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(54) **NON-POLAR AND SEMI-POLAR LIGHT EMITTING DEVICES**

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(21) Appl. No.: **12/001,227**

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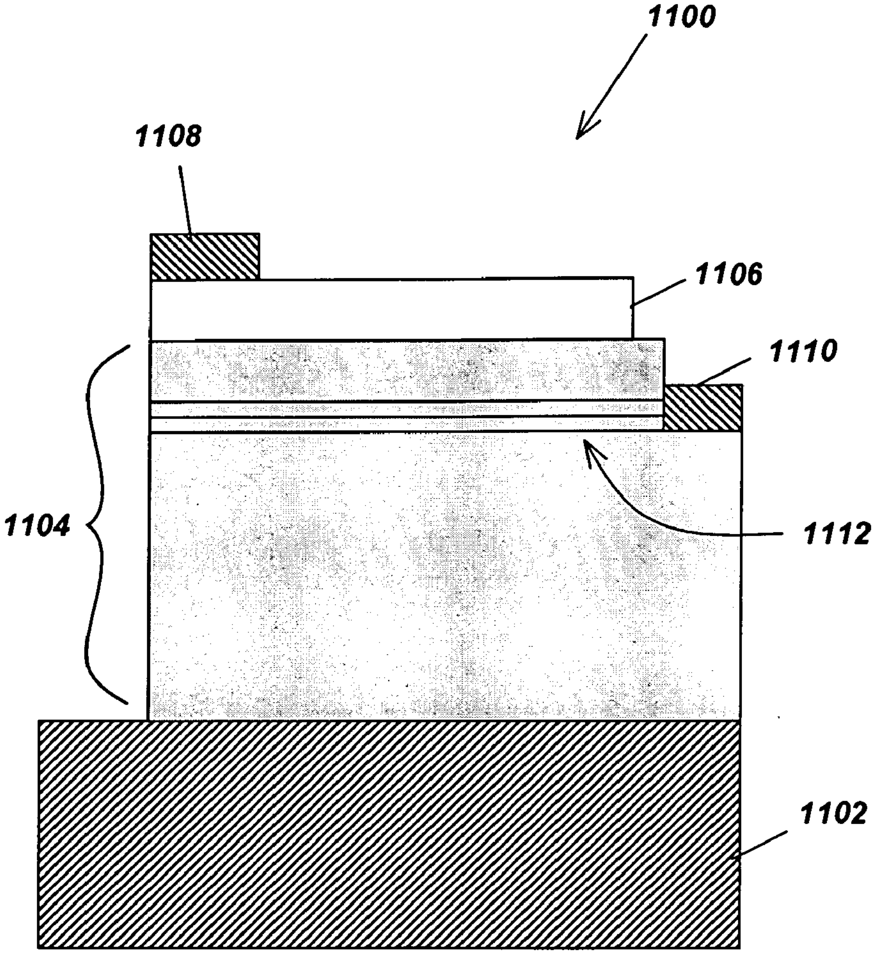
H01L 21/00 (2006.01)

(52) **U.S. Cl.** **257/94**; 438/46; 257/E33.001

(57) **ABSTRACT**

An (Al, Ga, In)N light emitting device, such as a light emitting diode (LED), in which high light generation efficiency is realized by fabricating the device on non-polar or semi-polar III-Nitride crystal geometries. Because non-polar and semi-polar emitting devices have significantly lower piezoelectric effects than c-plane emitting devices, higher efficiency emitting devices at higher current densities can be realized.



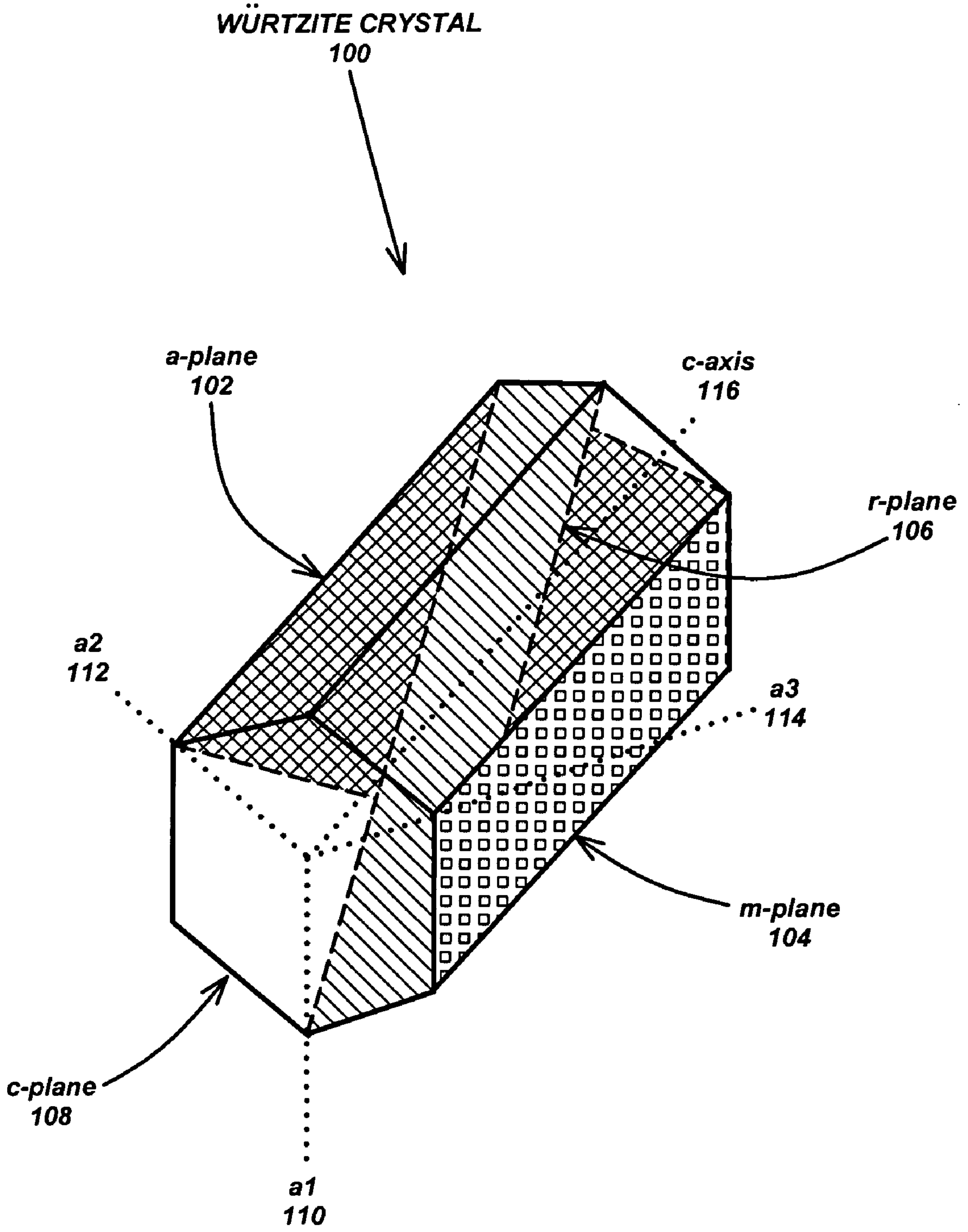

WÜRTZITE CRYSTAL
100
a-plane
102
c-axis
116
r-plane
106
a2
112
a3
114
m-plane
104
c-plane
108
a1
110

FIG. 1

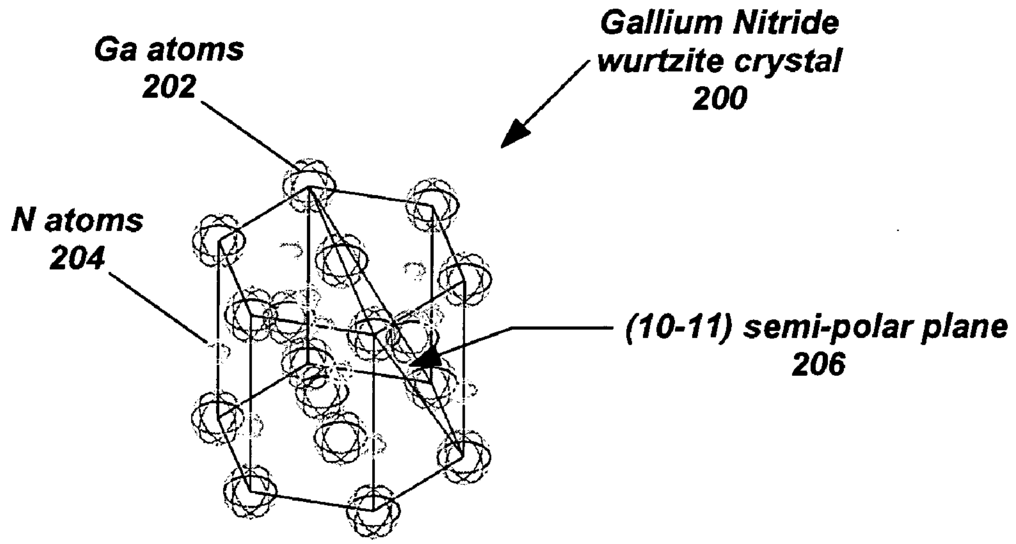

Gallium Nitride wurtzite crystal
200
Ga atoms
202
N atoms
204
(10-11) semi-polar plane
206

