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(54) NON-POLAR A-PLANE GALLIUM NITRIDE THIN FILMS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION

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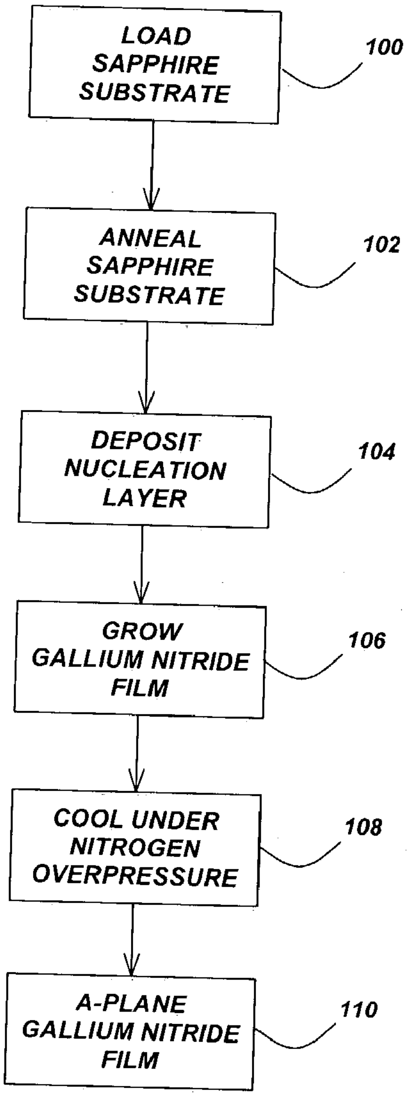
(57) **ABSTRACT**

Non-polar (1120) a-plane gallium nitride (GaN) films with planar surfaces are grown on (1$\bar{1}$02) r-plane sapphire substrates by employing a low temperature nucleation layer as a buffer layer prior to a high temperature growth of the non-polar (1120) a-plane GaN thin films.



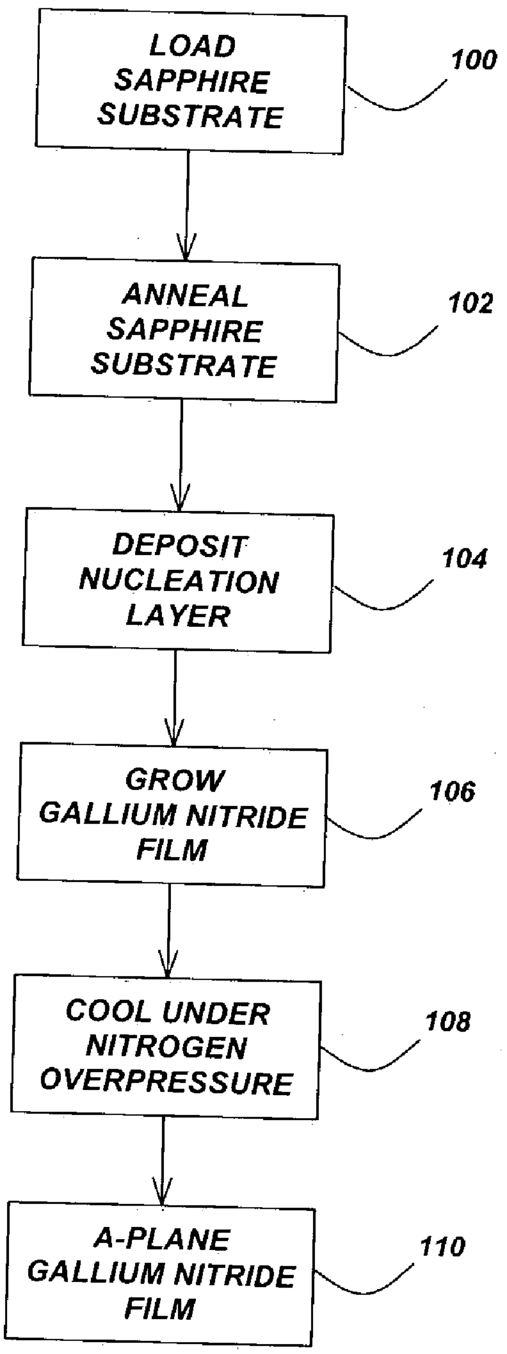

LOAD SAPPHIRE SUBSTRATE
100
ANNEAL SAPPHIRE SUBSTRATE
102
DEPOSIT NUCLEATION LAYER
104
GROW GALLIUM NITRIDE FILM
106
COOL UNDER NITROGEN OVERPRESSURE
108
A-PLANE GALLIUM NITRIDE FILM
110

