaN/$Al_{0.1}Ga_{0.9}$N MQWs on γ-LiAlO$_2$ (100) substrates and Ng grew a-plane GaN/$Al_{0.15}Ga_{0.85}$N MQW on r-plane sapphire substrates. See References 9-10.

[0013] Despite these results, the growth of non-polar GaN orientations remains difficult to achieve in a reproducible manner.

SUMMARY OF THE INVENTION

[0014] The present invention describes a method for forming non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices. First, non-polar ($1\bar{1}20$) a-plane GaN thin films are grown on a ($1\bar{1}02$) r-plane sapphire substrate using metalorganic chemical vapor deposition (MOCVD). These non-polar ($1\bar{1}20$) a-plane GaN thin films

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are templates for producing non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices thereon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015]   Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

[0016]   FIG. **1** is a flowchart that illustrates the steps of a method for forming non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices according to a preferred embodiment of the present invention;

[0017]   FIG. **2** illustrates the photoluminescence (PL) spectra of 5-period a-plane $In_{0.1}GaN/In_{0.03}GaN$ MQW structures with nominal well widths of 1.5 nm, 2.5 nm, and 5.0 nm measured at room temperature;

[0018]   FIG. **3** illustrates the PL spectra of an a-plane $In_{0.03}Ga_{0.97}N/In_{0.1}Ga_{0.6}N$ MQW structure with a nominal well width of 5.0 nm measured for various pump powers;

[0019]   FIG. **4**(*a*) shows a 2θ-ω x-ray diffraction scan of the 10-period $Al_{0.4}Ga_{0.6}N/GaN$ superlattice, which reveals clearly defined satellite peaks;

[0020]   FIG. **4**(*b*) illustrates the PL spectra of the superlattice characterized in FIG. **4**(*a*);

[0021]   FIG. **5**(*a*) shows a 2θ-ω diffraction scan that identifies the growth direction of the GaN film as (11$\overline{2}$0) a-plane GaN;

[0022]   FIG. **5**(*b*) is a compilation of off-axis φ scans used to determine the in-plane epitaxial relationship between GaN and r-sapphire, wherein the angle of inclination ψ used to access the off-axis reflections is noted for each scan;

[0023]   FIG. **5**(*c*) is a schematic illustration of the epitaxial relationship between the GaN and r-plane sapphire;

[0024]   FIGS. **6**(*a*) and **6**(*b*) are cross-sectional and plan-view transmission electron microscopy (TEM) images, respectively, of the defect structure of the a-plane GaN films on r-plane sapphire; and

[0025]   FIGS. **7**(*a*) and **7**(*b*) are atomic force microscopy (AFM) amplitude and height images, respectively, of the surface of the as-grown a-plane GaN films.

DETAILED DESCRIPTION OF THE INVENTION

[0026]   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.

[0027]   Overview

[0028]   The purpose of the present invention is to provide a method for producing non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices, using non-polar (11$\overline{2}$0) a-plane GaN thin films as templates.

[0029]   The growth of device-quality non-polar (11$\overline{2}$0) a-plane GaN thin films on (1$\overline{1}$02) r-plane sapphire substrates via MOCVD is described in co-pending and commonly-assigned U.S. Provisional Patent Application Ser. No. 60/372,909, entitled "NON-POLAR GALLIUM NITRIDE BASED THIN FILMS AND HETEROSTRUCTURE MATERIALS," filed on Apr. 15, 2002, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, attorneys' docket number 30794.95-US-P1, as well as co-pending and commonly-as-

signed U.S. Utility patent application Ser. No. 10/413,691, entitled "NON-POLAR A-PLANE GALLIUM NITRIDE THIN FILMS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION," filed on same date herewith, by Michael D. Craven and James S. Speck, attorneys docket number 30794.100-US-U1, both of which applications are incorporated by reference herein.

