



US00923117B2

(12) **United States Patent**
Shatalov et al.

(10) **Patent No.:** **US 9,923,117 B2**
(45) **Date of Patent:** ***Mar. 20, 2018**

(54) **SEMICONDUCTOR STRUCTURE WITH INHOMOGENEOUS REGIONS**

(71) Applicant: **Sensor Electronic Technology, Inc.**,
Columbia, SC (US)

(72) Inventors: **Maxim S. Shatalov**, Columbia, SC (US); **Alexander Dobrinsky**, Loudonville, NY (US); **Alexander Lunev**, Columbia, SC (US); **Rakesh Jain**, Columbia, SC (US); **Jinwei Yang**, Columbia, SC (US); **Michael Shur**, Latham, NY (US); **Remigijus Gaska**, Columbia, SC (US)

(73) Assignee: **Sensor Electronic Technology, Inc.**,
Columbia, SC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/984,156**

(22) Filed: **Dec. 30, 2015**

(65) **Prior Publication Data**

US 2016/0118536 A1 Apr. 28, 2016

Related U.S. Application Data

(63) Continuation-in-part of application No. 14/189,012, filed on Feb. 25, 2014, now Pat. No. 9,331,244.
(Continued)

(51) **Int. Cl.**
H01L 33/32 (2010.01)
H01L 33/10 (2010.01)
(Continued)

(52) **U.S. Cl.**
CPC **H01L 33/10** (2013.01); **H01L 33/007** (2013.01); **H01L 33/32** (2013.01); **H01L 33/12** (2013.01); **H01L 33/46** (2013.01)

(58) **Field of Classification Search**
CPC H01L 33/10; H01L 33/007; H01L 33/32
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,602,418 A 2/1997 Imai et al.
7,812,366 B1 10/2010 Sampath et al.
(Continued)

FOREIGN PATENT DOCUMENTS

WO 2013023197 A2 2/2013

OTHER PUBLICATIONS

Shatalov, M. et al., "AlGaIn Deep-Ultraviolet Light-Emitting Diodes with External Quantum Efficiency above 10%," Applied Physics Express, Jul. 2012, 3 pages, vol. 5, No. 8.
(Continued)

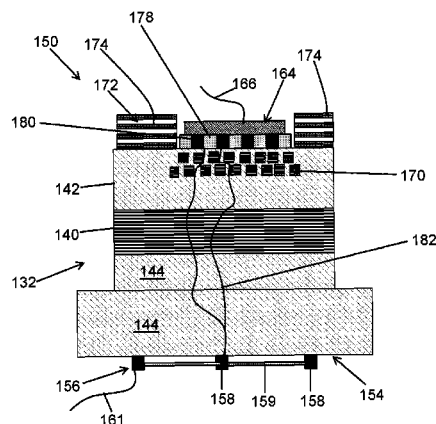
Primary Examiner — Fazli Erdem

(74) *Attorney, Agent, or Firm* — LaBatt, LLC

(57) **ABSTRACT**

A semiconductor layer including a plurality of inhomogeneous regions is provided. Each inhomogeneous region has one or more attributes that differ from a material forming the semiconductor layer. The inhomogeneous regions can include one or more regions configured based on radiation having a target wavelength. These regions can include transparent and/or reflective regions. The inhomogeneous regions also can include one or more regions having a higher conductivity than a conductivity of the radiation-based regions, e.g., at least ten percent higher. In one embodiment, the semiconductor layer is used to form an optoelectronic device.

20 Claims, 15 Drawing Sheets



Related U.S. Application Data

(60) Provisional application No. 61/768,581, filed on Feb. 25, 2013.

(51) **Int. Cl.**

H01L 33/00 (2010.01)
H01L 33/12 (2010.01)
H01L 33/46 (2010.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

9,331,244 B2 *	5/2016	Shatalov	.....	H01L 33/32
2004/0031956 A1 *	2/2004	Saxler	.....	H01L 21/02378
				257/14
2009/0272993 A1	11/2009	Cheong		
2013/0146907 A1	6/2013	Lunev et al.		
2013/0270514 A1 *	10/2013	Saxler	.....	H01L 33/08
				257/13
2013/0320352 A1	12/2013	Gaevski et al.		
2014/0016660 A1	1/2014	Lunev et al.		
2014/0110754 A1 *	4/2014	Jain	.....	H01L 21/0237
				257/190
2014/0134773 A1 *	5/2014	Jain	.....	H01L 33/32
				438/44

2015/0243840 A1	8/2015	Johnston et al.		
2015/0372193 A1 *	12/2015	Jain	.....	H01L 33/32
				257/98

2016/0118536 A1	4/2016	Shatalov et al.		
2016/0197228 A1	7/2016	Shatalov et al.		
2016/0336483 A1 *	11/2016	Shatalov	.....	H01L 33/10

OTHER PUBLICATIONS

White, S., U.S. Appl. No. 14/189,012, Notice of Allowance, dated Sep. 30, 2015, 8 pages.