FIG. 1

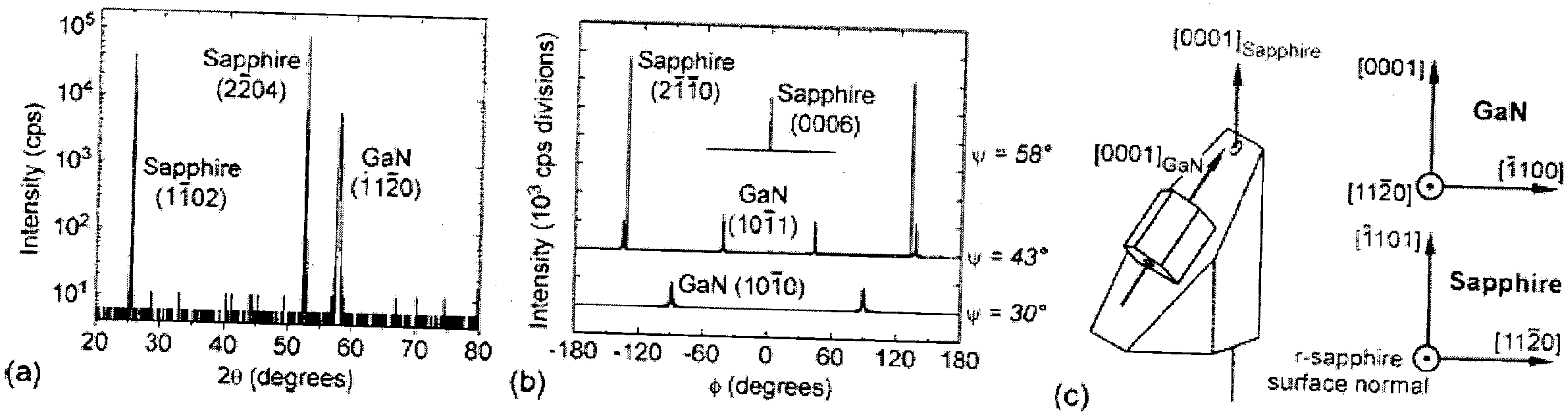

10^5
10^4
10^3
10^2
10^1
Intensity (cps)
Sapphire (2$\bar{2}$04)
Sapphire (1$\bar{1}$02)
GaN (11$\bar{2}$0)
20 30 40 50 60 70 80
2θ (degrees)
(a)
Intensity (10^3 cps divisions)
Sapphire (2$\bar{1}\bar{1}$0)
Sapphire (0006)
GaN (10$\bar{1}$1)
GaN (10$\bar{1}$0)
ψ = 58°
ψ = 43°
ψ = 30°
-180 -120 -60 0 60 120 180
ϕ (degrees)
(b)
$[0001]_{Sapphire}$
$[0001]_{GaN}$
(c)
[0001]
GaN
[11$\bar{2}$0]
[$\bar{1}$100]
[$\bar{1}$101]
Sapphire
r-sapphire surface normal
[11$\bar{2}$0]