[0030]   The present invention focuses on the subsequent growth of (Al,B,In,Ga)N quantum wells and heterostructures on the (11$\overline{2}$0) a-plane GaN layers. The luminescence characteristics of these structures indicate that polarization-induced electric fields do not affect their electronic band structure, and consequently, polarization-free structures have been attained. The development of non-polar (Al,B,In,Ga)N quantum wells and heterostructures is important to the realization of high-performance (Al,B,In,Ga)N-based devices which are unaffected by polarization-induced electric fields.

[0031]   Potential devices to be deposited on non-polar (11$\overline{2}$0) a-plane GaN layers include laser diodes (LDs), light emitting diodes (LEDs), resonant cavity LEDs (RC-LEDs), vertical cavity surface emitting lasers (VCSELs), high electron mobility transistors (HEMTs), heterojunction bipolar transistors (HBTs), heterojunction field effect transistors (HFETs), as well as UV and near-UV photodetectors.

[0032]   Process Steps

[0033]   FIG. **1** is a flowchart that illustrates the steps of a method for forming non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices according to a preferred embodiment of the present invention. The steps of this method include the growth of "template" (11$\overline{2}$0) a-plane GaN layers, followed by the growth of layers with differing alloy compositions for quantum wells and heterostructures.

[0034]   Block **100** represents loading of a sapphire substrate into a vertical, close-spaced, rotating disk, MOCVD reactor. For this step, epi-ready sapphire substrates with surfaces crystallographically oriented within +/−2° of the sapphire r-plane (1$\overline{1}$20) may be obtained from commercial vendors. No ex-situ preparations need be performed prior to loading the sapphire substrate into the MOCVD reactor, although ex-situ cleaning of the sapphire substrate could be used as a precautionary measure.

[0035]   Block **102** represents annealing the sapphire substrate in-situ at a high temperature (>1000° C.), which improves the quality of the substrate surface on the atomic scale. After annealing, the substrate temperature is reduced for the subsequent low temperature nucleation layer deposition.

[0036]   Block **104** represents depositing a thin, low temperature, low pressure, nitride-based nucleation layer as a buffer layer on the sapphire substrate. Such layers are commonly used in the heteroepitaxial growth of c-plane (0001) nitride semiconductors. In the preferred embodiment, the nucleation layer is comprised of, but is not limited to, 1-100 nanometers (nm) of GaN deposited at approximately 400-900° C. and 1 atm.

[0037]   After depositing the nucleation layer, the reactor temperature is raised to a high temperature, and Block **106** represents growing the epitaxial (11$\overline{2}$0) a-plane GaN layers to a thickness of approximately 1.5 μn. The high temperature growth conditions include, but are not limited to, approximately 1100° C. growth temperature, 0.2 atm or less growth pressure, 30 μmol per minute Ga flow, and 40,000 μmol per minute N flow, thereby providing a VIII ratio of approxi-

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mately 1300). In the preferred embodiment, the precursors used as the group III and group V sources are trimethylgallium and ammonia, respectively, although alternative precursors could be used as well. In addition, growth conditions may be varied to produce different growth rates, e.g., between 5 and 9 Å per second, without departing from the scope of the present invention.

[0038] Upon completion of the high temperature growth step, Block **108** represents cooling the epitaxial ($11\bar{2}0$) a-plane GaN layers down under a nitrogen overpressure.

[0039] Finally, Block **110** represents non-polar (Al,B,In, Ga)N layers, with differing alloy compositions and hence differing electrical properties, being grown on the non-polar ($11\bar{2}0$) a-plane GaN layers. These non-polar (Al,B,In,Ga)N layers are used to produce quantum wells and hetero structures.

[0040] The quantum wells employ alternating layers of different bandgap such that "wells" are formed in the structure's energy band profile. The precise number of layers in the structure depends on the number of quantum wells desired. Upon excitation, electrons and holes accumulate in the wells of the conduction and valence bands, respectively. Band-to-band recombination occurs in the well layers since the density-of-states is highest at these locations. Thus, quantum wells can be engineered according to the desired emission characteristics and available epitaxial growth capabilities.