FIG. 2

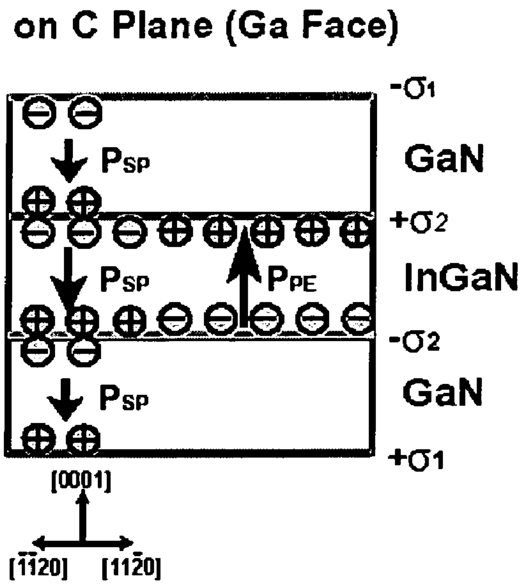


FIG. 3A

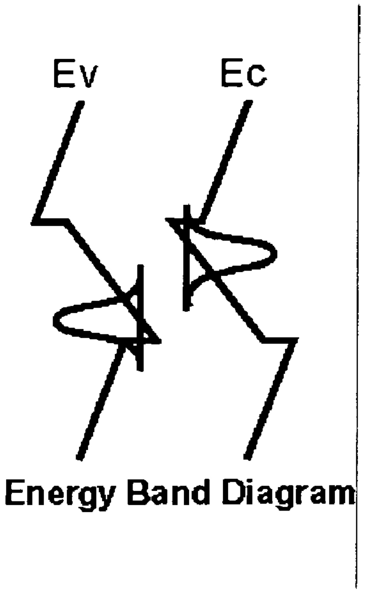


FIG. 3B

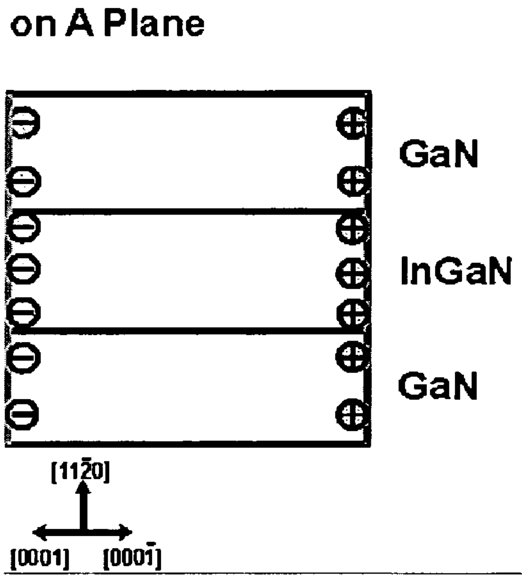


FIG. 3C

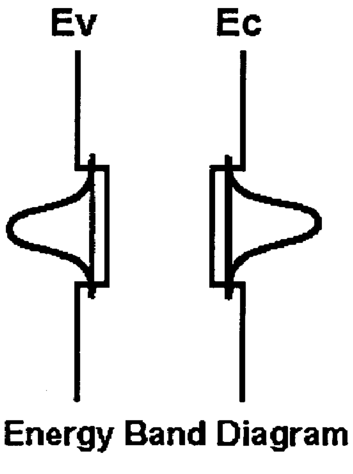


FIG. 3D

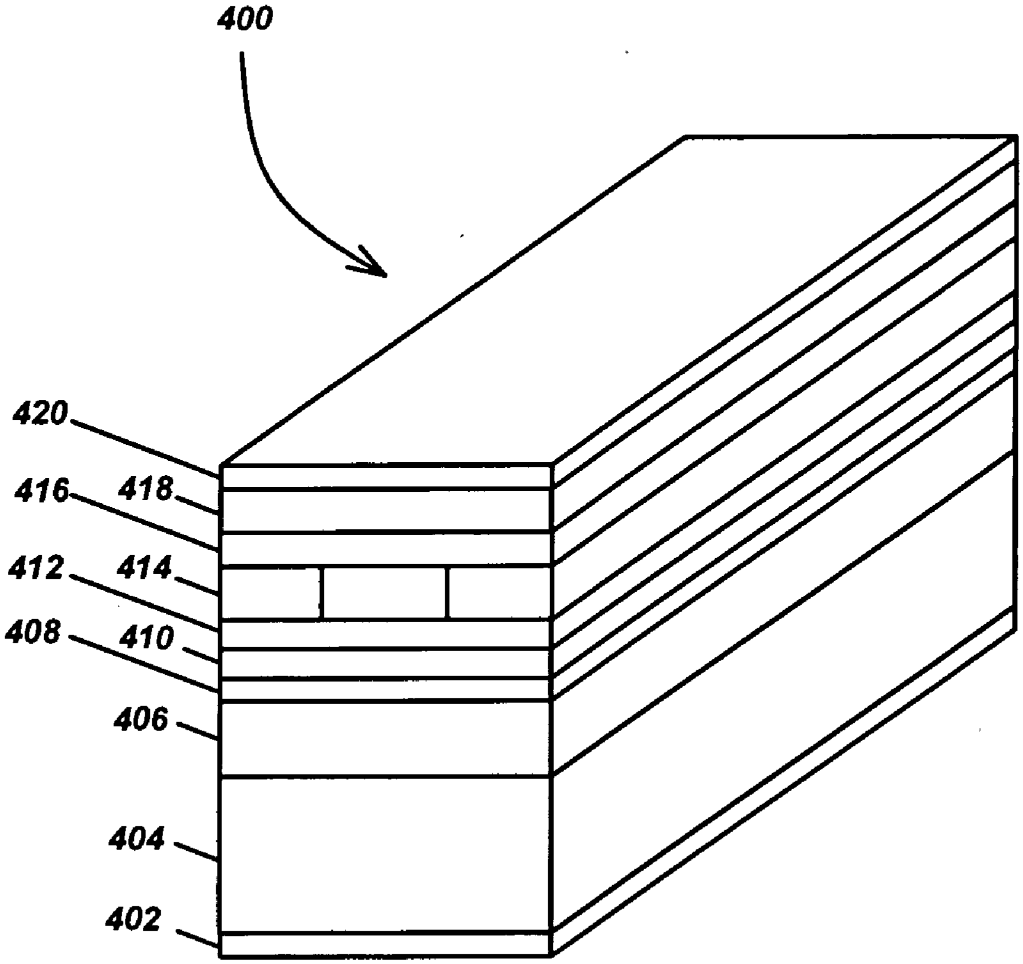


FIG. 4

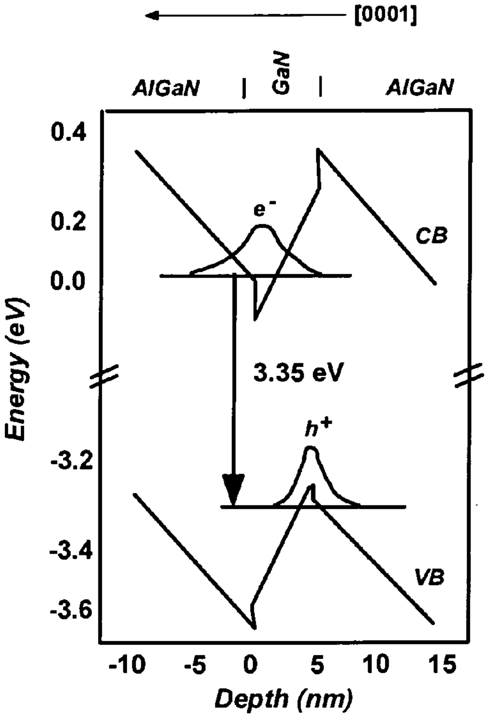

[0001]
AlGaN
GaN
AlGaN
0.4
0.2
0.0
-3.2
-3.4
-3.6
Energy (eV)
e⁻
CB
3.35 eV
h⁺
VB
-10
-5
0
5
10
15
Depth (nm)

FIG. 5A

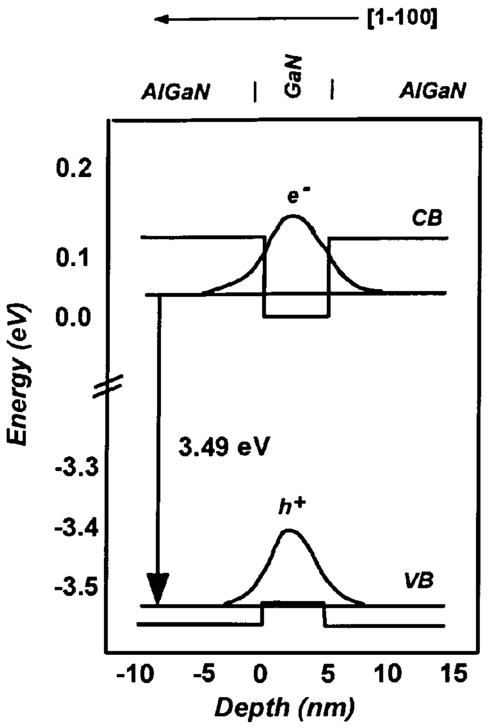

[1-100]
AlGaN
GaN
AlGaN
0.2
0.1
0.0
-3.3
-3.4
-3.5
Energy (eV)
e⁻
CB
3.49 eV
h⁺
VB
-10
-5
0
5
10
15
Depth (nm)

FIG. 5B

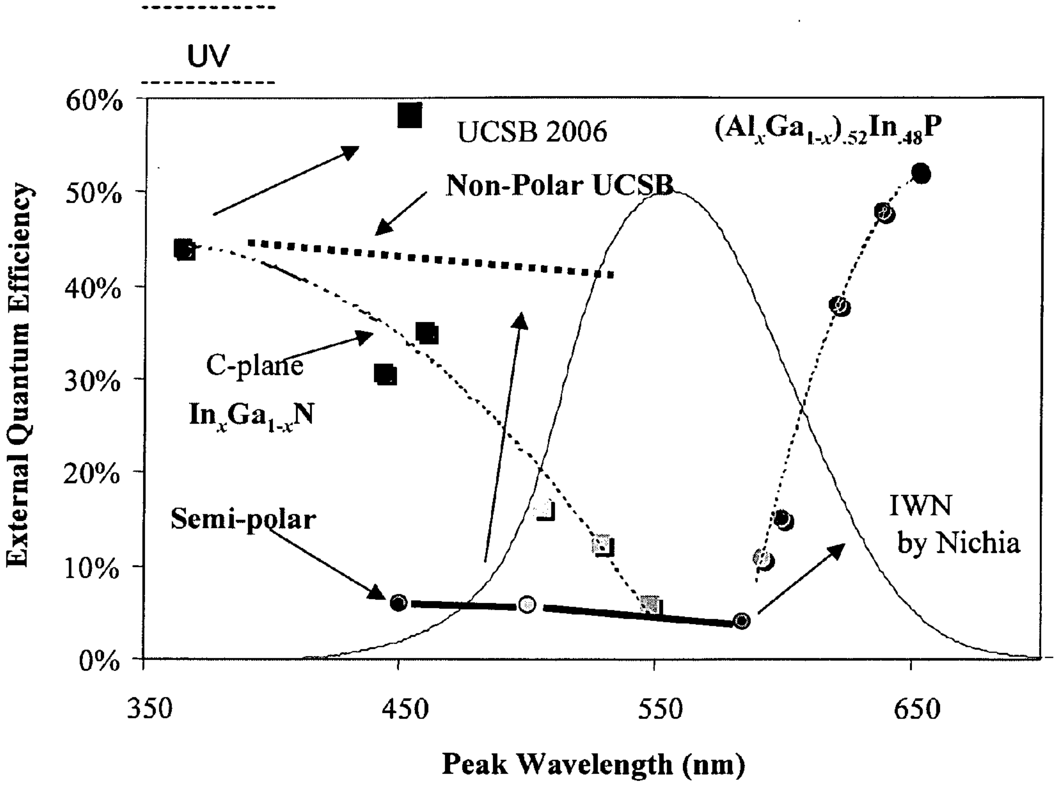

UV
60%
50%
40%
30%
20%
10%
0%
External Quantum Efficiency
UCSB 2006
$(Al_xGa_{1-x})_{.52}In_{.48}P$
Non-Polar UCSB
C-plane
$In_xGa_{1-x}N$
Semi-polar
IWN
by Nichia
350
450
550
650
Peak Wavelength (nm)

FIG. 5C

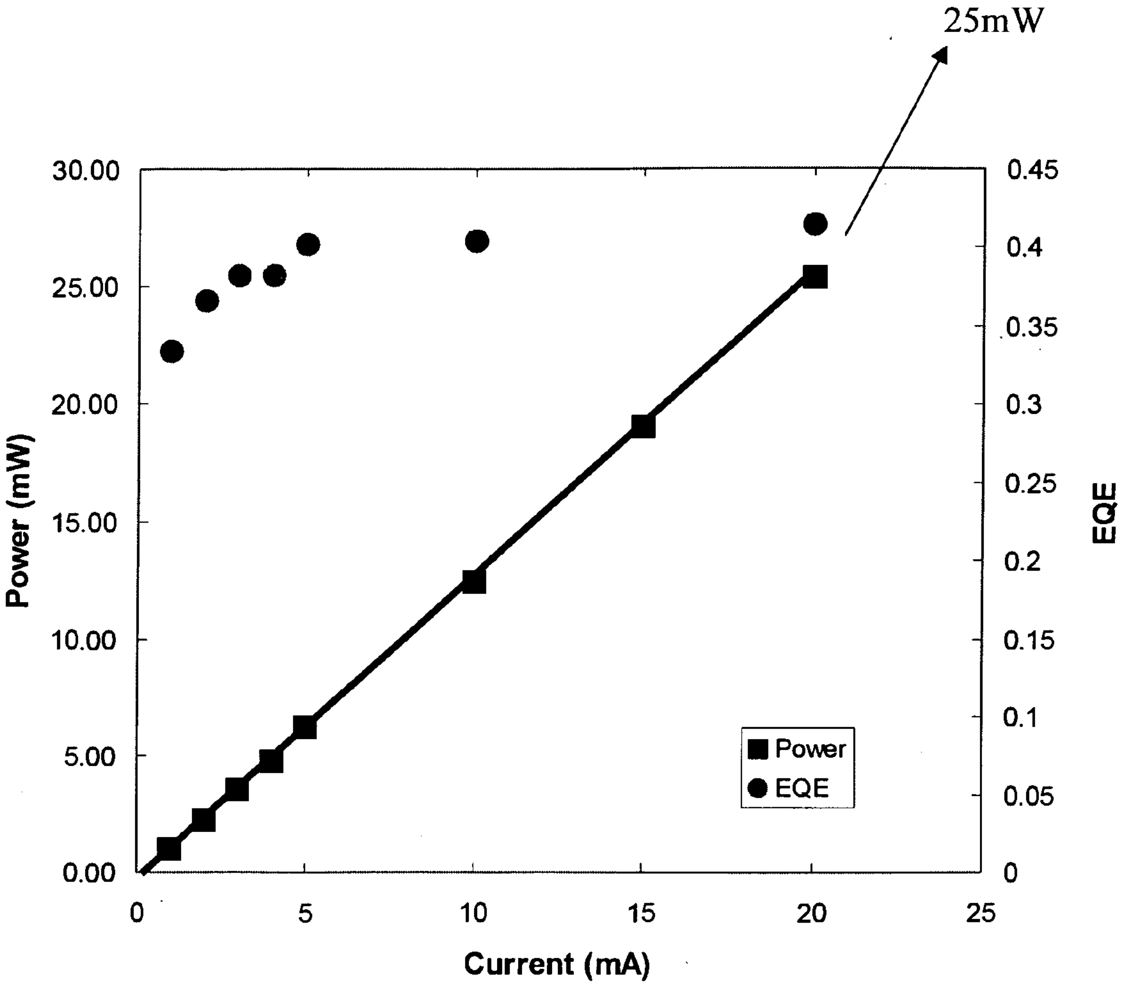

25mW
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Power (mW)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
EQE
0
5
10
15
20
25
Current (mA)
■ Power
● EQE

FIG. 6

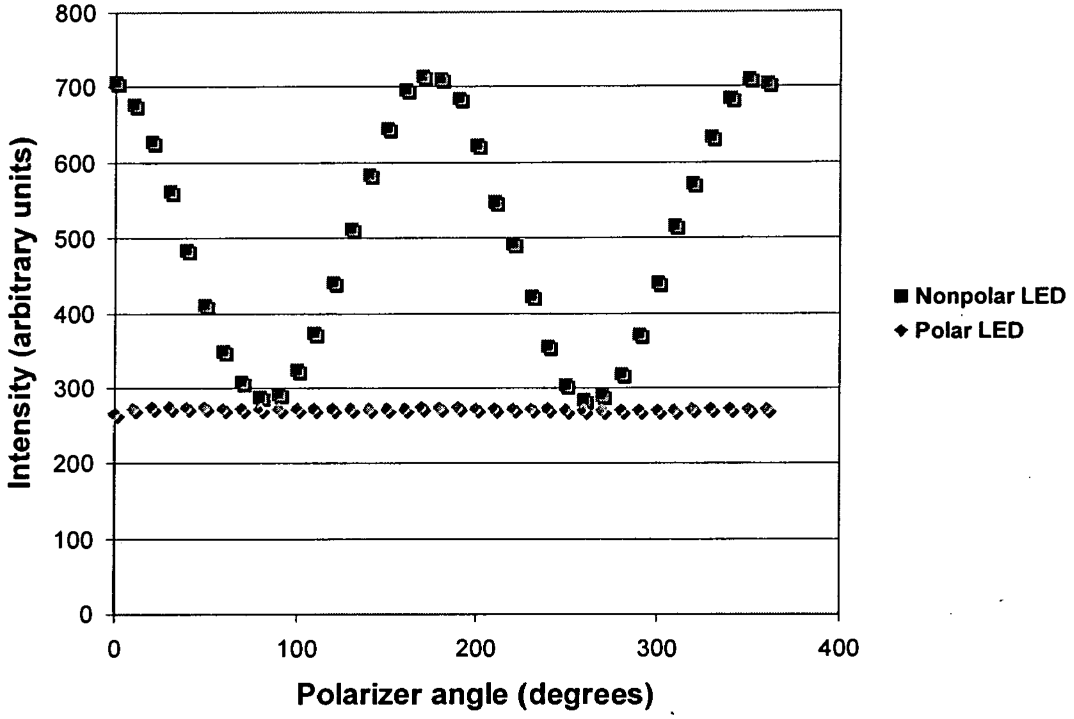

800
700
600
500
400
300
200
100
0
Intensity (arbitrary units)
0
100
200
300
400
Polarizer angle (degrees)
■ Nonpolar LED
◆ Polar LED