FIG. 2

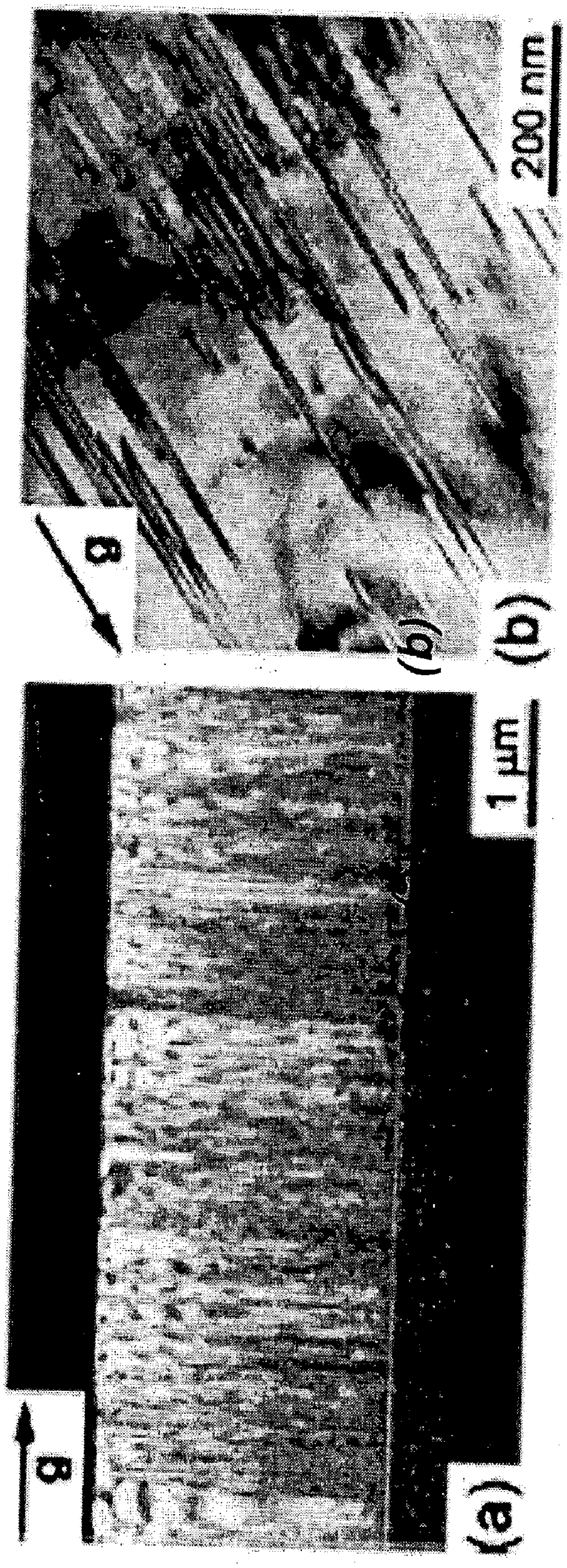


FIG. 3

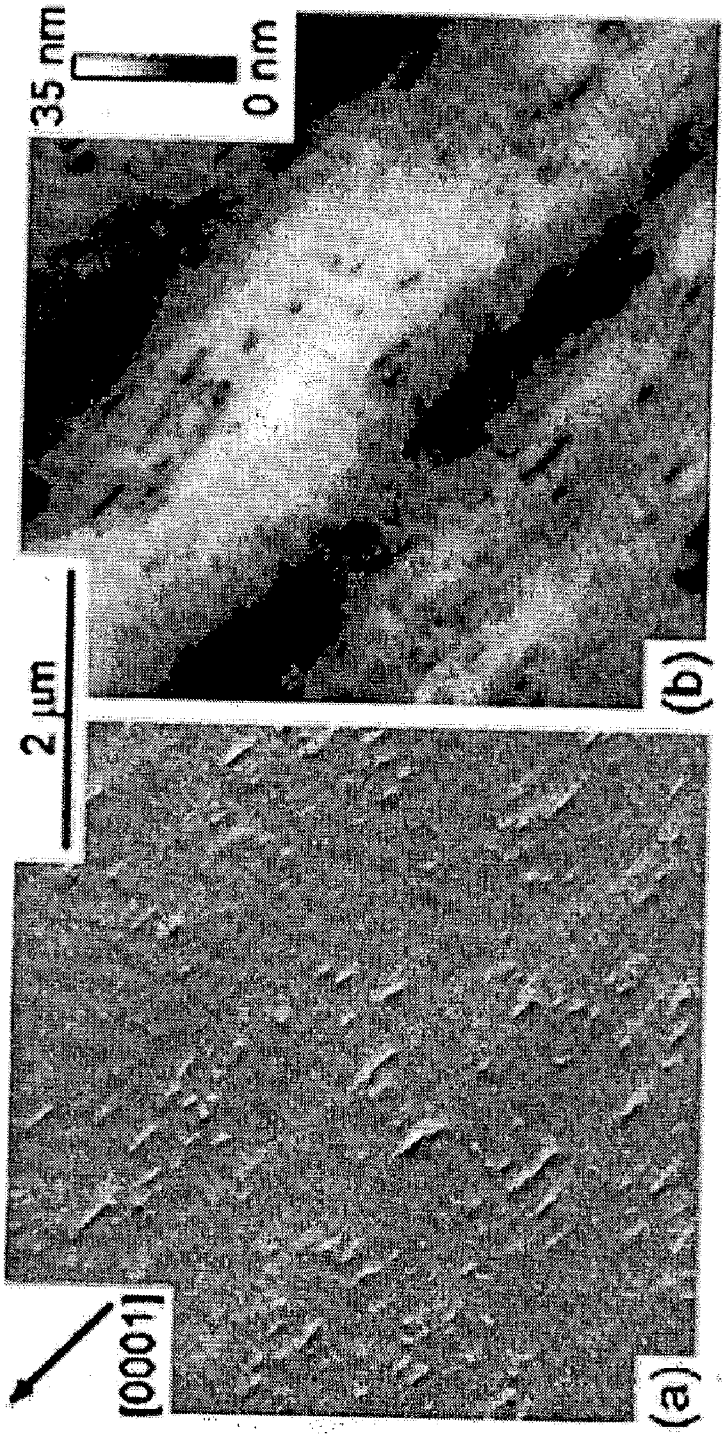


FIG. 4

NON-POLAR A-PLANE GALLIUM NITRIDE THIN FILMS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit under 35 U.S.C. §119(e) of the following copending and commonly-assigned U.S. Provisional Patent Application Serial 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-U.S. Pat. No. 1, which application is incorporated by reference herein.

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

> **[0003]** Ser. No. ______, entitled "NON-POLAR (Al, B,IN,GA)N QUANTUM WELL AND HETEROSTRUCTURE MATERIALS AND DEVICES," filed on same date herewith, by Michael D. Craven, Stacia Keller, Steven P. DenBaars, Tal Margalith, James S. Speck, Shuji Nakamura, and Umesh K. Mishra, attorneys docket number 30794.101-US-U1; and
>
> **[0004]** Ser. No. ______, entitled "DISLOCATION REDUCTION IN NON-POLAR GALLIUM NITRIDE THIN FILMS," filed on same date herewith, by Michael D. Craven, Steven P. DenBaars and James S. Speck, attorneys docket number 30794.102-US-U1;
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> **[0005]** both of which applications are incorporated by reference herein.

1. FIELD OF THE INVENTION

[0006] The invention is related to semiconductor materials, methods, and devices, and more particularly, to non-polar a-plane gallium nitride (GaN) thin films grown by metalorganic chemical vapor deposition (MOCVD).

2. 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] Polarization in wurtzite III-nitride compounds has attracted increased attention due to the large effect polarization-induced electric fields have on heterostructures commonly employed in nitride-based optoelectronic and electronic devices. Nitride-based optoelectronic and electronic devices are subject to polarization-induced effects because they employ nitride films grown in the polar c-direction [0001], the axis along which the spontaneous and piezoelectric polarization of nitride films are aligned. Since the total polarization of a nitride film depends on the composition and strain state, discontinuities exist at interfaces between adjacent device layers and are associated with fixed sheet charges that give rise to internal electric fields.