[0041] The nominal thickness and composition of the layers successfully grown on the non-polar ($11\bar{2}0$) a-plane GaN layers include, but are not limited to:

[0042] 8 nm Si-doped $In_{0.03}GaN$ barrier

[0043] 1.5, 2.5, or 5 nm $In_{0.1}GaN$ well

[0044] Moreover, the above Blocks may be repeated as necessary. In one example, Block **110** was repeated 5 times to form an MQW structure that was capped with GaN to maintain the integrity of the (In,Ga)N layers. In this example, the layers comprising the MQW structure were grown via MOCVD at a temperature of 825° C. and atmospheric pressure.

[0045] The luminescence characteristics of this structure indicate that polarization-induced electric fields do not affect the band profiles, and the quantum wells can be considered polarization-free. For example, FIG. **2** illustrates the photoluminescence (PL) spectra of 5-period a-plane $In_{0.1}GaN/In_{0.03}GaN$ MQW structures with nominal well widths of 1.5 nm, 2.5 nm, and 5.0 nm measured at room temperature. The peak PL emission wavelength and intensity increase with increasing well width.

[0046] Further, FIG. **3** illustrates the PL spectra of an a-plane $In_{0.03}Ga_{0.97}N/In_{0.1}Ga_{0.9}N$ MQW structure with a nominal well width of 5.0 nm measured for various pump powers. PL intensity increases with pump power as expected while the peak emission wavelength is pump power independent, indicating that the band profiles are not influenced by polarization-induced electric fields.

[0047] In addition to (In,Ga)N quantum wells, heterostructures containing (Al,Ga)N/GaN superlattices may also be grown on the non-polar ($11\bar{2}0$) a-plane GaN layers. For example, heterostructures typically consist of two layers, most commonly (AlGa)N on GaN, to produce an electrical channel necessary for transistor operation. The thickness and composition of the superlattice layers may comprise, but are not limited to:

[0048] 9 nm $Al_{0.4}GaN$ barrier

[0049] 11 nm GaN well

[0050] In one example, Block **110** was repeated 10 times to form a 10-period $Al_{0.4}Ga_{0.6}N/GaN$ superlattice that was terminated with a 11 nm GaN well layer. The superlattice was grown via MOCVD at conditions similar to those employed for the underlying template layer: ~1100° C. growth temperature, ~0.1 atm growth pressure, 38 μmol/min Al flow, 20 μmol/min Ga flow, and 40,000 μmol/min N flow. The Al flow was simply turned off to form the GaN well layers. Successful growth conditions are not strictly defined by the values presented above. Similar to the (In,Ga)N quantum wells, the luminescence characteristics of the superlattice described above indicate that polarization fields do not affect the structure.

[0051] FIG. **4**(*a*) shows a 2θ-ω x-ray diffraction scan of the 10-period $Al_{0.4}Ga_{0.6}N/GaN$ superlattice, which reveals clearly defined satellite peaks, while FIG. **4**(*b*) illustrates the PL spectra of the superlattice characterized in FIG. **4**(*a*). The absence of polarization-induced fields was evidenced by the 3.45 eV (~360 nm) band edge emission of the superlattice. The band edge emission did not experience the subtle redshift present in c-plane superlattices.

[0052] Experimental Results For As-Grown GaN

[0053] The crystallographic orientation and structural quality of the as-grown GaN films and r-plane sapphire were determined using a Philips™ four-circle, high-resolution, x-ray diffractometer (HR-XRD) operating in receiving slit mode with four bounce Ge(220)-monochromated Cu Kα radiation and a 1.2 mm slit on the detector arm. Convergent beam electron diffraction (CBED) was used to determine the polarity of the a-GaN films with respect to the sapphire substrate. Plan-view and cross-section transmission electron microscopy (TEM) samples, prepared by wedge polishing and ion milling, were analyzed to define the defect structure of a-GaN. A Digital Instruments D3000 Atomic Force Microscope (AFM) in tapping mode produced images of the surface morphology.