FIG. 7

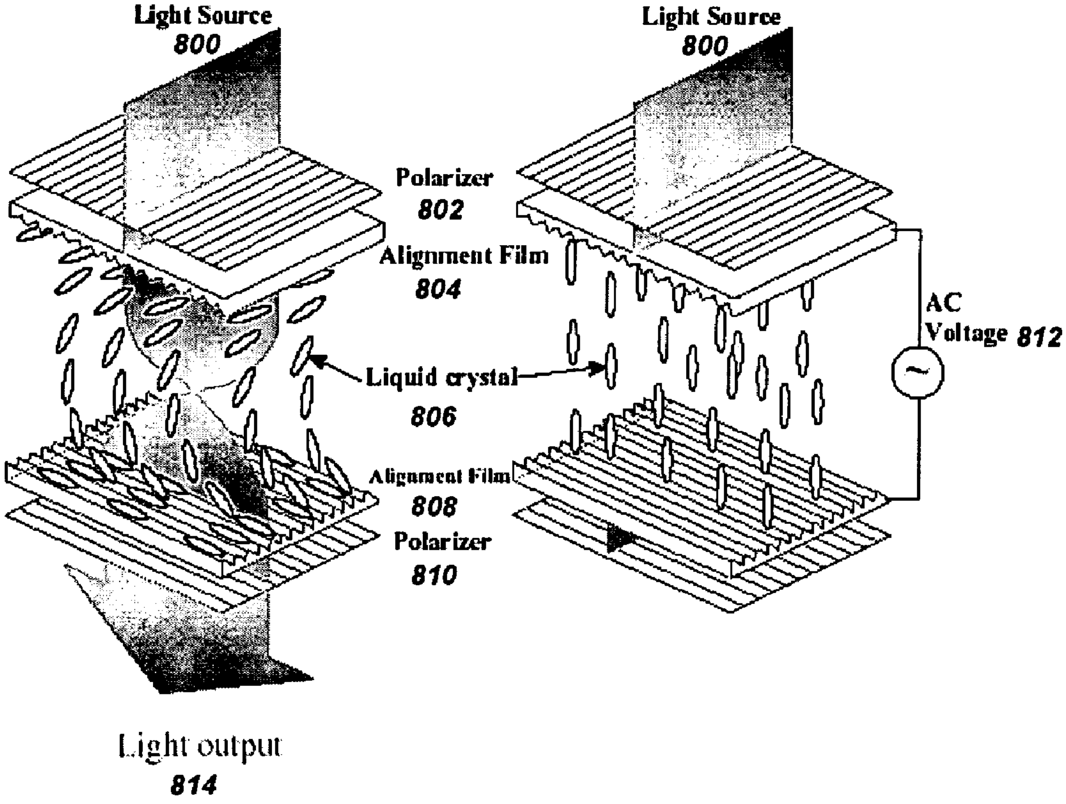

Light Source
800
Light Source
800
Polarizer
802
Alignment Film
804
AC
Voltage 812
Liquid crystal
806
Alignment Film
808
Polarizer
810
Light output
814