[0009] Polarization-induced electric fields, although advantageous for two-dimensional electron gas (2DEG) formation in nitride-based transistor structures, spatially separate electrons and hole wave functions in quantum well (QW) structures, thereby reducing carrier recombination efficiencies in QW based devices, such as laser diodes and light emitting diodes. See References 1. A corresponding reduction in oscillator strength and red-shift of optical transitions have been reported for AlGaN/GaN and GaN/InGaN quantum wells grown along the GaN c-axis. See References 2-7.

[0010] A potential means of eliminating the effects of these polarization-induced fields is through the growth of structures in directions perpendicular to the GaN c-axis (non-polar) direction. For example, m-plane AlGaN/GaN quantum wells have recently been grown on lithium aluminate substrates via plasma-assisted molecular beam epitaxy (MBE) without the presence of polarization-induced electric fields along the growth direction. See Reference 8.

[0011] Growth of a-plane nitride semiconductors also provides a means of eliminating polarization-induced electric field effects in wurtzite nitride quantum structures. For example, in the prior art, a-plane GaN growth had been achieved on r-plane sapphire via MOCVD and molecular beam epitaxy (MBE). See References 9-15. However, the film growth reported by these early efforts did not utilize a low temperature buffer layer and did not possess smooth planar surfaces, and therefore, these layers were poorly suited for heterostructure growth and analysis. Consequently, there is a need for improved methods of growing films that exhibit improved surface and structural quality as compared to previously reported growth of GaN on r-plane sapphire via MOCVD.