White, S., U.S. Appl. No. 14/189,012, Ex Parte Quayle, Sep. 24, 2015, 17 pages.

Erdem, F., U.S. Appl. No. 15/225,403, Office Action1, dated Apr. 5, 2017, 14 pages.

Tran, M., U.S. Appl. No. 15/069,178, Office Action1, dated Aug. 1, 2017, 18 pages.

Erdem, F., U.S. Appl. No. 15/225,403, Final Office Action1, dated Sep. 27, 2017, 15 pages.

Tran, M., U.S. Appl. No. 15/069,178, Notice of Allowance, dated Oct. 26, 2017, 12 pages.

Erdem, F., U.S. Appl. No. 15/225,403, Notice of Allowance, dated Oct. 30, 2017, 10 pages.

* cited by examiner

FIG. 1

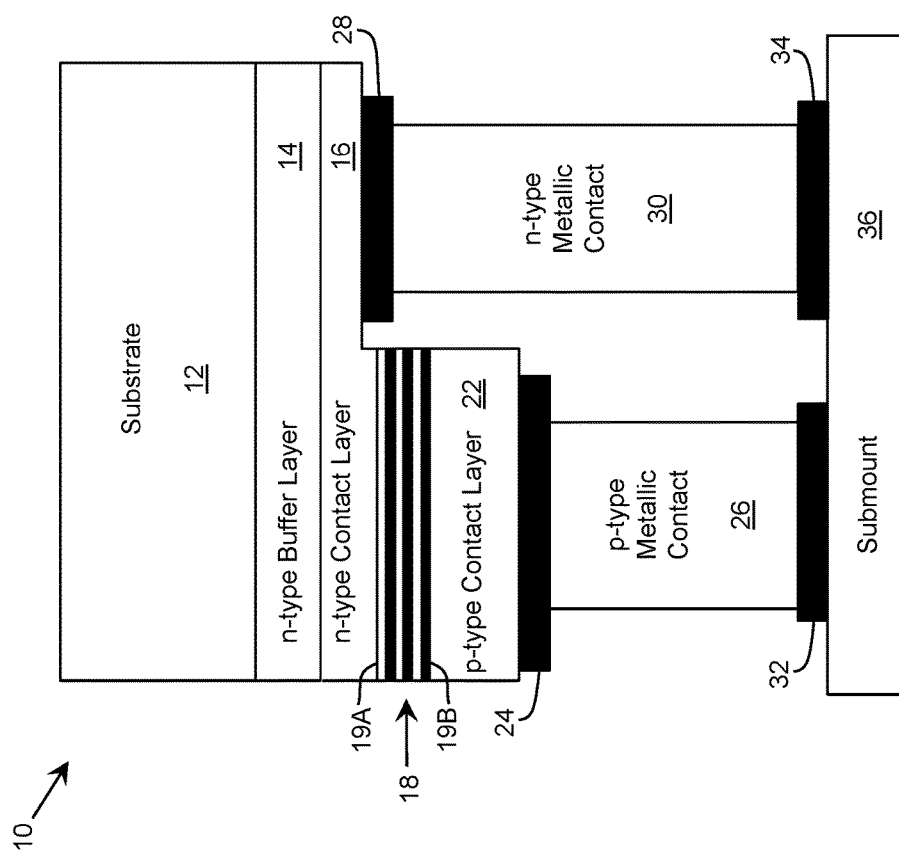


FIG. 2