FIG. 8

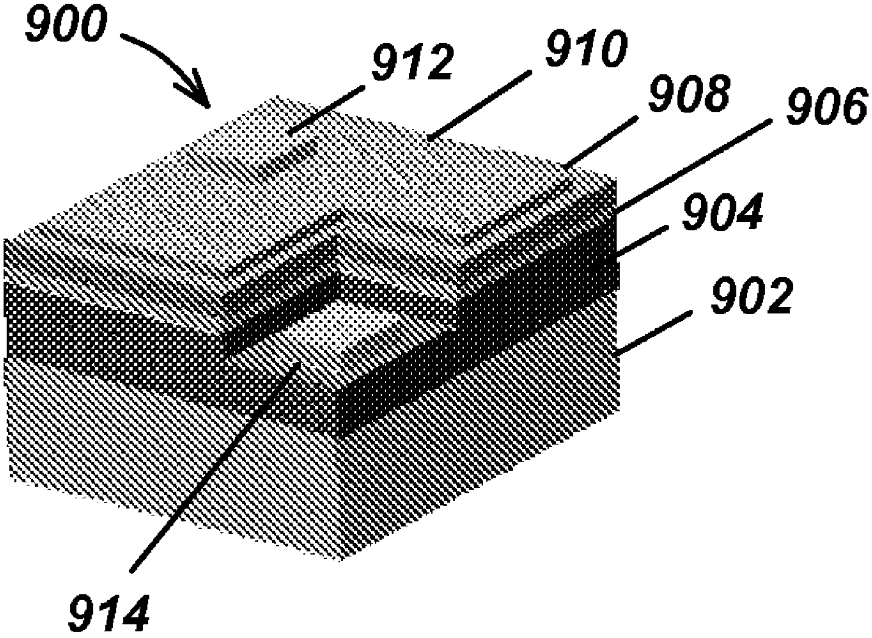


FIG. 9A

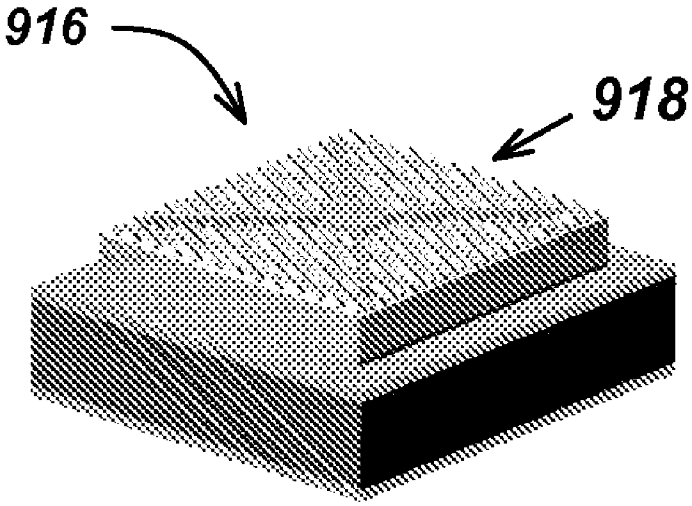


FIG. 9B

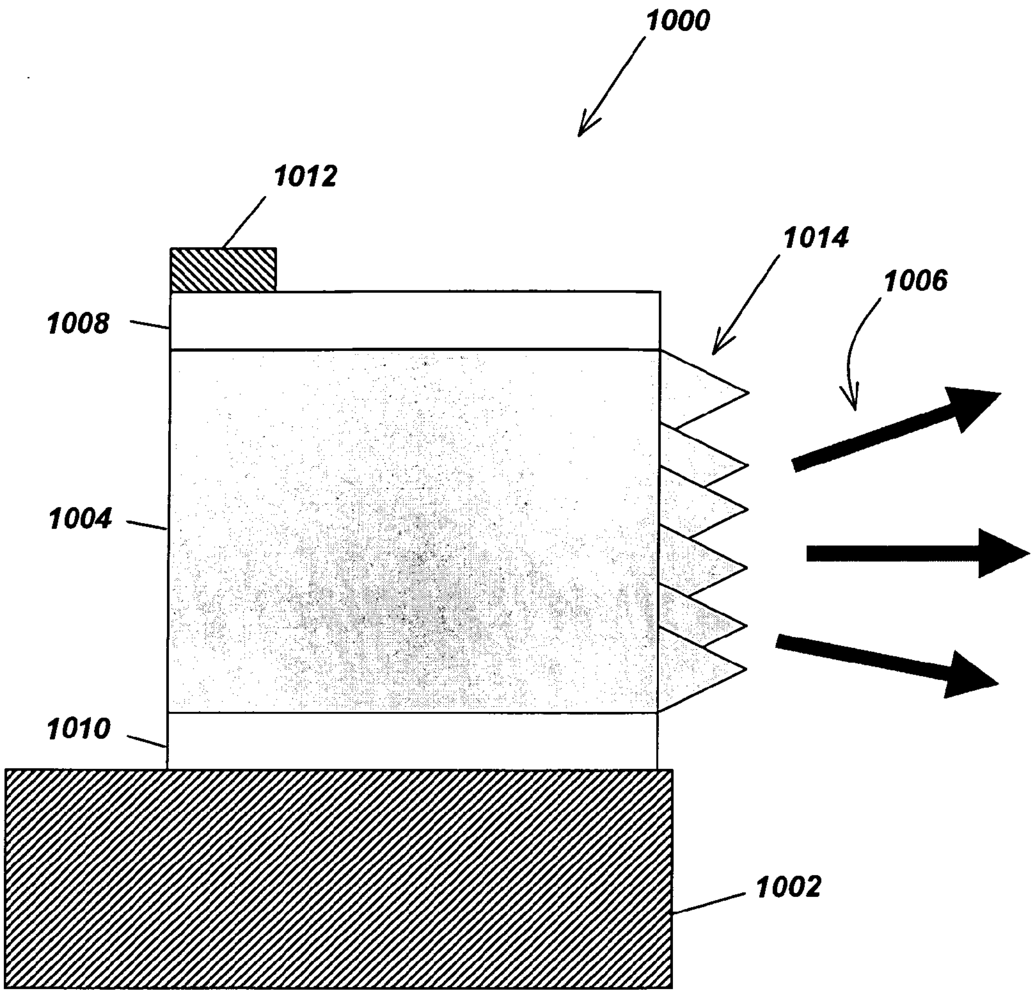


FIG. 10

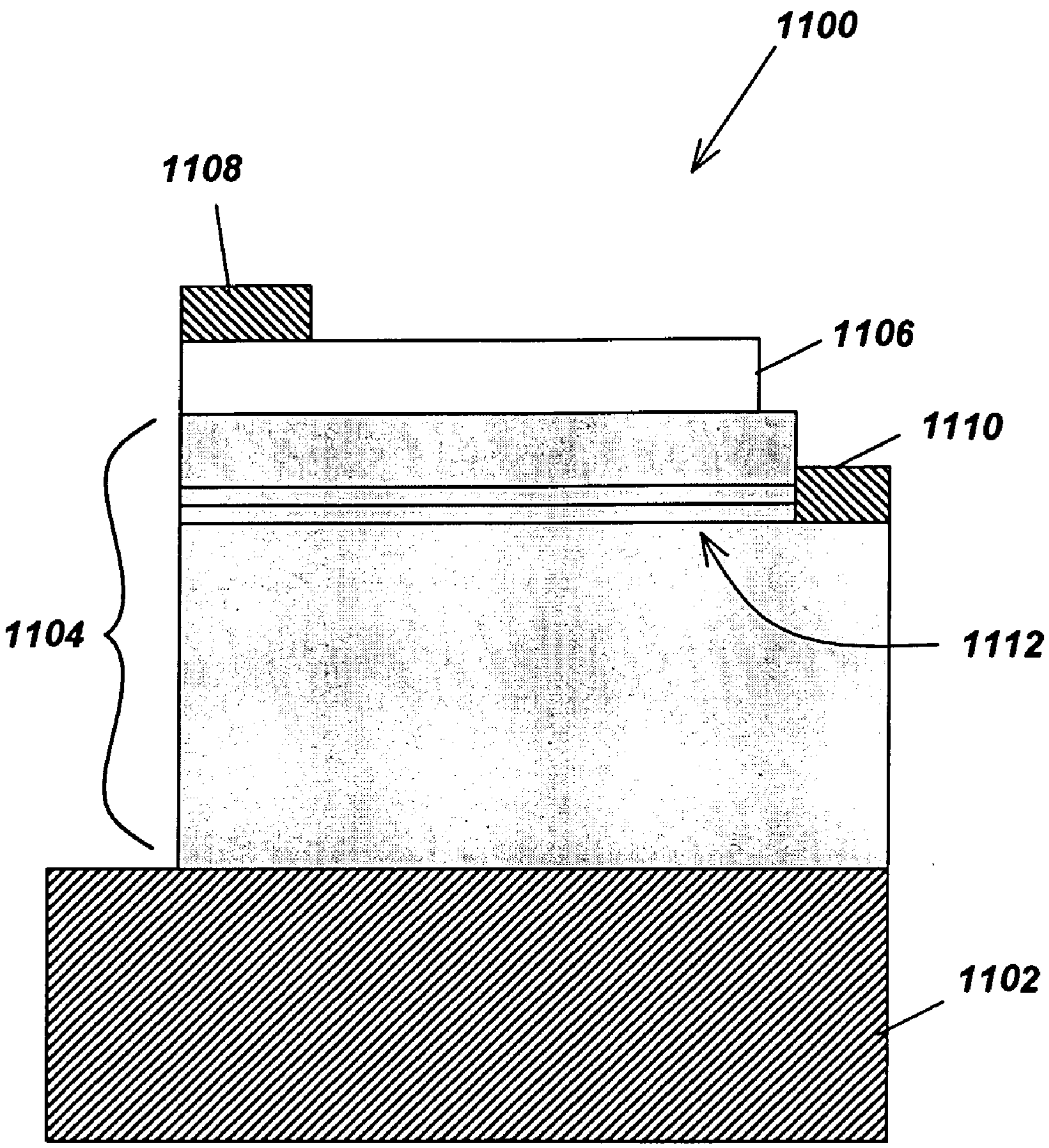


FIG. 11

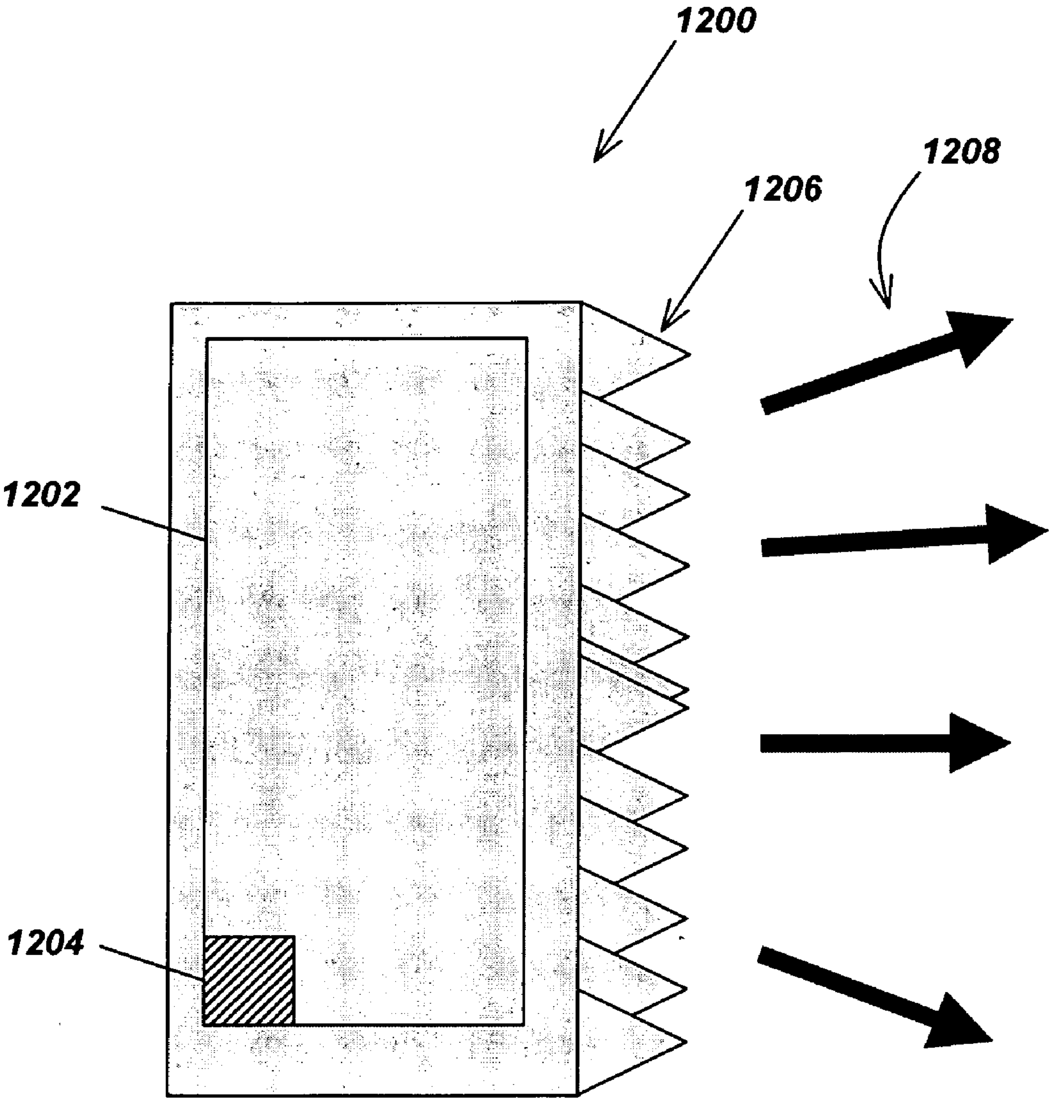


FIG. 12

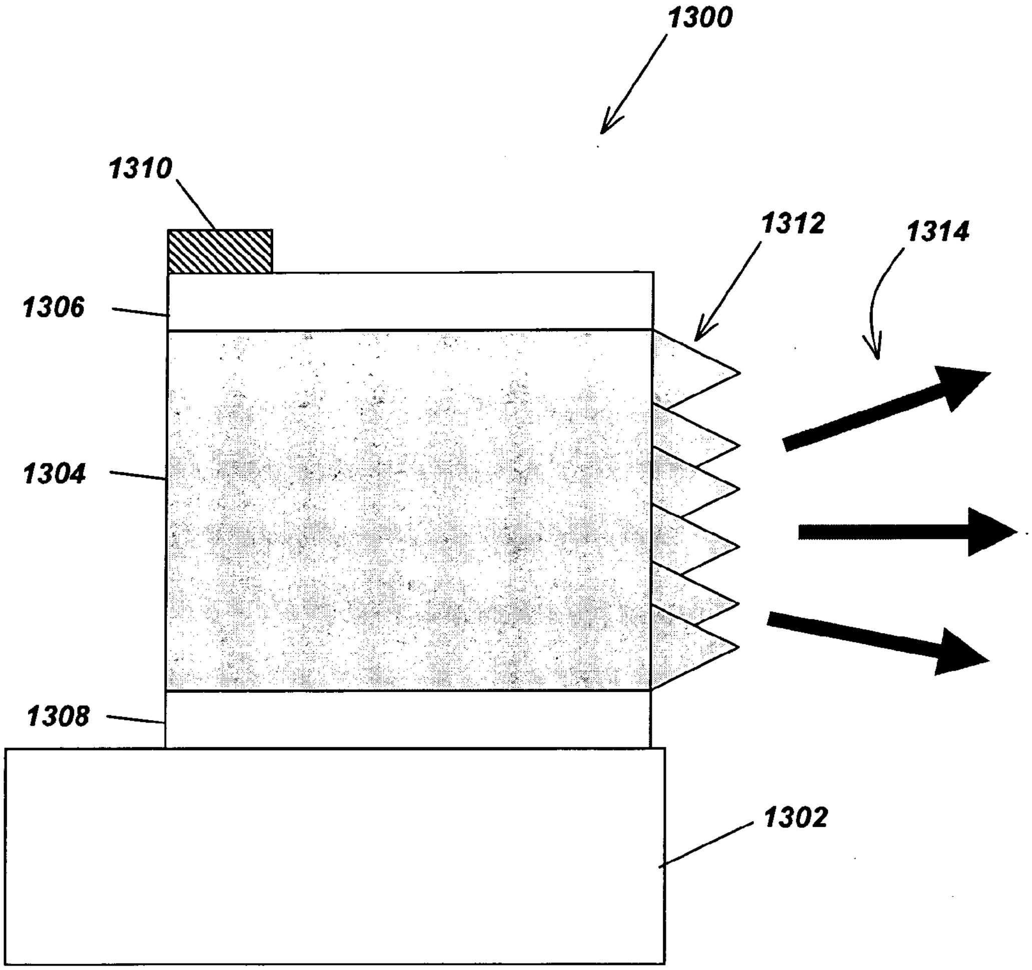


FIG. 13

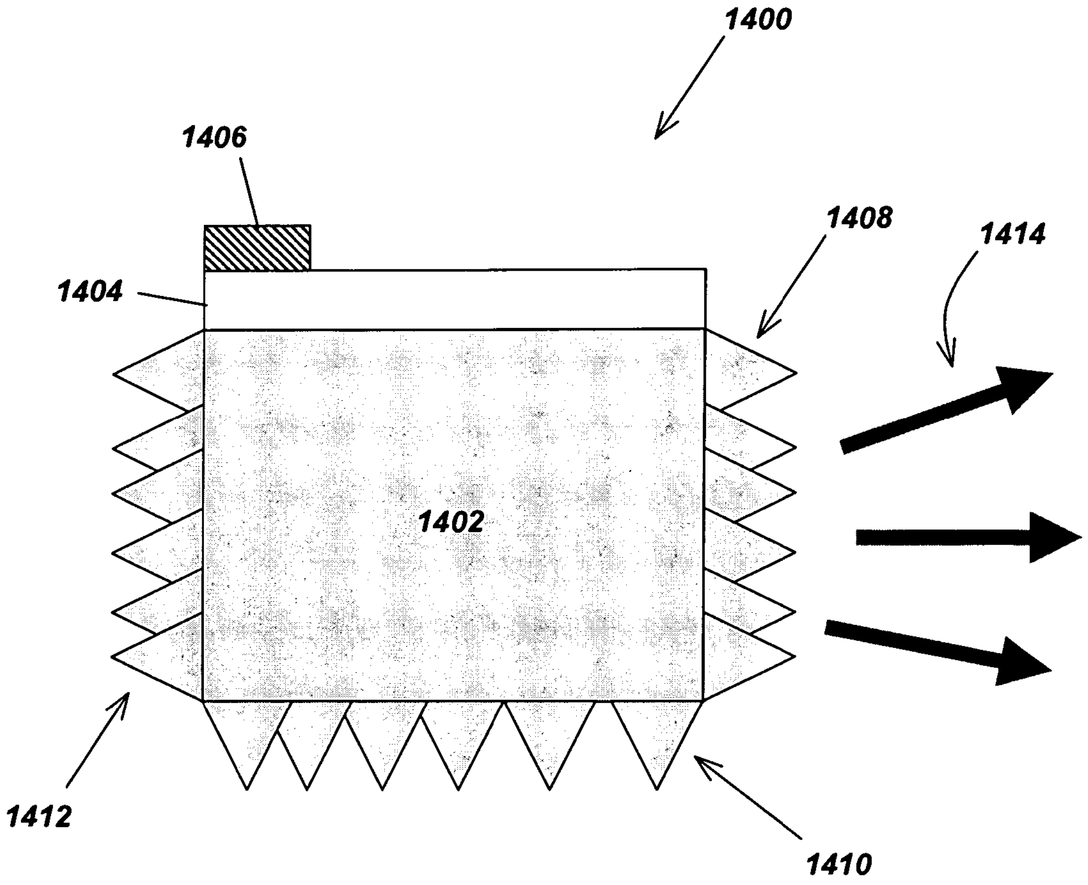


FIG. 14

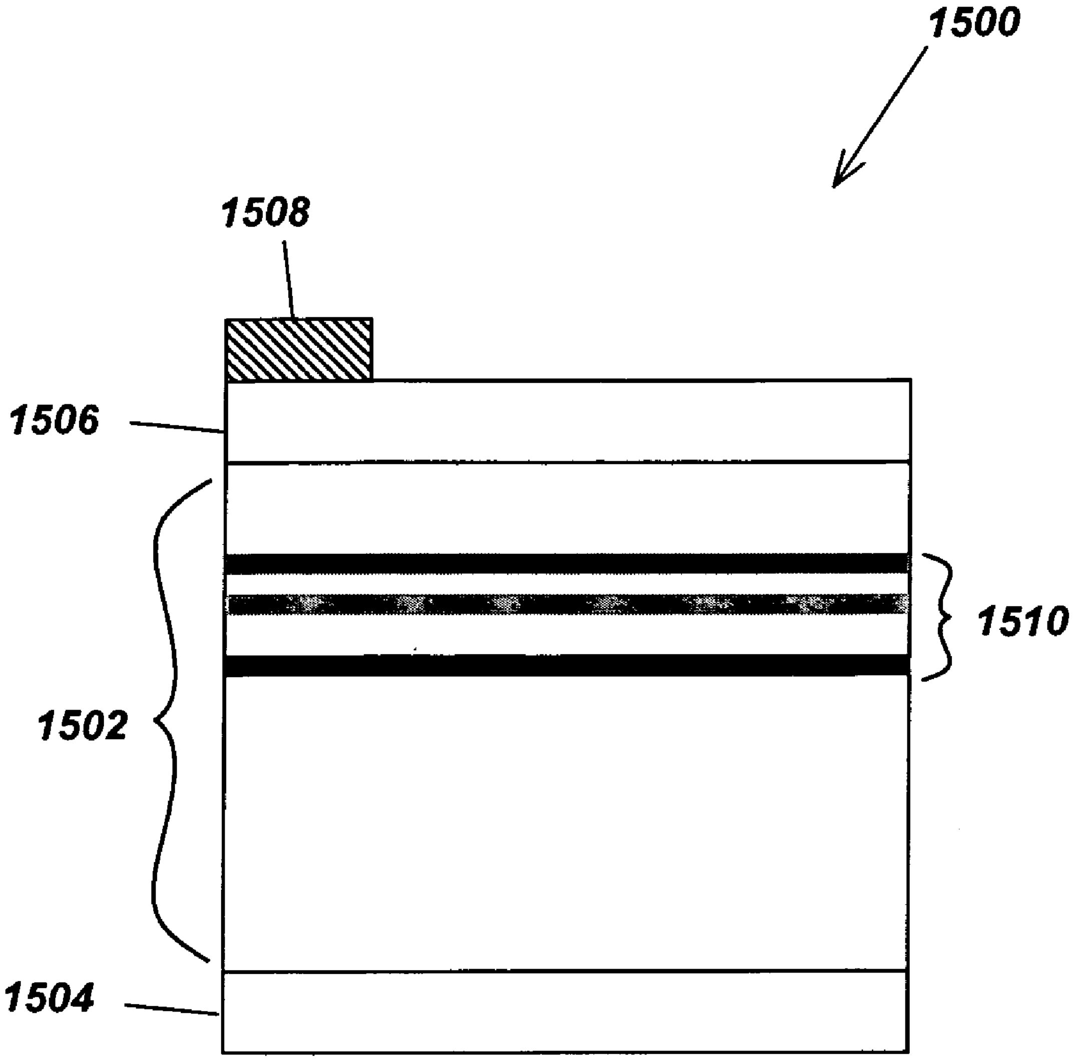


FIG. 15

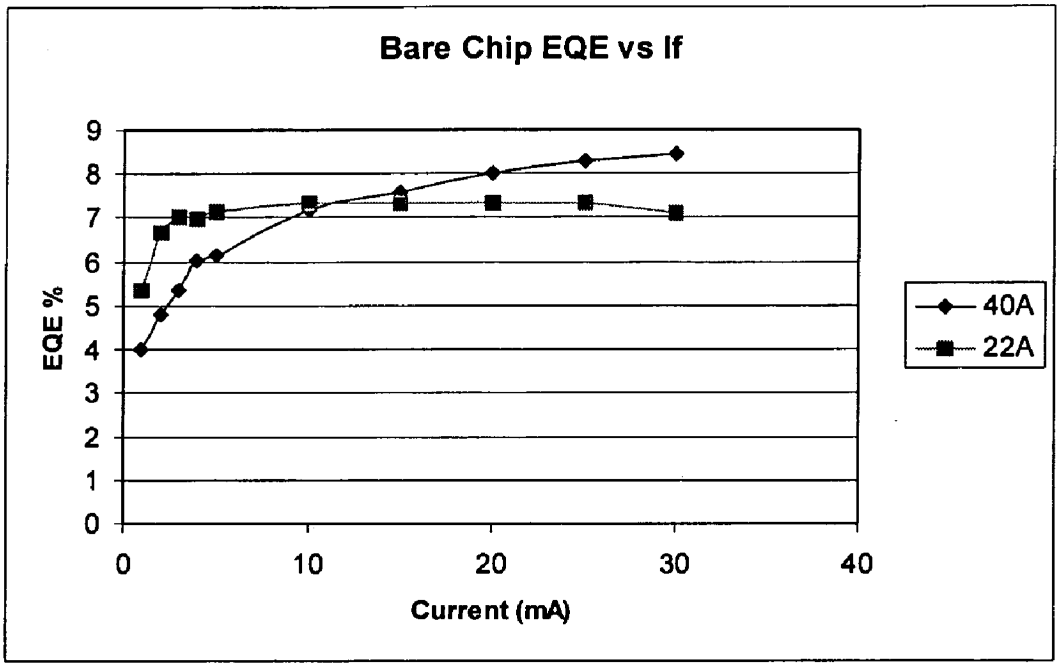

Bare Chip EQE vs If
EQE %
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
Current (mA)
40A
22A

FIG. 16

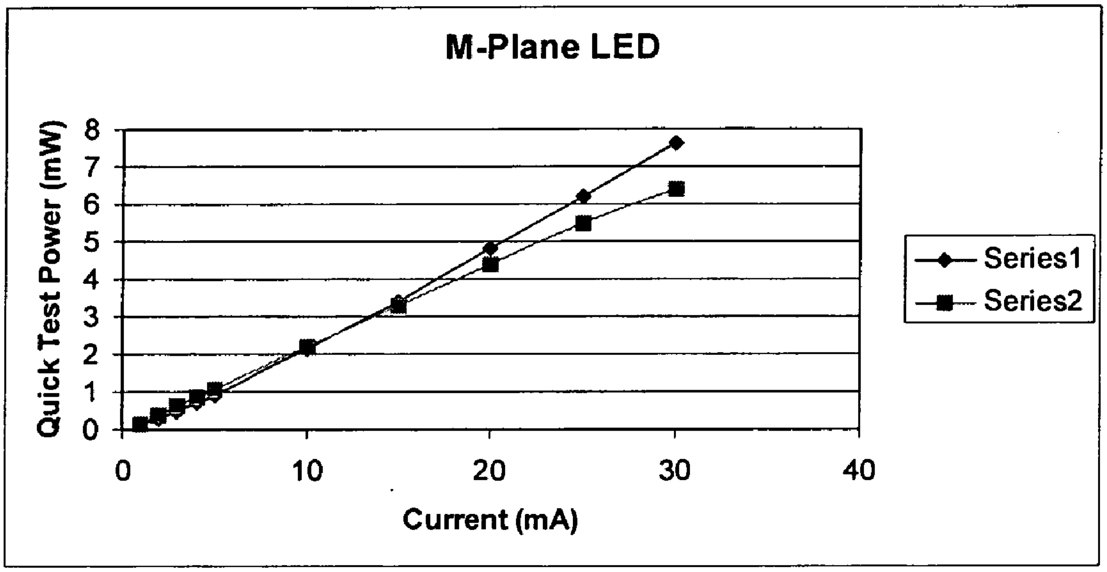

M-Plane LED
Quick Test Power (mW)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
Current (mA)
Series1
Series2

FIG. 17

NON-POLAR AND SEMI-POLAR LIGHT EMITTING DEVICES

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:

[0002] U.S. Provisional Application Ser. No. 60/869,540, filed on Dec. 11, 2006, by Steven P. DenBaars, Mathew C. Schmidt, Kwang Choong Kim, James S. Speck, and Shuji Nakamura, entitled "NON-POLAR (M-PLANE) AND SEMI-POLAR EMITTING DEVICES," attorneys' docket number 30794.213-US-P1 (2007-317-1);

[0003] which application is incorporated by reference herein.

[0004] This application is related to the following co-pending and commonly-assigned applications:

[0005] U.S. Utility application Ser. No. 10/581,940, filed on Jun. 7, 2006, by Tetsuo Fujii, Yan Gao, Evelyn. L. Hu, and Shuji Nakamura, entitled "HIGHLY EFFICIENT GALLIUM NITRIDE BASED LIGHT EMITTING DIODES VIA SURFACE ROUGHENING," attorney's docket number 30794.108-US-WO (2004-063), which application claims the benefit under 35 U.S.C Section 365(c) of PCT Application Serial No. US2003/03921, filed on Dec. 9, 2003, by Tetsuo Fujii, Yan Gao, Evelyn L. Hu, and Shuji Nakamura, entitled "HIGHLY EFFICIENT GALLIUM NITRIDE BASED LIGHT EMITTING DIODES VIA SURFACE ROUGHENING," attorney's docket number 30794.108-WO-01 (2004-063);

[0006] U.S. Utility application Ser. No. 11/054,271, filed on Feb. 9, 2005, by Rajat Sharma, P. Morgan Pattison, John F. Kaeding, and Shuji Nakamura, entitled "SEMICONDUCTOR LIGHT EMITTING DEVICE," attorney's docket number 30794.112-US-01 (2004-208);

[0007] U.S. Utility application Ser. No. 11/175,761, filed on Jul. 6, 2005, by Akihiko Murai, Lee McCarthy, Umesh K. Mishra and Steven P. DenBaars, entitled "METHOD FOR WAFER BONDING (Al, In, Ga)N and Zn(S, Se) FOR OPTOELECTRONICS APPLICATIONS," attorney's docket number 30794.116-US-U1 (2004-455), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/585,673, filed Jul. 6, 2004, by Akihiko Murai, Lee McCarthy, Umesh K. Mishra and Steven P. DenBaars, entitled "METHOD FOR WAFER BONDING (Al, In, Ga)N and Zn(S, Se) FOR OPTOELECTRONICS APPLICATIONS," attorney's docket number 30794.116-US-P1 (2004-455-1);

[0008] U.S. Utility application Ser. No. 11/697,457, filed Apr. 6, 2007, by, Benjamin A. Haskell, Melvin B. McLaurin, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF PLANAR REDUCED DISLOCATION DENSITY M-PLANE GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys' docket number 30794.119-US-C1 (2004-636-3), which application is a continuation of U.S. Utility application Ser. No. 11/140,893, filed May 31, 2005, by, Benjamin A. Haskell, Melvin B. McLaurin, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF PLANAR REDUCED DISLOCATION DENSITY M-PLANE GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys' docket number 30794.119-US-U1 (2004-636-2), now U.S. Pat. No. 7,208,393, issued Apr. 24, 2007, which application claims the benefit under 35 U.S.C. Section 119(e) of U.S. Provisional Application Ser. No. 60/576,685, filed Jun. 3, 2004, by Benjamin A. Haskell, Melvin B. McLaurin, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "GROWTH OF PLANAR REDUCED DISLOCATION DENSITY M-PLANE GALLIUM NITRIDE BY HYDRIDE VAPOR PHASE EPITAXY," attorneys' docket number 30794.119-US-P1 (2004-636-1);