SUMMARY OF THE INVENTION

[0012] The present invention describes a method for growing device-quality non-polar aplane GaN thin films via MOCVD on r-plane sapphire substrates. The present invention provides a pathway to nitride-based devices free from polarization-induced effects, since the growth direction of non-polar a-plane GaN thin films is perpendicular to the polar c-axis. Polarization-induced electric fields will have minimal effects, if any, on (Al,B,In,Ga)N device layers grown on non-polar a-plane GaN thin films.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

[0014] **FIG. 1** is a flowchart that illustrates the steps of the MOCVD process for the growth of non-polar (1120) a-plane GaN thin films on (1$\bar{1}$20) r-plane sapphire, according to the preferred embodiment of the present invention;

[0015] **FIG. 2**(*a*) shows a 2θ-ω diffraction scan that identifies the growth direction of the GaN film as (1$\bar{1}$20) a-plane GaN;

[0016] **FIG. 2**(*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;

[0017] **FIG. 2**(*c*) is a schematic illustration of the epitaxial relationship between the GaN and r-plane sapphire;

[**0018**] FIGS. **3**(*a*) and **3**(*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

[**0019**] FIGS. **4**(*a*) and **4**(*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

[**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.

[**0021**] Overview

[**0022**] The present invention describes a method for growing device quality non-polar (1120) a-plane GaN thin films via MOCVD on (1$\bar{1}$02) r-plane sapphire substrates. The method employs a low-temperature buffer layer grown at atmospheric pressure to initiate the GaN growth on r-plane sapphire. Thereafter, a high temperature growth step is performed at low pressures, e.g., ~0.1 atmospheres (atm) in order to produce a planar film.

[**0023**] Planar growth surfaces have been achieved using the present invention. Specifically, the in-plane orientation of the GaN with respect to the r-plane sapphire substrate has been confirmed to be $[0001]_{GaN} \| [\bar{1}101]_{sapphire}$ and $\| [\bar{1}100]_{GaN} \| [1120]_{sapphire}$.

[**0024**] The resulting films possess surfaces that are suitable for subsequent growth of (Al,B,In,Ga)N device layers. Specifically, polarization-induced electric fields will have minimal effects, if any, on (Al,B,In,Ga)N device layers grown on non-polar a-plane GaN base layers.

[**0025**] Process Steps

[**0026**] **FIG. 1** is a flowchart that illustrates the steps of the MOCVD process for the growth of non-polar (1120) a-plane GaN thin films on a (1$\bar{1}$20) r-plane sapphire substrate, according to the preferred embodiment of the present invention. The growth process was modeled after the two-step process that has become the standard for the growth of c-GaN on c-sapphire. See Reference 16.

[**0027**] 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$\bar{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.

[**0028**] 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.

[**0029**] Block **104** represents depositing a thin, low temperature, low pressure, nitride-based nucleation layer as a buffer layer on the sapphire substrate. In the preferred embodiment, the nucleation layer is comprised of, but is not limited to, 1-100 nanometers (nm) of GaN and is deposited at low temperature, low pressure depositing conditions of approximately 400-900° C. and 1 atm. Such layers are commonly used in the heteroepitaxial growth of c-plane (0001) nitride semiconductors. Specifically, this depositing step initiates GaN growth on the r-plane sapphire substrate.

[**0030**] After depositing the nucleation layer, the reactor temperature is raised to a high temperature, and Block **106** represents growing the non-polar (1120) a-plane GaN thin films on the substrate. In the preferred embodiment, the high temperature growth conditions comprise, but are not limited to, approximately 1100° C. growth temperature, approximately 0.2 atm or less growth pressure, 30 μmol per minute Ga flow, and 40,000 μmol per minute N flow, thereby providing a V/III ratio of approximately 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. Non-polar GaN approximately 1.5 μm thick have been grown and characterized.

[**0031**] Upon completion of the high temperature growth step, Block **108** represents cooling the non-polar (1120) a-plane GaN thin films under a nitrogen overpressure.

[**0032**] Finally, Block **110** represents the end result of the processing steps, which is a nonpolar (1120) a-plane GaN film on an r-plane sapphire substrate. Potential device layers to be manufactured using these process steps to form a non-polar (1120) a-plane GaN base layer for subsequent device growth 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), and UV and near-UV photodetectors.

[**0033**] Experimental Results

[**0034**] 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.

[**0035**] **FIG. 2**(*a*) shows a 2θ-ω diffraction scan that identifies the growth direction of the GaN film as (1120) a-plane GaN. The scan detected sapphire (1$\bar{1}$02), (2204), and GaN

(1120) 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.