[0054] FIG. **5**(*a*) shows a 2θ-ω diffraction scan that identifies the growth direction of the GaN film as ($11\bar{2}0$) a-plane GaN. The scan detected sapphire ($1\bar{1}02$), ($2\bar{2}04$), and GaN ($11\bar{2}0$) reflections. Within the sensitivity of these measurements, no GaN (0002) reflections corresponding to 2θ=34. 604° were detected, indicating that there is no c-plane (0002) content present in these films, and thus instabilities in the GaN growth orientation are not a concern.

[0055] FIG. **5**(*b*) is a compilation of off-axis φ scans used to determine the in-plane epitaxial relationship between GaN and r-sapphire, wherein the angle of inclination ψ used to access the off-axis reflections is noted for each scan. Having confirmed the a-plane growth surface, off-axis diffraction peaks were used to determine the in-epitaxial relationship between the GaN and the r-sapphire. Two sample rotations φ and ψ were adjusted in order to bring off-axis reflections into the scattering plane of the diffractometer, wherein φ is the angle of rotation about the sample surface normal and ψ is the angle of sample tilt about the axis formed by the intersection of the Bragg and scattering planes. After tilting the sample to the correct ψ for a particular off-axis reflection, φ scans detected GaN ($10\bar{1}0$), ($10\bar{1}1$), and sapphire (0006) peaks, as shown in FIG. **2**(*b*). The correlation between the φ positions of these peaks determined the following epitaxial relationship: $[0001]_{GaN}\|[\bar{1}101]_{sapphire}$ and $[\bar{1}100]_{GaN}\|[11\bar{2}0]_{sapphire}$.

[0056] FIG. 5(c) is a schematic illustration of the epitaxial relationship between the GaN and r-plane sapphire. To complement the x-ray analysis of the crystallographic orientation, the a-GaN polarity was determined using CBED. The polarity's sign is defined by the direction of the polar Ga-N bonds aligned along the GaN c-axis; the positive c-axis [0001] points from a gallium atom to a nitrogen atom. Consequently, a gallium-face c-GaN film has a [0001] growth direction, while a nitrogen-face c-GaN crystal has a [000$\bar{1}$] growth direction. For a-GaN grown on r-sapphire, $[0001]_{GaN}$ is aligned with the sapphire c-axis projection $[\bar{1}101]_{sapphire}$, and therefore, the epitaxial relationships defined above are accurate in terms of polarity. Consequently, the positive GaN c-axis points in same direction as the sapphire c-axis projection on the growth surface (as determined via CBED). This relationship concurs with the epitaxial relationships previously reported by groups using a variety of growth techniques. See References 17, 18 and 19. Therefore, the epitaxial relationship is specifically defined for the growth of GaN on an r-plane sapphire substrate.

[0057] FIGS. 6(a) and 6(b) are cross-sectional and plan-view TEM images, respectively, of the defect structure of the a-plane GaN films on an r-plane sapphire substrate. These images reveal the presence of line and planar defects, respectively. The diffraction conditions for FIGS. 3(a) and 3(b) are g=0002 and g=10$\bar{1}$0, respectively.

[0058] The cross-sectional TEM image in FIG. 6(a) reveals a large density of threading dislocations (TD's) originating at the sapphire/GaN interface with line directions parallel to the growth direction [11$\bar{2}$0]. The TD density, determined by plan view TEM, was 2.6×10^{10} cm^{-2}. With the TD line direction parallel to the growth direction, pure screw dislocations will have Burgers vectors aligned along the growth direction b=$\pm$[11$\bar{2}$0]) while pure edge dislocations will have b=$\pm$[0001]. The reduced symmetry of the a-GaN surface with respect to c-GaN complicates the characterization of mixed dislocations since the crystallographically equivalent [11$\bar{2}$0] directions cannot be treated as the family <11$\bar{2}$0>. Specifically, the possible Burgers vectors of mixed dislocations can be divided into three subdivisions: (1) b=$\pm$[1$\bar{2}$10]b=and (3) b=$\pm$[$\bar{2}$110], (2) b=$\pm$[11$\bar{2}$0]$\pm$[0001], and (3) b=$\pm$[11$\bar{2}$0]$\pm$[1$\bar{2}$10] and b=$\pm$[11$\bar{2}$0]$\pm$[$\bar{2}$110].