[0009] U.S. Utility application Ser. No. 11/067,957, filed Feb. 28, 2005, by Claude C. A. Weisbuch, Aurelien J. F. David, James S. Speck and Steven P. DenBaars, entitled "HORIZONTAL EMITTING, VERTICAL EMITTING, BEAM SHAPED, DISTRIBUTED FEEDBACK (DFB) LASERS BY GROWTH OVER A PATTERNED SUBSTRATE," attorneys' docket number 30794.121-US-01 (2005-144-1);

[0010] U.S. Utility application Ser. No. 11/923,414, filed Oct. 24, 2007, by Claude C. A. Weisbuch, Aurelien J. F. David, James S. Speck and Steven P. DenBaars, entitled "SINGLE OR MULTI-COLOR HIGH EFFICIENCY LIGHT EMITTING DIODE (LED) BY GROWTH OVER A PATTERNED SUBSTRATE," attorneys' docket number 30794.122-US-C1 (2005-145-2), which application is a continuation of U.S. Pat. No. 7,291,864, issued Nov. 6, 2007, to Claude C. A. Weisbuch, Aurelien J. F. David, James S. Speck and Steven P. DenBaars, entitled "SINGLE OR MULTI-COLOR HIGH EFFICIENCY LIGHT EMITTING DIODE (LED) BY GROWTH OVER A PATTERNED SUBSTRATE," attorneys' docket number 30794.122-US-01 (2005-145-1);

[0011] U.S. Utility application Ser. No. 11/067,956, filed Feb. 28, 2005, by Aurelien J. F. David, Claude C. A Weisbuch and Steven P. DenBaars, entitled "HIGH EFFICIENCY LIGHT EMITTING DIODE (LED) WITH OPTIMIZED PHOTONIC CRYSTAL EXTRACTOR," attorneys' docket number 30794.126-US-01 (2005-198-1);

[0012] U.S. Utility application Ser. No. 11/621,482, filed Jan. 9, 2007, 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 number 30794.128-US-C1 (2005-471-3), which application is a continuation of U.S. Utility application Ser. No. 11/372,914, filed Mar. 10, 2006, 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 number 30794.128-US-U1 (2005-471-2), now U.S. Pat. No. 7,220,324, issued May 22, 2007, which application claims the benefit under 35 U.S.C. Section 119(e) of U.S. Provisional Application Ser. No. 60/660,283, filed Mar. 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 number 30794.128-US-P1 (2005-471-1);

[0013] U.S. Utility application Ser. No. 11/403,624, filed Apr. 13, 2006, by James S. Speck, Troy J. Baker and Benjamin A. Haskell, entitled "WAFER SEPARATION TECHNIQUE FOR THE FABRICATION OF FREE-STANDING (AL, IN, GA)N WAFERS," attorneys' docket number 30794.131-US-U1 (2005-482-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/670,810, filed Apr. 13, 2005, by James S. Speck, Troy J. Baker and Benjamin A. Haskell, entitled "WAFER SEPARATION TECHNIQUE FOR THE FABRICATION OF FREE-STANDING (AL, IN, GA)N WAFERS," attorneys' docket number 30794.131-US-P1 (2005-482-1);

[0014] U.S. Utility application Ser. No. 11/403,288, filed Apr. 13, 2006, by James S. Speck, Benjamin A. Haskell, P. Morgan Pattison and Troy J. Baker, entitled "ETCHING TECHNIQUE FOR THE FABRICATION OF THIN (AL, IN, GA)N LAYERS," attorneys' docket number 30794.132-US-U1 (2005-509-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/670,790, filed Apr. 13, 2005, by James S. Speck, Benjamin A. Haskell, P. Morgan Pattison and Troy J. Baker, entitled "ETCHING TECHNIQUE FOR THE FABRICATION OF THIN (AL, IN, GA)N LAYERS," attorneys' docket number 30794.132-US-P1 (2005-509-1);