[0036] **FIG. 2**(*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 (1010), (1011), and sapphire (0006) peaks, as shown in **FIG. 2**(*b*). The correlation between the ϕ positions of these peaks determined the following epitaxial relationship: $[0001]_{\mathrm{GaN}} \| [1101]_{\mathrm{sapphire}}$ and $[1100]_{\mathrm{GaN}} \| [1120]_{\mathrm{sapphire}}$.

[0037] **FIG. 2**(*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 [0001] growth direction. For a-GaN grown on r-sapphire, $[0001]_{\mathrm{GaN}}$ is aligned with the sapphire c-axis projection $[1101]_{\mathrm{sapphire}}$, 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 9, 12 and 14. Therefore, the epitaxial relationship is specifically defined for the growth of GaN on an r-plane sapphire substrate.

[0038] FIGS. **3**(*a*) and **3**(*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=1010, respectively.

[0039] The cross-sectional TEM image in **FIG. 3**(*a*) reveals a large density of threading dislocations (TD's) originating at the sapphire/GaN interface with line directions parallel to the growth direction [1120]. 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=±[1120]) while pure edge dislocations will have b=±[0001]. The reduced symmetry of the a-GaN surface with respect to c-GaN complicates the characterization of mixed dislocations since the crystallographically equivalent [1120] directions cannot be treated as the family<1120>. Specifically, the possible Burgers vectors of mixed dislocations can be divided into three subdivisions: (1) b=±[1210] b and (3) b=±[2110], (2) b=±[1120]±[0001], and (3) b=[1120]±[1210] and b=±[1120]±[2110].

[0040] In addition to line defects, the plan view TEM image in **FIG. 3**(*b*) reveals the planar defects observed in the a-GaN films. Stacking faults aligned perpendicular to the c-axis with a density of $\mathbf{3.8\times10^5}$ 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 17. The stacking faults have a common faulting plane parallel to the close-packed (0001) and a density of ~3.8×10^5 cm^{-1} .

[0041] Omega rocking curves were measured for both the GaN on-axis (1120) and off-axis (1011) 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 18. 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.

[0042] FIGS. **4**(*a*) and **4**(*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. 4**(*a*) are uniformly aligned parallel to the GaN c-axis, while the terraces visible in the AFM height image of **FIG. 4**(*b*) are aligned perpendicular to the c-axis.

[0043] 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. 4**(*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.

[0044] In addition to small surface pits aligned along GaN c-axis [0001], the AFM height image in **FIG. 4**(*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.

REFERENCES

[0045] The following references are incorporated by reference herein:

[0046] 1. I. P. Smorchkova, C. R. Elsass, J. P. Ibbetson, R. Vetury, B. Heying, P. Fini, E. Haus, S. P. DenBaars, J. S. Speck, and U. K. Mishra, J. Appl. Phys. 86, 4520 (1999).

[0047] 2. O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, J. Appl. Phys. 85, 3222 (1999).

[0048] 3. I. Jin Seo, H. Kollmer, J. Off, A. Sohmer, F. Scholz, and A. Hangleiter, Phys. Rev. B 57, R9435 (1998).

[0049] 4. R. Langer, J. Simon, V. Ortiz, N. T. Pelekanos, A. Barski, R. Andre, and M. Godlewski, Appl. Phys. Lett. 74, 3827 (1999).

[0050] 5. P. Lefebvre, J. Allegre, B. Gil, H. Mathieu, N. Grandjean, M. Leroux, J. Massies, and P. Bigenwald, Phys. Rev. B 59, 15363 (1999).

[0051] 6. P. Lefebvre, A. Morel, M. Gallart, T. Taliercio, J. Allegre, B. Gil, H. Mathieu, B. Damilano, N. Grandjean, and J. Massies, Appl. Phys. Lett. 78, 1252 (2001).

[0052] 7. T. Takeuchi, C. Wetzel, S. Yamaguchi, H. Sakai, H. Amano, I. Akasaki, Y. Kaneko, S. Nakagawa, Y. Yamaoka, and N. Yamada, Appl. Phys. Lett. 73, 1691 (1998).

[0053] 8. P. Waltereit, O. Brandt, A. Trampert, H. T. Grahn, J. Menniger, M. Ramsteiner, M. Reiche, and K. H. Ploog, Nature (London 406, 865 (2000).

[0054] 9. T. Sasaki and S. Zembutsu, J. Appl. Phys. 61, 2533 (1987).

[0055] 10. C. J. Sun and M. Razeghi, Appl. Phys. Lett. 63, 973 (1993).