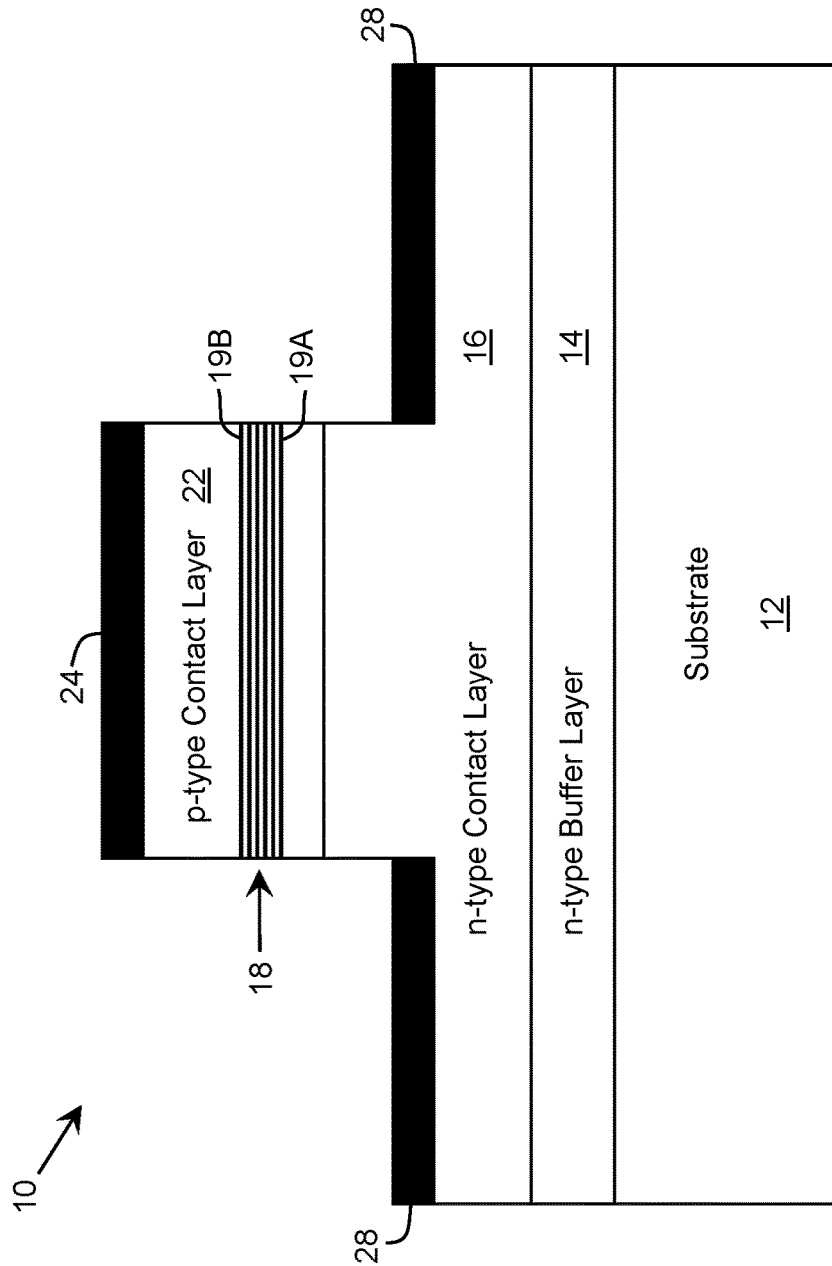


FIG. 3A

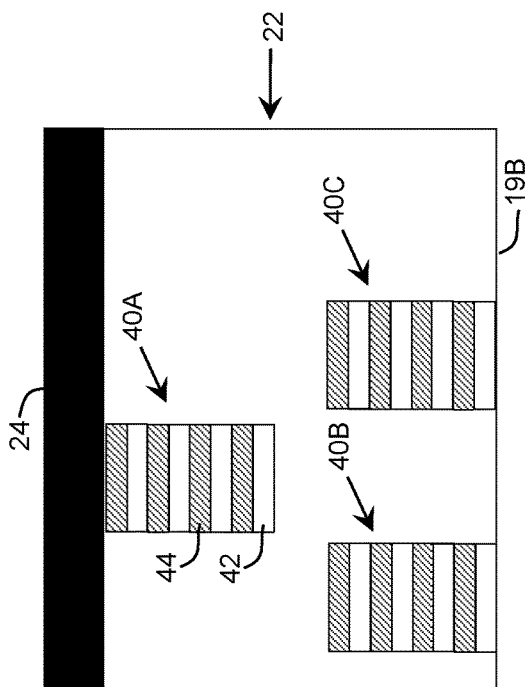


FIG. 3B

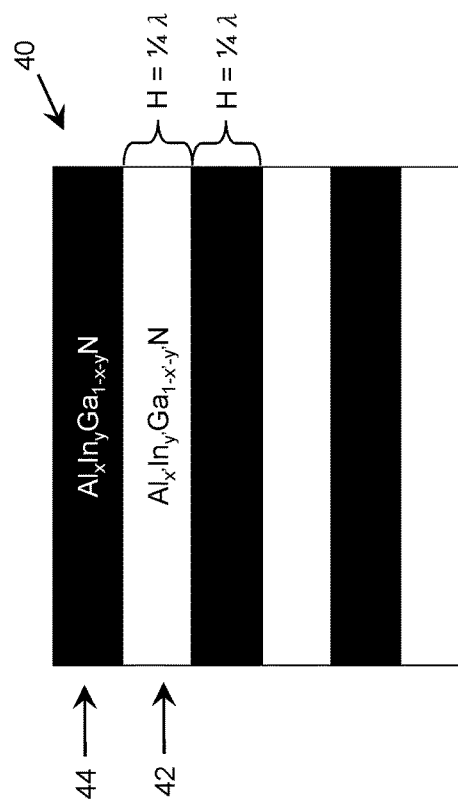


FIG. 4

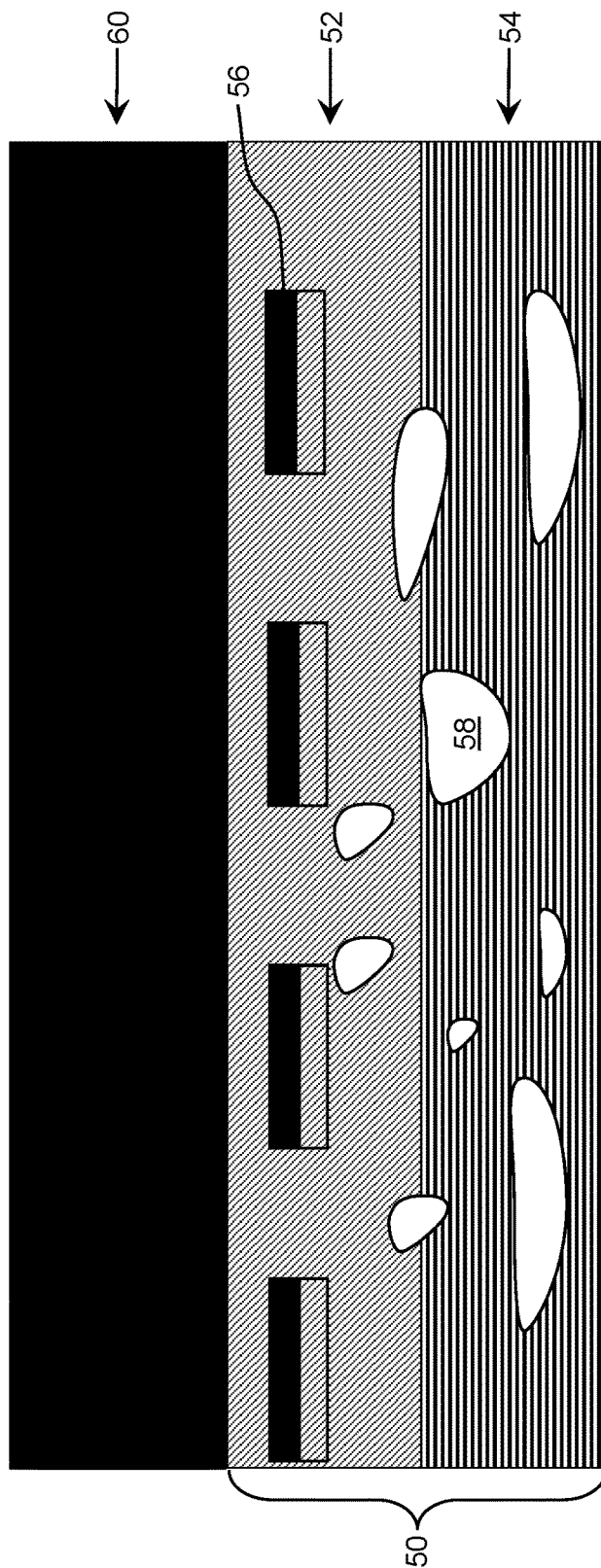


FIG. 5