[0015] U.S. Utility application Ser. No. 11/454,691, filed on Jun. 16, 2006, by Akihiko Murai, Christina Ye Chen, Daniel B. Thompson, Lee S. McCarthy, Steven P. DenBaars, Shuji Nakamura, and Umesh K. Mishra, entitled "(Al,Ga, In)N AND ZnO DIRECT WAFER BONDING STRUCTURE FOR OPTOELECTRONIC APPLICATIONS AND ITS FABRICATION METHOD," attorneys' docket number 30794.134-US-U1 (2005-536-4), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/691,710, filed on Jun. 17, 2005, by Akihiko Murai, Christina Ye Chen, Lee S. McCarthy, Steven P. DenBaars, Shuji Nakamura, and Umesh K. Mishra, entitled "(Al, Ga, In)N AND ZnO DIRECT WAFER BONDING STRUCTURE FOR OPTOELECTRONIC APPLICATIONS, AND ITS FABRICATION METHOD," attorneys' docket number 30794.134-US-P1 (2005-536-1), U.S. Provisional Application Ser. No. 60/732,319, filed on Nov. 1, 2005, by Akihiko Murai, Christina Ye Chen, Daniel B. Thompson, Lee S. McCarthy, Steven P. DenBaars, Shuji Nakamura, and Umesh K. Mishra, entitled "(Al, Ga, In)N AND ZnO DIRECT WAFER BONDED STRUCTURE FOR OPTOELECTRONIC APPLICATIONS, AND ITS FABRICATION METHOD," attorneys' docket number 30794.134-US-P2 (2005-536-2), and U.S. Provisional Application Ser. No. 60/764,881, filed on Feb. 3, 2006, by Akihiko Murai, Christina Ye Chen, Daniel B. Thompson, Lee S. McCarthy, Steven P. DenBaars, Shuji Nakamura, and Umesh K. Mishra, entitled "(Al,Ga,In)N AND ZnO DIRECT WAFER BONDED STRUCTURE FOR OPTOELECTRONIC APPLICATIONS AND ITS FABRICATION METHOD," attorneys' docket number 30794.134-US-P3 (2005-536-3);

[0016] U.S. Utility application Ser. No. 11/444,084, filed May 31, 2006, by Bilge M, Imer, James S. Speck, and Steven P. DenBaars, entitled "DEFECT REDUCTION OF NON-POLAR GALLIUM NITRIDE WITH SINGLE-STEP SIDE-WALL LATERAL EPITAXIAL OVERGROWTH," attorneys' docket number 30794.135-US-U1 (2005-565-2), which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Application Ser. No. 60/685,952, filed on May 31, 2005, by Bilge M, Imer, James S. Speck, and Steven P. DenBaars, entitled "DEFECT REDUCTION OF NON-POLAR GALLIUM NITRIDE WITH SINGLE-STEP SIDEWALL LATERAL EPITAXIAL OVERGROWTH," attorneys' docket number 30794.135-US-P1 (2005-565-1);

[0017] U.S. Utility application Ser. No. 11/870,115, filed Oct. 10, 2007, by Bilge M, Imer, James S. Speck, Steven P. DenBaars and Shuji Nakamura, entitled "GROWTH OF PLANAR NON-POLAR M-PLANE III-NITRIDE USING METALORGANIC CHEMICAL VAPOR DEPOSITION (MOCVD)," attorneys' docket number 30794.136-US-C1 (2005-566-3), which application is a continuation of U.S. Utility application Ser. No. 11/444,946, filed May 31, 2006, by Bilge M, Imer, James S. Speck, and Steven P. DenBaars, entitled "GROWTH OF PLANAR NON-POLAR {1-100} M-PLANE GALLIUM NITRIDE WITH METALORGANIC CHEMICAL VAPOR DEPOSITION (MOCVD)," attorneys' docket number 30794.136-US-U1 (2005-566-2), which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Application Ser. No. 60/685,908, filed on May 31, 2005, by Bilge M, Imer, James S. Speck, and Steven P. DenBaars, entitled "GROWTH OF PLANAR NON-POLAR {1-100} M-PLANE GALLIUM NITRIDE WITH METALORGANIC CHEMICAL VAPOR DEPOSITION (MOCVD)," attorneys' docket number 30794.136-US-P1 (2005-566-1);

[0018] U.S. Utility application Ser. No. 11/444,946, filed Jun. 1, 2006, 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 SEMI-POLAR (Ga, Al, In, B)N THIN FILMS, HETEROSTRUCTURES, AND DEVICES," attorneys' docket number 30794.140-US-U1 (2005-668-2), which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Application Ser. No. 60/686,244, filed on Jun. 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 SEMI-POLAR (Ga, Al, In, B)N THIN FILMS, HETEROSTRUCTURES, AND DEVICES," attorneys' docket number 30794.140-US-P1 (2005-668-1);

[0019] U.S. Utility application Ser. No. 11/251,365 filed Oct. 14, 2005, by Frederic S. Diana, Aurelien J. F. David, Pierre M. Petroff, and Claude C. A. Weisbuch, entitled "PHOTONIC STRUCTURES FOR EFFICIENT LIGHT EXTRACTION AND CONVERSION IN MULTI-COLOR LIGHT EMITTING DEVICES," attorneys' docket number 30794.142-US-01 (2005-534-1);

[0020] U.S. Utility application Ser. No. 11/633,148, filed Dec. 4, 2006, Claude C. A. Weisbuch and Shuji Nakamura, entitled "IMPROVED HORIZONTAL EMITTING, VERTICAL EMITTING, BEAM SHAPED, DISTRIBUTED FEEDBACK (DFB) LASERS FABRICATED BY GROWTH OVER A PATTERNED SUBSTRATE WITH MULTIPLE OVERGROWTH," attorneys' docket number 30794.143-US-U1 (2005-721-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/741,935, filed Dec. 2, 2005, Claude C. A. Weisbuch and Shuji Nakamura, entitled "IMPROVED HORIZONTAL EMITTING, VERTICAL EMITTING, BEAM SHAPED, DFB LASERS FABRICATED BY GROWTH OVER PATTERNED SUBSTRATE WITH MULTIPLE OVERGROWTH," attorneys' docket number 30794.143-US-P1 (2005-721-1);

[0021] U.S. Utility application Ser. No. 11/517,797, filed Sep. 8, 2006, by Michael Iza, Troy J. Baker, Benjamin A. Haskell, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR ENHANCING GROWTH OF SEMI-POLAR (Al, In, Ga, B)N VIA METALORGANIC CHEMICAL

VAPOR DEPOSITION," attorneys' docket number 30794.144-US-U1 (2005-722-2), which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Application Ser. No. 60/715,491, filed on Sep. 9, 2005, by Michael Iza, Troy J. Baker, Benjamin A. Haskell, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR ENHANCING GROWTH OF SEMI-POLAR (Al, In, Ga, B)N VIA METALORGANIC CHEMICAL VAPOR DEPOSITION," attorneys' docket number 30794.144-US-U1 (2005-722-1);

[0022] U.S. Utility application Ser. No. 11/593,268, filed on Nov. 6, 2006, by Steven P. DenBaars, Shuji Nakamura, Hisashi Masui, Natalie N. Fellows, and Akihiko Murai, entitled "HIGH LIGHT EXTRACTION EFFICIENCY LIGHT EMITTING DIODE (LED)," attorneys' docket number 30794.161-US-U1 (2006-271-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/734,040, filed on Nov. 4, 2005, by Steven P. DenBaars, Shuji Nakamura, Hisashi Masui, Natalie N. Fellows, and Akihiko Murai, entitled "HIGH LIGHT EXTRACTION EFFICIENCY LIGHT EMITTING DIODE (LED)," attorneys' docket number 30794.161-US-P1 (2006-271-1);

[0023] U.S. Utility application Ser. No. 11/608,439, filed on Dec. 8, 2006, by Steven P. DenBaars, Shuji Nakamura and James S. Speck, entitled "HIGH EFFICIENCY LIGHT EMITTING DIODE (LED)," attorneys' docket number 30794.164-US-U1 (2006-318-3), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/748,480, filed on Dec. 8, 2005, by Steven P. DenBaars, Shuji Nakamura and James S. Speck, entitled "HIGH EFFICIENCY LIGHT EMITTING DIODE (LED)," attorneys' docket number 30794.164-US-P1 (2006-318-1), and U.S. Provisional Application Ser. No. 60/764,975, filed on Feb. 3, 2006, by Steven P. DenBaars, Shuji Nakamura and James S. Speck, entitled "HIGH EFFICIENCY LIGHT EMITTING DIODE (LED)," attorneys' docket number 30794.164-US-P2 (2006-318-2);

[0024] U.S. Utility application Ser. No. 11/676,999, filed on Feb. 20, 2007, by Hong Zhong, John F. Kaeding, Rajat Sharma, James S. Speck, Steven P. DenBaars and Shuji Nakamura, entitled "METHOD FOR GROWTH OF SEMI-POLAR (Al,In,Ga,B)N OPTOELECTRONIC DEVICES," attorneys' docket number 30794.173-US-U1 (2006-422-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Application Ser. No. 60/774,467, filed on Feb. 17, 2006, by Hong Zhong, John F. Kaeding, Rajat Sharma, James S. Speck, Steven P. DenBaars and Shuji Nakamura, entitled "METHOD FOR GROWTH OF SEMI-POLAR (Al,In,Ga,B)N OPTOELECTRONIC DEVICES," attorneys' docket number 30794.173-US-P1 (2006-422-1);

[0025] U.S. Utility patent application Ser. No. 11/840,057, filed on Aug. 16, 2007, by Michael Iza, Hitoshi Sato, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR DEPOSITION OF MAGNESIUM DOPED (Al, In, Ga, B)N LAYERS," attorney's docket number 30794.187-US-U1 (2006-678-2), which claims the benefit under 35 U.S.C. 119 (e) of U.S. Provisional Patent Application Ser. No. 60/822,600, filed on Aug. 16, 2006, by Michael Iza, Hitoshi Sato, Steven P. DenBaars, and Shuji Nakamura, entitled "METHOD FOR DEPOSITION OF MAGNESIUM DOPED (Al, In, Ga, B)N LAYERS," attorney's docket number 30794.187-US-P1 (2006-678-1);

[0026] U.S. Utility patent application Ser. No. 11/940,848, filed on Nov. 15, 2007, by Aurelien J. F. David, Claude C. A. Weisbuch and Steven P. DenBaars entitled "HIGH LIGHT EXTRACTION EFFICIENCY LIGHT EMITTING DIODE (LED) THROUGH MULTIPLE EXTRACTORS," attorney's docket number 30794.191-US-U1 (2007-047-3), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,014, filed on Nov. 15, 2006, by Aurelien J. F. David, Claude C. A. Weisbuch and Steven P. DenBaars entitled "HIGH LIGHT EXTRACTION EFFICIENCY LIGHT EMITTING DIODE (LED) THROUGH MULTIPLE EXTRACTORS," attorney's docket number 30794.191-US-P1 (2007-047-1), and U.S. Provisional Patent Application Ser. No. 60/883,977, filed on Jan. 8, 2007, by Aurelien J. F. David, Claude C. A. Weisbuch and Steven P. DenBaars entitled "HIGH LIGHT EXTRACTION EFFICIENCY LIGHT EMITTING DIODE (LED) THROUGH MULTIPLE EXTRACTORS," attorney's docket number 30794.191-US-P2 (2007-047-2);

[0027] U.S. Utility patent application Ser. No. 11/940,853, filed on Nov. 15, 2007, by Claude C. A. Weisbuch, James S. Speck and Steven P. DenBaars entitled "HIGH EFFICIENCY WHITE, SINGLE OR MULTI-COLOUR LIGHT EMITTING DIODES (LEDS) BY INDEX MATCHING STRUCTURES," attorney's docket number 30794.196-US-U1 (2007-114-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,026, filed on Nov. 15, 2006, by Claude C. A. Weisbuch, James S. Speck and Steven P. DenBaars entitled "HIGH EFFICIENCY WHITE, SINGLE OR MULTI-COLOUR LED BY INDEX MATCHING STRUCTURES," attorney's docket number 30794.196-US-P1 (2007-114-1);

[0028] U.S. Utility patent application Ser. No. 11/940,866, filed on Nov. 15, 2007, by Aurelien J. F. David, Claude C. A. Weisbuch, Steven P. DenBaars and Stacia Keller, entitled "HIGH LIGHT EXTRACTION EFFICIENCY LIGHT EMITTING DIODE (LED) WITH EMITTERS WITHIN STRUCTURED MATERIALS," attorney's docket number 30794.197-US-U1 (2007-113-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,015, filed on Nov. 15, 2006, by Aurelien J. F. David, Claude C. A. Weisbuch, Steven P. DenBaars and Stacia Keller, entitled "HIGH LIGHT EXTRACTION EFFICIENCY LED WITH EMITTERS WITHIN STRUCTURED MATERIALS," attorney's docket number 30794.197-US-P1 (2007-113-1);

[0029] U.S. Utility patent application Ser. No. 11/940,876, filed on Nov. 15, 2007, by Evelyn L. Hu, Shuji Nakamura, Yong Seok Choi, Rajat Sharma and Chiou-Fu Wang, entitled "ION BEAM TREATMENT FOR THE STRUCTURAL INTEGRITY OF AIR-GAP III-NITRIDE DEVICES PRODUCED BY PHOTOELECTROCHEMICAL (PEC) ETCHING," attorney's docket number 30794.201-US-U1 (2007-161-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,027, filed on Nov. 15, 2006, by Evelyn L. Hu, Shuji Nakamura, Yong Seok Choi, Rajat Sharma and Chiou-Fu Wang, entitled "ION BEAM TREATMENT FOR THE STRUCTURAL INTEGRITY OF AIR-GAP III-NITRIDE DEVICES PRODUCED BY PHOTOELECTROCHEMICAL (PEC) ETCHING," attorney's docket number 30794.201-US-P1 (2007-161-1);

[0030] U.S. Utility patent application Ser. No. 11/940,885, filed on Nov. 15, 2007, by Natalie N. Fellows, Steven P. DenBaars and Shuji Nakamura, entitled "TEXTURED PHOSPHOR CONVERSION LAYER LIGHT EMITTING