[0059] In addition to line defects, the plan view TEM image in FIG. 6(b) reveals the planar defects observed in the a-GaN films. Stacking faults aligned perpendicular to the c-axis with a density of 3.8×10^5 cm^{-1} were observed in the plan-view TEM images. The stacking faults, commonly associated with epitaxial growth of close-packed planes, most likely originate on the c-plane sidewalls of three-dimensional (3D) islands that form during the initial stages of the high temperature growth. Consequently, the stacking faults are currently assumed to be intrinsic and terminated by Shockley partial dislocations of opposite sign. Stacking faults with similar characteristics were observed in a-plane AlN films grown on r-plane sapphire substrates. See Reference 20. The stacking faults have a common faulting plane parallel to the close-packed (0001) and a density of ~3.8×10^5 cm^{-1}.

[0060] Omega rocking curves were measured for both the GaN on-axis (11$\bar{2}$0) and off-axis (10$\bar{1}$1) reflections to characterize the a-plane GaN crystal quality. The full-width half-maximum (FWHM) of the on-axis peak was 0.29° (1037"), while the off-axis peak exhibited a larger orientational spread with a FWHM of 0.46° (1659"). The large FWHM values are expected since the microstructure contains a substantial dislocation density. According to the analysis presented by Heying et al. for c-GaN films on c-sapphire, on-axis peak widths are broadened by screw and mixed dislocations, while off-axis widths are broadened by edge-component TD's (assuming the TD line is parallel to the film normal). See Reference 21. A relatively large edge dislocation density is expected for a-GaN on r-sapphire due to the broadening of the off-axis peak compared to the on-axis peak. Additional microstructural analyses are required to correlate a-GaN TD geometry to rocking curve measurements.

[0061] FIGS. 7(a) and 7(b) are AFM amplitude and height images, respectively, of the surface of the as-grown a-plane GaN film. The surface pits in the AFM amplitude image of FIG. 7(a) are uniformly aligned parallel to the GaN c-axis, while the terraces visible in the AFM height image of FIG. 7(b) are aligned perpendicular to the c-axis.

[0062] Although optically specular with a surface RMS roughness of 2.6 nm, the a-GaN growth surface is pitted on a sub-micron scale, as can be clearly observed in the AFM amplitude image shown in FIG. 7(a). It has been proposed that the surface pits are decorating dislocation terminations with the surface; the dislocation density determined by plan view TEM correlates with the surface pit density within an order of magnitude.

[0063] In addition to small surface pits aligned along GaN c-axis [0001], the AFM height image in FIG. 7(b) reveals faint terraces perpendicular to the c-axis. Although the seams are not clearly defined atomic steps, these crystallographic features could be the early signs of the surface growth mode. At this early point in the development of the a-plane growth process, neither the pits nor the terraces have been correlated to particular defect structures.

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Conclusion

[0085]   This concludes the description of the preferred embodiment of the present invention. The following describes some alternative embodiments for accomplishing the present invention.

[0086]   For example, variations in non-polar (Al,In,Ga)N quantum wells and heterostructures design and MOCVD growth conditions may be used in alternative embodiments. Moreover, the specific thickness and composition of the layers, in addition to the number of quantum wells grown, are variables inherent to quantum well structure design and may be used in alternative embodiments of the present invention.

[0087]   Further, the specific MOCVD growth conditions determine the dimensions and compositions of the quantum well structure layers. In this regard, MOCVD growth conditions are reactor dependent and may vary between specific reactor designs. Many variations of this process are possible with the variety of reactor designs currently being using in industry and academia.

[0088]   Variations in conditions such as growth temperature, growth pressure, VIII ratio, precursor flows, and source materials are possible without departing from the scope of the present invention. Control of interface quality is another important aspect of the process and is directly related to the flow switching capabilities of particular reactor designs. Continued optimization of the growth conditions will result in more accurate compositional and thickness control of the integrated quantum well layers described above.