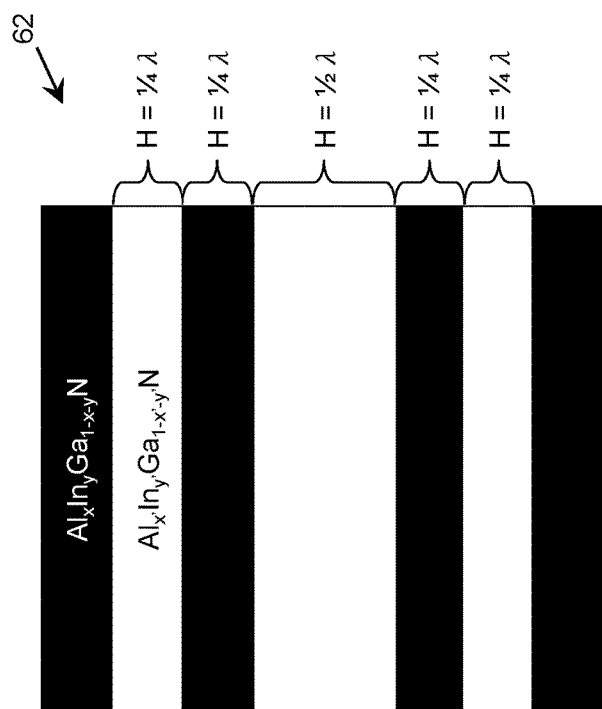


FIG. 6

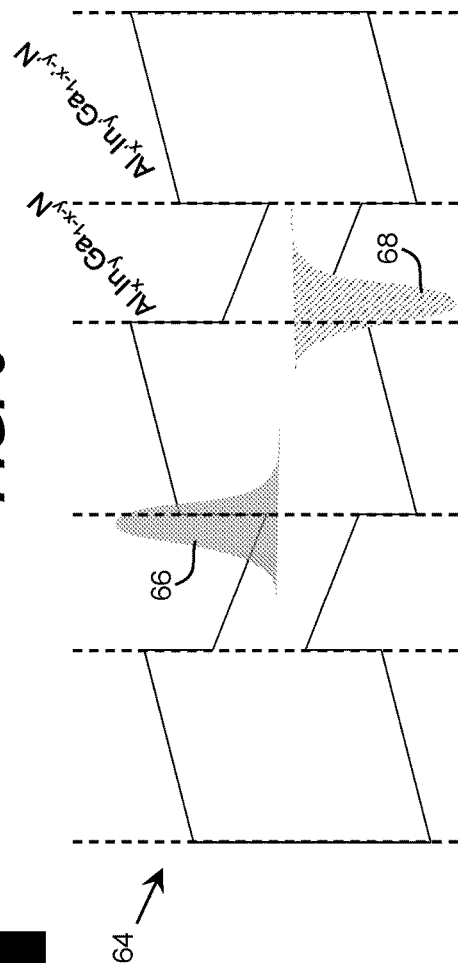


FIG. 7A

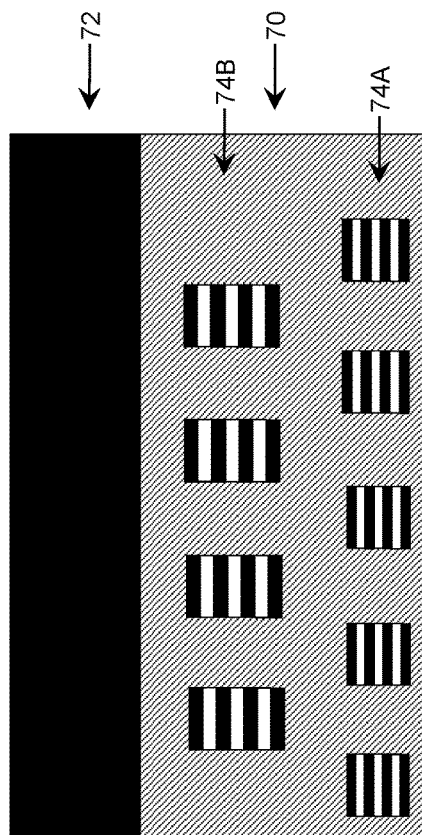


FIG. 7B

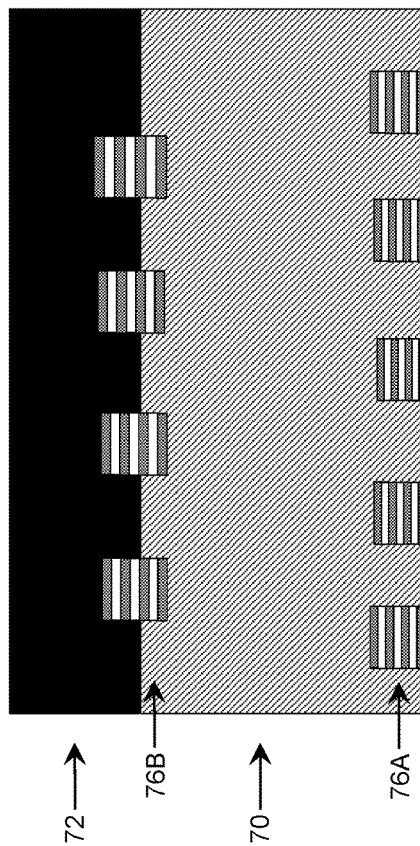


FIG. 7C