[0056] 11. T. Metzger, H. Angerer, O. Ambacher, M. Stutzmann, and E. Born, Phys. Status Solidi B 193, 391 (1996).

[0057] 12. T. Lei, K. F. Ludwig, Jr., and T. D. Moustakas, J. Appl. Phys. 74, 4430 (1993).

[0058] 13. C. R. Eddy, Jr., T. D. Moustakas, and J. Scanlon, J. Appl. Phys. 73, 448 (1993).

[0059] 14. T. D. Moustakas, T. Lei, and R. J. Molnar, Physica B 185, 36 (1993).

[0060] 15. K. Iwata, H. Asahi, K. Asami, R. Kuroiwa, and S. Gonda, Jpn. J. Appl. Phys., Part 236, L661 (1997).

[0061] 16. H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, Appl. Phys. Lett. 48, 353 (1986).

[0062] 17. K. Dovidenko, S. Oktyabrsky, and J. Narayan, J. Appl. Phys. 82, 4296 (1997).

[0063] 18. B. Heying, X. H. Wu, A. S. Keller, Y. Li, D. Kapolnek, B. P. Keller, S. P. DenBaars, and J. S. Speck, Appl. Phys. Lett. 68, 643 (1996).

[0064] Conclusion

[0065] This concludes the description of the preferred embodiment of the present invention. The following describes some alternative embodiments for accomplishing the present invention.

[0066] For example, as the inclusions in the description above indicate, there are many modifications and variations of the MOCVD technique and equipment that could be used to grow non-polar (1120) a-plane GaN thin films on $(1\bar{1}02)$ r-plane sapphire substrates. Moreover, different growth conditions may be optimal for different MOCVD reactor designs. Many variations of this process are possible with the variety of reactor designs currently being using in industry and academia. Despite these differences, the growth parameters can most likely be optimized to improve the quality of the films. The most important variables for the MOCVD growth include growth temperature, V/III ratio, precursor flows, and growth pressure.

[0067] In addition to the numerous modifications possible with the MOCVD growth technique, other modifications are possible. For example, the specific crystallographic orientation of the r-plane sapphire substrate might be changed in order to optimize the subsequent epitaxial GaN growth. Further, r-plane sapphire substrates with a particular degree of miscut in a particular crystallographic direction might be optimal for growth.

[0068] In addition, the nucleation layer deposition is crucial to achieving epitaxial GaN films with smooth growth surfaces and minimal crystalline defects. Other than optimizing the fundamental MOCVD parameters, use of AlN or AlGaN nucleation layers in place of GaN could prove useful in obtaining high quality a-plane GaN films.

[0069] 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.

[0070] 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.

[0071] In summary, the present invention describes the growth of non-polar (1120) a-plane GaN thin films on r-plane $(1\bar{1}02)$ sapphire substrates by employing a low temperature nucleation layer as a buffer layer prior to a high temperature growth of the epitaxial (1120) a-plane GaN films. The epitaxial relationship is $[0001]_{GaN} \| [\bar{1}101]_{sapphire}$ and $[\bar{1}100]_{GaN} \| [1120]_{sapphire}$ with the positive GaN c-axis pointing in the same direction as the sapphire c-axis projection on the growth surface.

[0072] 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 method of growing a non-polar a-plane gallium nitride thin film on an r-plane substrate through metalorganic chemical vapor deposition, comprising:

(a) annealing the substrate;

(b) depositing a nitride-based nucleation layer on the substrate;

(c) growing the non-polar a-plane gallium nitride film on the nucleation layer; and

(d) cooling the non-polar a-plane gallium nitride film under a nitrogen overpressure.

2. The method of claim 1, wherein the substrate is an r-plane sapphire substrate.

3. The method of claim 2, wherein an in-plane orientation of the gallium nitride film with respect to the r-plane substrate is $[0001_{]\mathrm{GaN}}\|[\bar{1}101]_{\mathrm{sapphire}}$ and $[\bar{1}100]_{\mathrm{GaN}}\|[1120]_{\mathrm{sapphire}}$.

4. The method of claim 1, wherein the substrate is selected from a group comprising silicon carbide, gallium nitride, silicon, zinc oxide, boron nitride, lithium aluminate, lithium niobate, germanium, aluminum nitride, and lithium gallate.

5. The method of claim 1, wherein the annealing step (a) comprises a high temperature annealing of the substrate.

6. The method of claim 1, wherein the depositing step (b) comprises a low temperature deposit of the nitride-based nucleation layer on the substrate.