DIODE," attorney's docket number 30794.203-US-U1 (2007-270-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,024, filed on Nov. 15, 2006, by Natalie N. Fellows, Steven P. DenBaars and Shuji Nakamura, entitled "TEXTURED PHOSPHOR CONVERSION LAYER LIGHT EMITTING DIODE," attorney's docket number 30794.203-US-P1 (2007-270-1);

[0031] U.S. Utility patent application Ser. No. 11/940,872, filed on Nov. 15, 2007, by Steven P. DenBaars, Shuji Nakamura and Hisashi Masui, entitled "HIGH LIGHT EXTRACTION EFFICIENCY SPHERE LED," attorney's docket number 30794.204-US-U1 (2007-271-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,025, filed on Nov. 15, 2006, by Steven P. DenBaars, Shuji Nakamura and Hisashi Masui, entitled "HIGH LIGHT EXTRACTION EFFICIENCY SPHERE LED," attorney's docket number 30794.204-US-P1 (2007-271-1);

[0032] U.S. Utility patent application Ser. No. 11/940,883, filed on Nov. 15, 2007, by Shuji Nakamura and Steven P. DenBaars, entitled "STANDING TRANSPARENT MIRRORLESS LIGHT EMITTING DIODE," attorney's docket number 30794.205-US-U1 (2007-272-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,017, filed on Nov. 15, 2006, by Shuji Nakamura and Steven P. DenBaars, entitled "STANDING TRANSPARENT MIRROR-LESS (STML) LIGHT EMITTING DIODE," attorney's docket number 30794.205-US-P1 (2007-272-1); and

[0033] U.S. Utility patent application Ser. No. 11/940,898, filed on Nov. 15, 2007, by Steven P. DenBaars, Shuji Nakamura and James S. Speck, entitled "TRANSPARENT MIRRORLESS LIGHT EMITTING DIODE," attorney's docket number 30794.206-US-U1 (2007-273-2), which application claims the benefit under 35 U.S.C Section 119(e) of U.S. Provisional Patent Application Ser. No. 60/866,023, filed on Nov. 15, 2006, by Steven P. DenBaars, Shuji Nakamura and James S. Speck, entitled "TRANSPARENT MIRROR-LESS (TML) LIGHT EMITTING DIODE," attorney's docket number 30794.206-US-P1 (2007-273-1);

[0034] U.S. Utility patent application Ser. No. ______, filed on Dec. 11, 2007, by Steven P. DenBaars and Shuji Nakamura, entitled "LEAD FRAME FOR TRANSPARENT MIRRORLESS LIGHT EMITTING DIODE," attorney's docket number 30794.210-US-U1 (2007-281-2), which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Patent Application Ser. No. 60/869,454, filed on Dec. 11, 2006, by Steven P. DenBaars and Shuji Nakamura, entitled "LEAD FRAME FOR TM-LED," attorney's docket number 30794.210-US-P1 (2007-281-1);

[0035] U.S. Utility patent application Ser. No. ______, filed on Dec. 11, 2007, by Shuji Nakamura, Steven P. DenBaars, and Hirokuni Asamizu, entitled, "TRANSPARENT LIGHT EMITTING DIODES," attorney's docket number 30794.211-US-U1 (2007-282-2), which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Patent Application Ser. No. 60/869,447, filed on Dec. 11, 2006, by Shuji Nakamura, Steven P. DenBaars, and Hirokuni Asamizu, entitled, "TRANSPARENT LEDS," attorney's docket number 30794.211-US-P1 (2007-282-1);

[0036] U.S. Utility patent application Ser. No. ______, filed on Dec. 11, 2007, by Mathew C. Schmidt, Kwang Choong Kim, Hitoshi Sato, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "METALORGANIC CHEMICAL VAPOR DEPOSITION (MOCVD) GROWTH OF HIGH PERFORMANCE NON-POLAR III-NITRIDE OPTICAL DEVICES," attorney's docket number 30794.212-US-U1 (2007-316-2), which claims the benefit under 35 U.S.C. 119(e) of U.S. Provisional Patent Application Ser. No. 60/869,535, filed on Dec. 11, 2006, by Mathew C. Schmidt, Kwang Choong Kim, Hitoshi Sato, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "MOCVD GROWTH OF HIGH PERFORMANCE M-PLANE GAN OPTICAL DEVICES," attorney's docket number 30794.212-US-P1 (2007-316-1);

[0037] U.S. Utility patent application Ser. No. ______, filed on Dec. 11, 2007, by Kwang Choong Kim, Mathew C. Schmidt, Feng Wu, Asako Hirai, Melvin B. McLaurin, Steven P. DenBaars, Shuji Nakamura, and James S. Speck, entitled, "CRYSTAL GROWTH OF M-PLANE AND SEMI-POLAR PLANES OF (AL, IN, GA, B)N ON VARIOUS SUBSTRATES," attorney's docket number 30794.214-US-U1 (2007-334-2), which claims the benefit under 35 U.S.C. 119 (e) of U.S. Provisional Patent Application Ser. No. 60/869,701, filed on Dec. 12, 2006, by Kwang Choong Kim, Mathew C. Schmidt, Feng Wu, Asako Hirai, Melvin B. McLaurin, Steven P. DenBaars, Shuji Nakamura, and James S. Speck, entitled, "CRYSTAL GROWTH OF M-PLANE AND SEMI-POLAR PLANES OF (AL, IN, GA, B)N ON VARIOUS SUBSTRATES," attorney's docket number 30794.214-US-P1 (2007-334-1);

[0038] all of which applications are incorporated by reference herein.

BACKGROUND OF THE INVENTION

[0039] 1. Field of the Invention

[0040] The present invention is related to high efficiency non-polar and semi-polar light emitting devices such as light emitting diodes (LEDs) and laser diodes (LDs).

[0041] 2. Description of the Related Art

[0042] (Note: This application references a number of different publications as indicated throughout the specification. In addition, a list of a number of different publications can be found below in the section entitled "References." Each of these publications is incorporated by reference herein.)

[0043] Currently, most commercial gallium nitride (GaN) based light emitting devices are constructed on c-axis oriented crystals. As a result, strong piezo-electric fields control light emission efficiency. In the structure of conventional LEDs and LDs, the thickness of the quantum well (QW) is only around 2-5 nm. When the thickness of the QW layer becomes larger than 5 nm, the conduction energy band and valence energy band of the QW layer is bent due to a strong piezoelectric field, and then the radiative recombination efficiency becomes small, and then the emitting efficiency of the LED and LD becomes smaller.

[0044] However, in the case of non-polar or semi-polar GaN, the piezoelectric polarization is minimized. So, the energy band bending in the QW is small. It is expected that the thickness of the QW can be increased to improve the emitting efficiency of the LED and LD. Recently, the inventors of the present invention found that the thickness of the QW should be increased up to 10 nm in the case of non-polar and semi-polar LED and LD to increase the emitting efficiency.

[0045] In the case of conventional LEDs, in order to increase the light output power from the front side of the LED, the emitted light is reflected by a mirror placed on the backside of the substrate or is reflected by a mirror coating on the lead frame, even if there are no mirrors on the backside of the sapphire substrate, and if the bonding material is transparent on the emission wavelength. However, this reflected light is re-absorbed by the emitting layer (active layer), because the photon energy is almost same as the band-gap energy of the light emitting species, such as AlInGaN multiple quantum wells (MQWs). The efficiency or output power of the LEDs is decreased due to this re-absorption of the LED light by the emitting layer. See, for example, FIGS. **1**, **2** and **3**, which are described in more detail below. See also J. J. Appl. Phys. 34, L797-99 (1995) and J. J. Appl. Phys. 43, L180-82 (2004).

[0046] What is needed in the art are LED and LD structures that generate light more efficiently in the blue, green, amber, and red regions and that more effectively extract light. The present invention satisfies that need.

SUMMARY OF THE INVENTION

[0047] The present invention describes an (Al, Ga, In)N light emitting device in which high light generation efficiency is realized by fabricating the device of novel non-polar or semi-polar GaN crystal geometries. Because non-polar and semi-polar devices have significantly lower piezoelectric effects than polar devices, higher efficiency LEDs and LDs can be realized.

[0048] The devices of the present invention can have greater QW thickness, namely greater than 4 nm, preferably from approximately 8-12 μm, and more preferably approximately 10 nm. Through the use of thicker quantum wells in non-polar and semi-polar LEDs, higher efficiencies at higher current densities are achieved. For LDs, the thicker QWs result in increased modal gain, and decreased threshold current density. In another instance, a larger number of QWs can be used to increase efficiency without suffering from higher voltages.

[0049] By fabricating the non-polar and semi-polar LEDs with a transparent contact layer, nearly ideal light extraction is realized, even at high current density.

[0050] An additional benefit is the fact that the non-polar and semi-polar LEDs generate polarized light much more effectively than c-plane devices. Polarized light emission ratios as high as 0.83 have been observed, making them useful for numerous applications, such as LCD back-lighting, signs, protection displays, and illumination.

[0051] The present invention also minimizes internal reflections within the LED by eliminating mirrors and/or mirrored surfaces, in order to minimize re-absorption of light by the emitting or active layer of the LED. To assist in minimizing internal reflections, transparent electrodes, such as ITO or ZnO, may be used.

[0052] Surface roughening, texturing, patterning or shaping, for example, by means of anisotropically etching (i.e., creating a cone shaped surface) or otherwise, may also assist in light extraction, as well as minimizing internal reflections. Die shaping also realizes higher light extraction efficiencies.

BRIEF DESCRIPTION OF THE DRAWINGS

[0053] Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

[0054] FIG. **1** is a schematic of a hexagonal würtzite crystal structure of gallium nitride.

[0055] FIG. **2** is another schematic of the crystalline structure of gallium nitride.

[0056] FIGS. **3**A, **3**B, **3**C and **3**D illustrate the motivation behind using non-polar of gallium nitride planes for device structures and growth.

[0057] FIG. **4** is a schematic of a device structure according to the present invention.

[0058] FIGS. **5**A, **5**B and **5**C illustrate the External Quantum Efficiency (EQE) versus Peak Wavelength (nm) for various polar and non-polar gallium nitride devices.

[0059] FIG. **6** illustrates the Power Output and External Quantum Efficiency (EQE) vs. Current (mA) for a device manufactured in accordance with the present invention.

[0060] FIG. **7** illustrates the Intensity (arbitrary units) vs. Polarizer Angle (degrees) for polarized light of non-polar (or semi-polar) and polar light emitting diodes.

[0061] FIG. **8** illustrates additional device structures and additional advantages associated with the present invention.

[0062] FIGS. **9**A and **9**B illustrate the structure of c-plane light emitting diodes, which are typically grown along the c-axis.

[0063] FIG. **10** is a schematic illustrating a side-emitting m-plane light emitting diode in accordance with the present invention.

[0064] FIG. **11** is a schematic illustrates an vertical top-emitting m-plane light emitting diode in accordance with the present invention.

[0065] FIG. **12** is a schematic illustrating a top view of a side-emitting m-plane light emitting diode in accordance with the present invention.

[0066] FIG. **13** is a schematic illustrating a side-emitting m-plane light emitting diode in accordance with the present invention.

[0067] FIG. **14** is a schematic illustrating a shaped m-plane light emitting diode in accordance with the present invention.

[0068] FIG. **15** is a schematic that illustrates a non-polar light emitting diode with multiple emitting layers that emits white light in accordance with the present invention.

[0069] FIG. **16** is a graph that illustrates External Quantum Efficiency (EQE) percentage measurements vs. Current (mA) of the non-polar light emitting diodes of the present invention.

[0070] FIG. **17** is a graph that illustrates Quick Test Power (mV) vs. Current (mA) of the non-polar light emitting diodes of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0071] 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.

[0072] Overview

[0073] 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.

[0074] FIG. **1** is a schematic of a hexagonal würtzite crystal structure **100** of GaN that illustrates the major planes of interest, namely the a-plane {11-20} **102**, m-plane {1-100} **104**, r-plane {10-12} **106**, c-plane [0001] **108**, with these axes a**1** [1000] **110**, a**2** [0100] **112**, and a**3** [0010], along with the c-axis **116**, identified therein, wherein the fill patterns are intended to illustrate the planes of interest **102**, **104** and **106**, but do not represent the materials of the structure **100**.

[0075] FIG. **2** is another schematic of the crystalline structure **200** of GaN, illustrating the placement of Ga atoms **202** and N atoms **204**, and showing a semi-polar plane (**10-11**) **206**, which is shown as the shaded plane in the crystalline structure. The group III atoms **202** and nitrogen atoms **204** occupy alternating c-planes along the c-axis of the crystal **200**. The symmetry elements included in the würtzite structure **200** dictate that III-nitrides possess a bulk spontaneous polarization along this c-axis. Furthermore, as the würtzite crystal structure **200** is non-centro-symmetric, würtzite nitrides can and do additionally exhibit piezoelectric polarization, also along the c-axis.

[0076] 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.

[0077] FIGS. **3**A, **3**B, **3**C and **3**D illustrate the motivation behind using non-polar GaN planes for device structures and growth.

[0078] FIG. **3**A illustrates the spontaneous polarization (P_{SP}) and piezoelectric polarization (P_{PE}) effects in c-plane (Ga face) structures, wherein ⊕ indicates a positive charge, ⊙ indicates a negative charge, the arrows represent the direction of polarization, and $-\sigma_1$, $+\sigma_2$, $-\sigma_2$, and $-\sigma_1$, represent energy band inflection points for the GaN (p-type and n-type) and InGaN (active) layers. FIG. **3**B illustrates the energy band diagram corresponding to FIG. **3**A for the valence band (Ev) and conduction band (Ec).