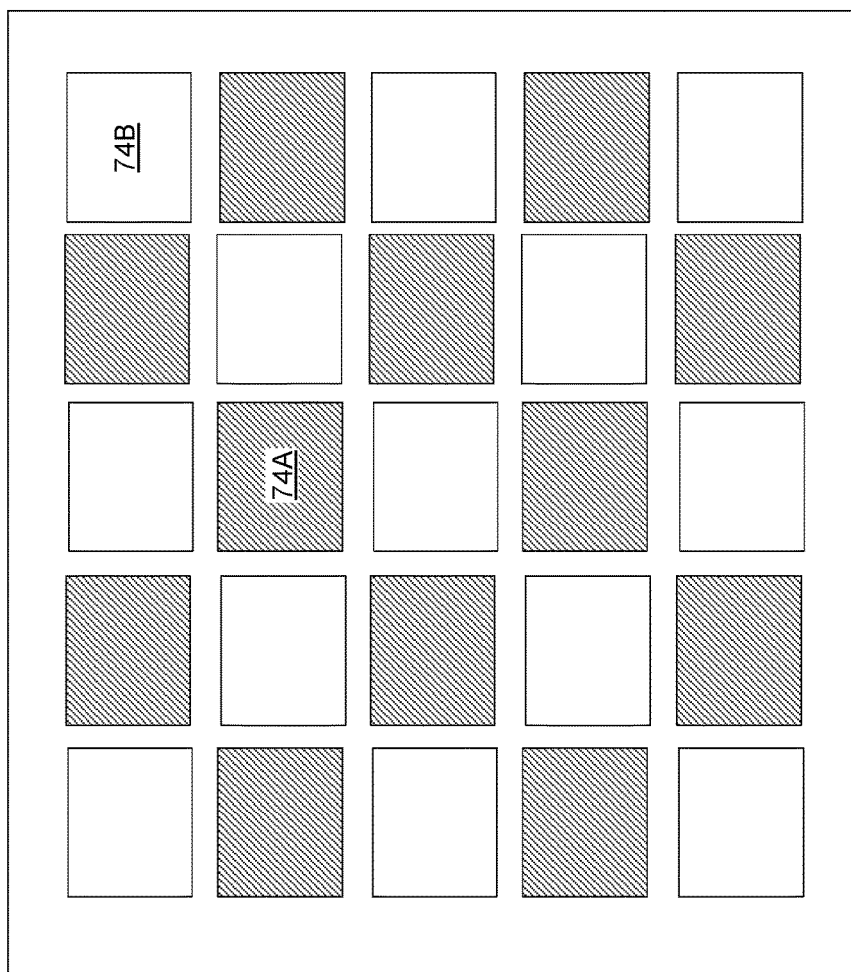


FIG. 8A

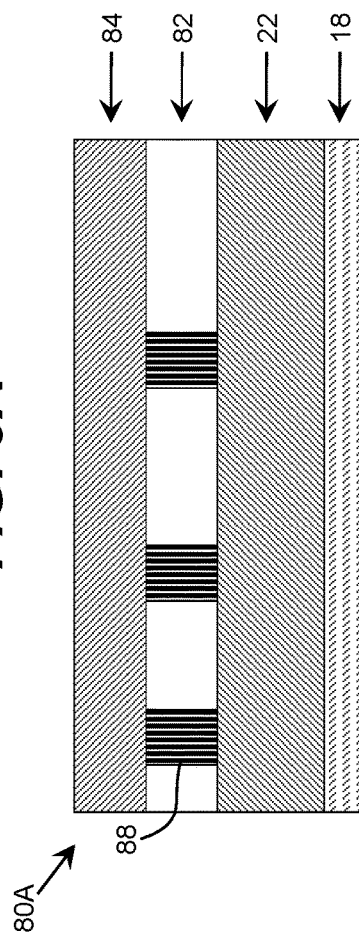


FIG. 8B

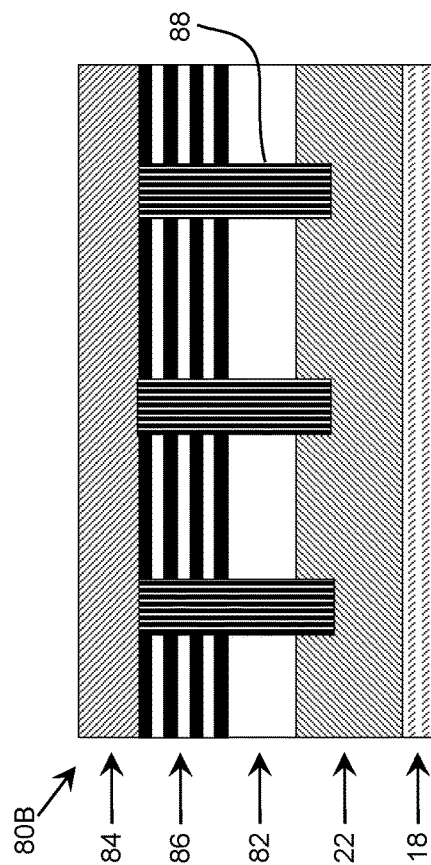


FIG. 9

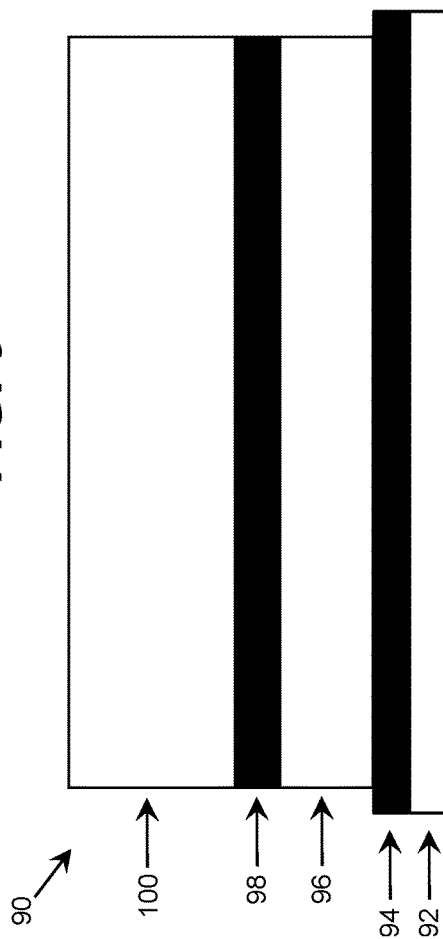


FIG. 10