7. The method of claim 1, wherein the depositing step (b) comprises a low pressure deposit of the nitride-based nucleation layer on the substrate.

8. The method of claim 1, wherein the low temperature depositing conditions comprise approximately 400-900° C. and atmospheric pressure.

9. The method of claim 1, wherein the depositing step (b) initiates gallium nitride growth on the r-plane substrate.

10. The method of claim 1, wherein the nucleation layer comprises 1-100 nanometers of gallium nitride.

11. The method of claim 1, wherein the growing step (b) comprises a high temperature growth of the non-polar a-plane gallium nitride film on the nucleation layer.

12. The method of claim 11, wherein the high temperature layer is deposited at 0.2 atmospheres or less.

13. The method of claim 11, wherein the high temperature growth conditions comprise approximately 1100° C. growth temperature, approximately 0.2 atmosphere or less growth pressure, 30 μmol per minute gallium flow, and 40,000 μmol per minute nitrogen flow.

14. The method of claim 1, wherein the growing step (b) produces the planar gallium nitride film.

15. A device manufactured using the method of claim 1.

16. A non-polar a-plane gallium nitride thin film on an r-plane substrate, wherein the thin film is created using a process comprising:

(a) annealing the substrate;

(b) depositing a nitride-based nucleation layer on the substrate;

(c) growing the non-polar a-plane gallium nitride film on the nucleation layer; and

(d) cooling the non-polar a-plane gallium nitride film under a nitrogen overpressure.

17. The thin film of claim 16, wherein the substrate is an r-plane sapphire substrate.

18. The thin film of claim 17, wherein an in-plane orientation of the gallium nitride films with respect to the r-plane substrate is $[0001]_{\mathrm{GaN}}\|[\bar{1}101]_{\mathrm{sapphire}}$ and $[\bar{1}100]_{\mathrm{GaN}}\|[1120]_{\mathrm{sapphire}}$.

19. The thin film of claim 16, wherein the substrate is selected from a group comprising silicon carbide, gallium nitride, silicon, zinc oxide, boron nitride, lithium aluminate, lithium niobate, germanium, aluminum nitride, and lithium gallate.

20. The thin film of claim 16, wherein the annealing step (a) comprises a high temperature annealing of the substrate.

21. The thin film of claim 16, wherein the depositing step (b) comprises a low temperature deposit of the nitride-based nucleation layer on the substrate.

22. The thin film of claim 16, wherein the depositing step (b) comprises a low pressure deposit of the nitride-based nucleation layer on the substrate.

23. The thin film of claim 16, wherein the low temperature depositing conditions comprise approximately 400-900° C. and atmospheric pressure.

24. The thin film of claim 16, wherein the depositing step (b) initiates gallium nitride growth on the r-plane substrate.

25. The thin film of claim 16, wherein the nucleation layer comprises 1-100 nanometers of gallium nitride.

26. The thin film of claim 16, wherein the growing step (b) comprises a high temperature growth of the non-polar a-plane gallium nitride films on the nucleation layer.

27. The thin film of claim 26, wherein the high temperature layer is deposited at 0.2 atmospheres or less.

28. The thin film of claim 26, wherein the high temperature growth conditions comprise approximately 1100° C. growth temperature, approximately 0.2 atmosphere or less growth pressure, 30 μmol per minute gallium flow, and 40,000 μmol per minute nitrogen flow.

29. The thin film of claim 16, wherein the growing step (b) produces a planar gallium nitride film.

30. A structure having a non-polar a-plane gallium nitride thin film on an r-plane substrate, comprising:

(a) an annealed substrate;

(b) a nitride-based nucleation layer deposited on the substrate; and

(c) a non-polar a-plane gallium nitride film grown on the nucleation layer and cooled under a nitrogen overpressure.

31. The structure of claim 30, wherein the substrate is an r-plane sapphire substrate.

32. The structure of claim 31, wherein an in-plane orientation of the gallium nitride film with respect to the r-plane substrate is $[0001]_{\mathrm{GaN}}\|[\bar{1}101]_{\mathrm{sapphire}}$ and $[\bar{1}100]_{\mathrm{GaN}}\|[1120]_{\mathrm{sapphire}}$.

33. The structure of claim 30, wherein the substrate is selected from a group comprising silicon carbide, gallium nitride, silicon, zinc oxide, boron nitride, lithium aluminate, lithium niobate, germanium, aluminum nitride, and lithium gallate.

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