[0079] FIG. **3**C illustrates the lack of spontaneous polarization (P_{SP}) and piezoelectric polarization (P_{PE}) effects in non-polar (a-plane) structures. FIG. **3**D illustrates the energy band diagram corresponding to FIG. **3**C for the valence band (Ev) and conduction band (Ec).

[0080] When using certain planes of the GaN structure, polarization and piezoelectric polarization cause band bending and charge separation, which leads to a light emission red shift, a low recombination efficiency, and a high threshold current, all of which create problems in finished devices. This is especially apparent in the c-plane (Ga face) where the Ev and Ec bands are shown as very disjointed.

[0081] FIG. **4** is a schematic of a device structure according to the present invention, that further illustrates the motivation behind using non-polar III-nitride layers, which may comprise m-plane or a-plane III-nitride layers. In this figure, a non-polar III-nitride light emitting device comprises a laser diode (LD) structure **400**, which includes a Ti—Al contact layer **402**, a-plane n-GaN layer **404**, n-AlGaN cladding layer **406**, n-GaN guiding layer **408**, GaN active layer **410**, p-GaN guiding layer **412**, GaN active layer **414**, p-AlGaN cladding layer **416**, p-GaN layer **418** and Ni—Au contact layer **420**. When a-plane and m-plane growth is achieved, lower dislocation densities are achieved. Further, no polarization field-induced charge separation in the quantum wells occurs, and there is higher mobility in the layers. This results in a lower threshold current, and higher reliability for the finished devices.

[0082] FIGS. **5**A, **5**B and **5**C illustrate the External Quantum Efficiency (EQE) versus Peak Wavelength (nm) for various polar and non-polar GaN devices. The polarization fields in the quantum well region discussed above creates a “gap” in emission in the green region of the visible spectrum, as well as in the ultraviolet region. By using non-polar (m-plane or a-plane) devices, rather than polar c-plane devices, or by using semi-polar device structures, the polarization fields in the quantum well region are reduced or eliminated, which can solve the emission gap problem.

[0083] FIG. **6** illustrates the Power Output and External Quantum Efficiency (EQE) vs. Current (mA) for a device manufactured in accordance with the present invention. The EQE is a figure of merit for these devices. Further, a 25 milliwatt (mW) device is shown at a 20 milliamp (mA) current input. This result far exceeds any results seen by any non-polar LED device to date.

[0084] FIG. **7** illustrates the Intensity (arbitrary units) vs. Polarizer Angle (degrees) for polarized light of non-polar (or semi-polar) and polar LEDs. Further, non-polar and semi-polar LEDs made in accordance with the present invention directly emit polarized light. This is useful for many applications, such as Liquid Crystal Display (LCD) back-lighting, which requires polarized light. With the devices of the present invention, a polarizing filter is not required between the light source and the LCD display, because the light being emitted is already polarized.

[0085] FIG. **8** illustrates additional device structures and additional advantages associated with the present invention. For example, the non-polar or semi-polar devices manufactured according to the present invention can be used for LCD back-lighting, because these devices reduce or eliminate built-in polarization fields. A structure for LCD back-lighting includes a light source **800**, polarizer **802**, alignment film **804**, liquid crystals **806**, alignment film **808**, polarizer **810**, which when activated by an AC voltage source **812** results in light output **814**. Moreover, the devices provide a p-type concentration of approximately 7×10^{18} cm^{-3} with minimal LED peak wavelength shift vs. current. In addition, as discussed with respect to FIG. **7**, since the non-polar (e.g., m-plane or a-plane) or semi-polar LEDs directly emit polarized light, more light **814** is available for the LCD displays. Typically, an additional percentage of light **814** is available, and such percentage has been observed to be approximately 40-70% additional light is available. However, a larger or smaller percentage of light may be available without departing from the scope of the present invention.

[0086] FIGS. **9**A and **9**B illustrate the structure of c-plane LEDs, which are typically grown along the c-axis. In FIG. **9**A, the c-plane LED **900** includes a substrate **902**, p-type layer **904**, active layer **906**, n-type layer **908**, electrode **910**, bonding pad **912** and electrode **914**. FIG. **9**B shows a similar c-plane LED **916**, wherein the emitting surface is typically on the nitrogen face (N face), which can be roughened **918** or otherwise treated to increase light production from such devices.

[0087] FIG. **10** is a schematic illustrating a non-polar III-nitride light emitting device having a plurality of non-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers in accordance with the present invention. In this embodiment, the device is a side-emitting m-plane LED **1000**, which includes a metal lead frame **1002**, an ensemble **1004** of p-GaN/GaN/n-GaN layers that emit light **1006**, transparent electrode layers **1008**, **1010** and p-contact **1012**. One or more emitting surfaces of the device **1000** may be a roughened, textured, patterned or shaped surface **1012** to enhance the extraction of light (e.g., the emitting surface of the device **1000** may be a cone shaped surface). Further, the device **1000** comprises a side-emitting device, with appropriate placement of the contact **1012** and metal frame **1002** shown.

[0088] FIG. **11** is a schematic illustrating another non-polar III-nitride light emitting device having a plurality of non-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers in accordance with the present invention. In this embodiment, the device is a vertical top-emitting m-plane LED **1100**, which includes a substrate **1102**, an ensemble **1104** of p-GaN/GaN/n-GaN layers that emit light, a top transparent layer **1006**, as well as p-contact **1008** and n-contact **1010**. In this embodiment, the ensemble **1104** includes an active region **1112** that comprises one or more QWs having a thickness greater than 4 nm, preferably a thickness of approximately 8-12 nm, and more preferably a thickness of approximately 10 nm.

[0089] FIG. **12** is a schematic illustrating another non-polar III-nitride light emitting device having a plurality of non-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers in accordance with the present invention. In this embodiment, the device is a top view of a side-emitting m-plane LED **1200**, which includes a p-type electrode layer **1202**, a metal p-type bonding pad **1204**, and a roughened, textured, patterned or shaped surface **1206** to enhance the extraction of light **1208**.

[0090] The p-type electrode layer **1202** is an electrically conductive transparent layer that may be roughened, textured, patterned or shaped. The p-type electrode layer **1202** is typically an ITO or ZnO layer, but can be other transparent metal oxides or other conductive materials which are substantially or completely transparent at the wavelengths of interest. The p-type electrode layer **1202** is formed adjacent the ensemble of non-polar III-nitride layers and covers substantially the entire top of the die. A current spreading layer may deposited before the p-type electrode layer **1202**, and a metal bonding pad **1204** is deposited on the p-type electrode layer **1202** and occupies a small portion of the p-type electrode layer **1202**. The bulk of the emissions **1208** emanate from the side of the device **1200**, although some emissions may exit through the p-type electrode layer **1202** as well.

[0091] FIG. **13** is a schematic illustrating another non-polar III-nitride light emitting device having a plurality of non-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers in accordance with the present invention. In this embodiment, the device is a side-emitting m-plane LED **1300**, which includes a transparent conducting mount **1302**, an ensemble **1304** of p-GaN/GaN/n-GaN layers that emit light, transparent electrode layers **1306**, **1308** and p-contact **1310**. This device **1300** also includes a roughened, textured, patterned or shaped surface **1312** to enhance the extraction of light **1314**. Further, the device **1300** comprises a side-emitting device, with appropriate placement of contacts **1306**, **1308**. The device **1300** may be placed on a transparent mounting structure **1302**, which is substantially or completely transparent at the wavelengths of interest, and is comprised of glass, epoxy, plastics, or other transparent materials.

[0092] FIG. **14** is a schematic illustrating another non-polar III-nitride light emitting device having a plurality of non-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers in accordance with the present invention. In this embodiment, the device is a shaped m-plane LED **1400**, which includes a transparent lead frame (not shown), an ensemble **1402** of p-GaN/GaN/n-GaN layers that emit light, transparent electrode layer **1404** and p-contact **1406**. Moreover, more than one emitting surface **1408**, **1410**, and **1412** of the device **1400** is roughened, textured, patterned or shaped to enhance the extraction of light **1414** from multiple facets of the device **1400** (although extraction from surface **1408** is the only one shown in FIG. **14**).

[0093] FIG. **15** is a schematic illustrating another non-polar III-nitride light emitting device having a plurality of non-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers in accordance with the present invention. In this embodiment, the device is a non-polar LED **1500** with multiple emitting layers that emit white light. The non-polar LED **1500** includes an ensemble **1502** of p-GaN/GaN/n-GaN layers that emit light, transparent layers **1504**, **1506**, as well as p-contact **15008**. In this embodiment, the ensemble **1502** includes an active region **1510**, which can be a QW well layer if desired, comprised of multiple emitting layers emitting light at more than one wavelength. For example, the active region **1510** preferably emits at red, green, and blue wavelengths, which when combined, creates white light (or any other color of light). This is now possible because of the lack of interfering field-induced charge separations that are present in c-plane devices.

[0094] FIG. **16** is a graph that illustrates EQE percentage measurements vs. Current (mA) of the non-polar LEDs of the present invention. As seen, the non-polar LEDs of the present invention have a flattened EQE once the forward current reaches a threshold.

[0095] FIG. **17** is a graph that illustrates Quick Test Power (mV) vs. Current (mA) of the non-polar LEDs of the present invention. The power output shown is linear with respect to current input for m-plane LEDs of the present invention.

REFERENCES

[0096] The following references are incorporated by reference herein:

[0097] 1. Appl. Phys. Lett. 56, 737-39 (1990).

[0098] 2. Appl. Phys. Lett. 64, 2839-41 (1994).

[0099] 3. Appl. Phys. Lett. 81, 3152-54 (2002).

[0100] 4. Jpn. J. Appl. Phys., 43, L1275-77 (2004).

[0101] 5. Jpn. J. Appl. Phys., 45, L1084-L1086 (2006).

[0102] 6. Jpn. J. Appl. Phys., 34, L797-99 (1995).

[0103] 7. Jpn. J. Appl. Phys., 43, L180-82 (2004).

[0104] 8. Fujii T., Gao Y., Sharma R., Hu E. L., DenBaars S. P., Nakamura S., "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening," Appl. Phys. Lett., vol. 84, no. 6, 9 Febuary 2004, pp. 855-7.

CONCLUSION

[0105] Although discussed primarily with respect to m-plane gallium nitride, other non-polar and semi-polar geometries of gallium nitride and other related material systems can benefit from the present invention. Further, other materials that are used for other electronic devices or similar electronic devices, can also benefit from the present invention, such as Laser Diodes (LDs), High Electron Mobility Transistors (HEMTs), Vertical Cavity Side Emitting Lasers (VCSELs), solar cells, transistors, diodes, other emitting devices, and other devices fabricated using semiconductor processing techniques.

[0106] 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.

What is claimed is:

1. A non-polar or semi-polar III-nitride light emitting device, comprising:

a plurality of non-polar or semi-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers, wherein the active region includes one or more quantum wells having a thickness greater than 4 nanometers.

2. The device of claim **1**, wherein the quantum wells have a thickness of approximately 8-12 nanometers.

3. The device of claim **1**, wherein the quantum wells have a thickness of approximately 10 nanometers.

4. The device of claim **1**, wherein the non-polar III-nitride layers comprise m-plane or a-plane III-nitride layers.

5. The device of claim **1**, wherein one or more emitting surfaces of the device is roughened, textured, patterned or shaped.

6. The device of claim **5**, wherein more than one emitting surface of the device is roughened, textured, patterned or shaped.

7. The device of claim **5**, wherein the emitting surface of the device is a cone shaped surface.

8. The device of claim **1**, wherein the active region is comprised of multiple emitting layers emitting light at more than one wavelength.

9. The device of claim **1**, further comprising a transparent electrode layer is formed adjacent the non-polar or semi-polar III-nitride layers.

10. The device of claim **9**, wherein the transparent electrode layer is an electrically conductive contact layer.

11. The device of claim **9**, wherein a surface of the transparent layer is roughened, textured, patterned or shaped.

12. The device of claim **9**, wherein a current spreading layer is deposited before the transparent electrode layer.

13. The device of claim **1**, wherein the device is placed on a transparent mounting structure.

14. A method of fabricating a non-polar or semi-polar III-nitride light emitting device, comprising:

forming a plurality of non-polar or semi-polar III-nitride layers comprising one or more p-type layers, an active region, and one or more n-type layers, wherein the active region includes one or more quantum wells having a thickness greater than 4 nanometers.

15. The method of claim **14**, wherein the quantum wells have a thickness of approximately 8-12 nanometers.

16. The method of claim **14**, wherein the quantum wells have a thickness of approximately 10 nanometers.

17. The method of claim **14**, wherein the non-polar III-nitride layers comprise m-plane or a-plane III-nitride layers.

18. The method of claim **14**, wherein one or more emitting surfaces of the device is roughened, textured, patterned or shaped.

19. The method of claim **18**, wherein more than one emitting surface of the device is roughened, textured, patterned or shaped.

20. The method of claim **18**, wherein the emitting surface of the device is a cone shaped surface.

21. The method of claim **14**, wherein the active region is comprised of multiple emitting layers emitting light at more than one wavelength.

22. The method of claim **14**, further comprising forming a transparent electrode layer adjacent the non-polar or semi-polar III-nitride layers.

23. The method of claim **22**, wherein the transparent electrode layer is an electrically conductive contact layer.

24. The method of claim **22**, wherein a surface of the transparent layer is roughened, textured, patterned or shaped.

25. The method of claim **22**, wherein a current spreading layer is deposited before the transparent electrode layer.

26. The method of claim **14**, wherein the device is placed on a transparent mounting structure.

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