[0089]   In addition, a number of different growth methods other than MOCVD could be used in the present invention. For example, the growth method could also be molecular beam epitaxy (MBE), liquid phase epitaxy (LPE), hydride vapor phase epitaxy (HVPE), sublimation, or plasma-enhanced chemical vapor deposition (PECVD).

[0090]   Further, although non-polar a-plan GaN thin films are described herein, the same techniques are applicable to non-polar m-plane GaN thin films. Moreover, non-polar InN, AlN, and AlInGaN thin films could be created instead of GaN thin films.

[0091]   Finally, substrates other than sapphire substrate could be employed for non-polar GaN growth. These substrates include silicon carbide, gallium nitride, silicon, zinc oxide, boron nitride, lithium aluminate, lithium niobate, germanium, aluminum nitride, and lithium gallate.

[0092]   In summary, the present invention describes a method for forming non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices. First, non-polar ($11\bar{2}0$) a-plane GaN thin film layers are grown on a ($1\bar{1}02$) r-plane sapphire substrate using MOCVD. These non-polar ($11\bar{2}0$) a-plane GaN layers comprise templates for producing non-polar (Al,B,In,Ga)N quantum well and heterostructure materials and devices.

[0093]   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.

What is claimed is:

1. A nitride semiconductor device, comprising:
   one or more non-polar Group III nitride layers grown on or above a non-polar surface of a Gallium Nitride (GaN) substrate, wherein the non-polar surface of the GaN substrate is a grown surface.

2. The device of claim 1, wherein the non-polar Group III nitride layers comprise one or more non-polar Group III nitride quantum well layers.

3. The device of claim 2, wherein at least one of the non-polar Group III nitride quantum well layers has a thickness greater than 5 nanometers and emits light having a peak photoluminescence (PL) emission wavelength and an intensity that are greater than a PL emission wavelength and an intensity of light emitted from a non-polar Group III nitride quantum well layer having a thickness of 5 nanometers or less.

4. The device of claim 1, wherein the non-polar Group III nitride layers comprise one or more non-polar Group III nitride heterostructures.

5. The device of claim 4, wherein at least one of the non-polar Group III nitride heterostructures contains a superlattice.

6. The device of claim 5, wherein the superlattice produces an electrical channel for transistor operation.

7. The device of claim 1, wherein the GaN substrate is a GaN template.

8. The device of claim 1, wherein the GaN substrate has a threading dislocation density of no more than 2.6×10^{10} cm^{-2}.

9. The device of claim 1, wherein the GaN substrate has a stacking fault density of no more than 3.8×10^5 cm^{-1}.

10. A method for fabricating a nitride semiconductor device, comprising:
   growing one or more non-polar Group III nitride layers on or above a non-polar surface of a Gallium Nitride (GaN) substrate, wherein the non-polar surface of the GaN substrate is a grown surface.

11. The method of claim 10, wherein the non-polar Group III nitride layers comprise one or more non-polar Group III nitride quantum well layers.

12. The method of claim 11, wherein at least one of the non-polar Group III nitride quantum well layers has a thickness greater than 5 nanometers and emits light having a peak

photoluminescence (PL) emission wavelength and an intensity that are greater than a PL emission wavelength and an intensity of light emitted from a non-polar Group III nitride quantum well layer having a thickness of 5 nanometers or less.

13. The method of claim 10, wherein the non-polar Group III nitride layers comprise one or more non-polar Group III nitride heterostructures.

14. The method of claim 13, wherein at least one of the non-polar Group III nitride heterostructures contains a superlattice.

15. The method of claim 14, wherein the superlattice produces an electrical channel for transistor operation.

16. The method of claim 10, wherein the GaN substrate is a GaN template.

17. The method of claim 10, wherein the GaN substrate has a threading dislocation density of no more than 2.6×10^{10} cm^{-2}.

18. The method of claim 10, wherein the GaN substrate has a stacking fault density of no more than 3.8×10^5 cm^{-1}.

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