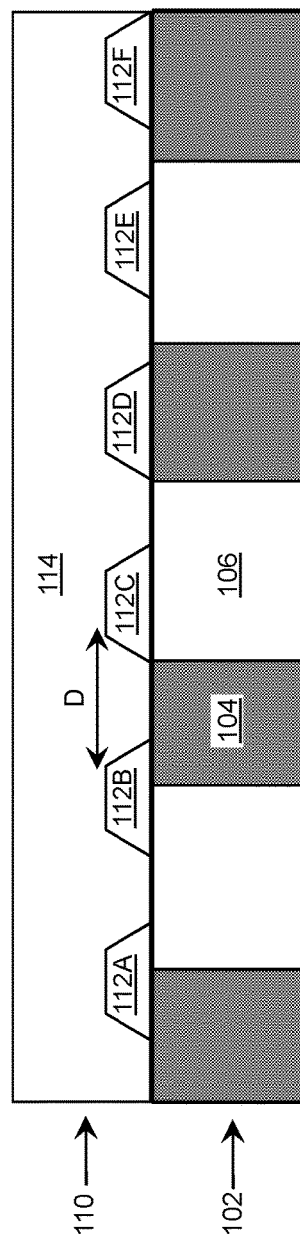


FIG. 11A

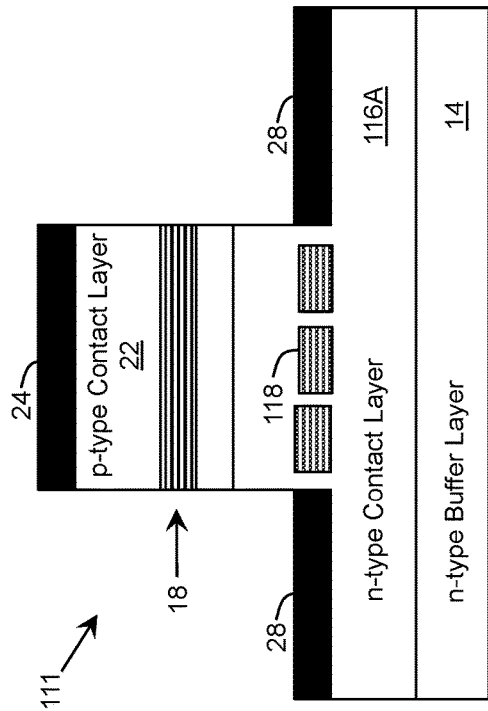


FIG. 11B

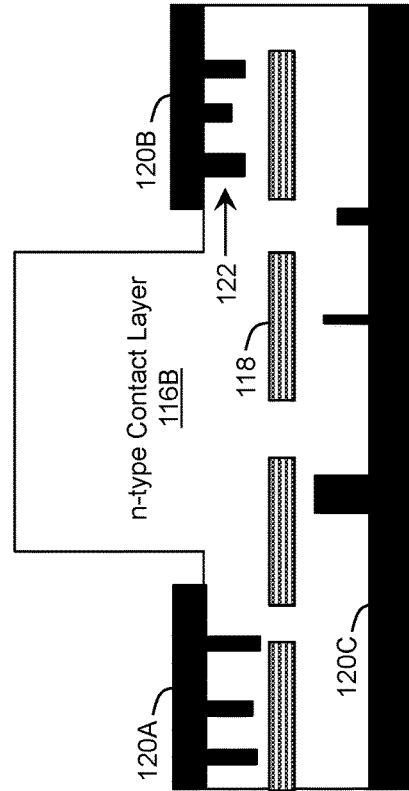


FIG. 11C

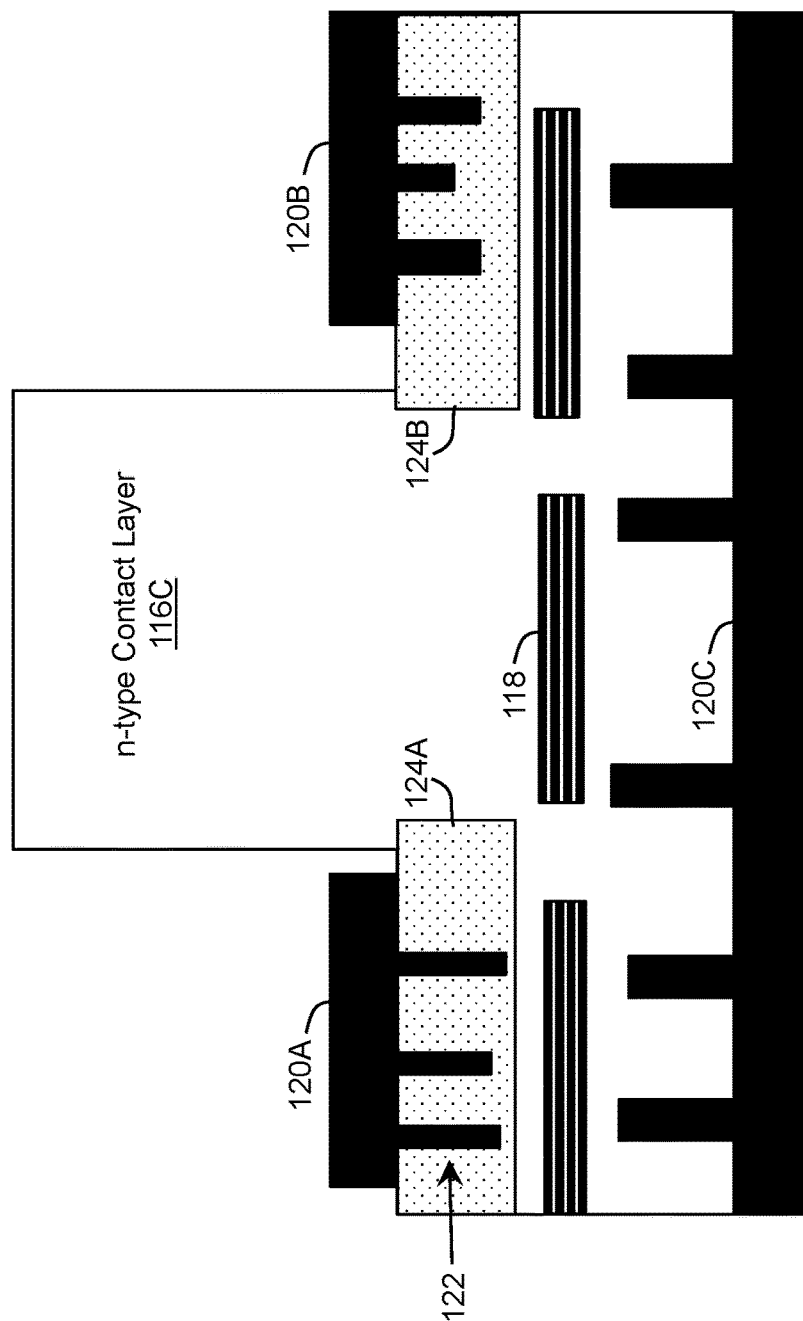


FIG. 12

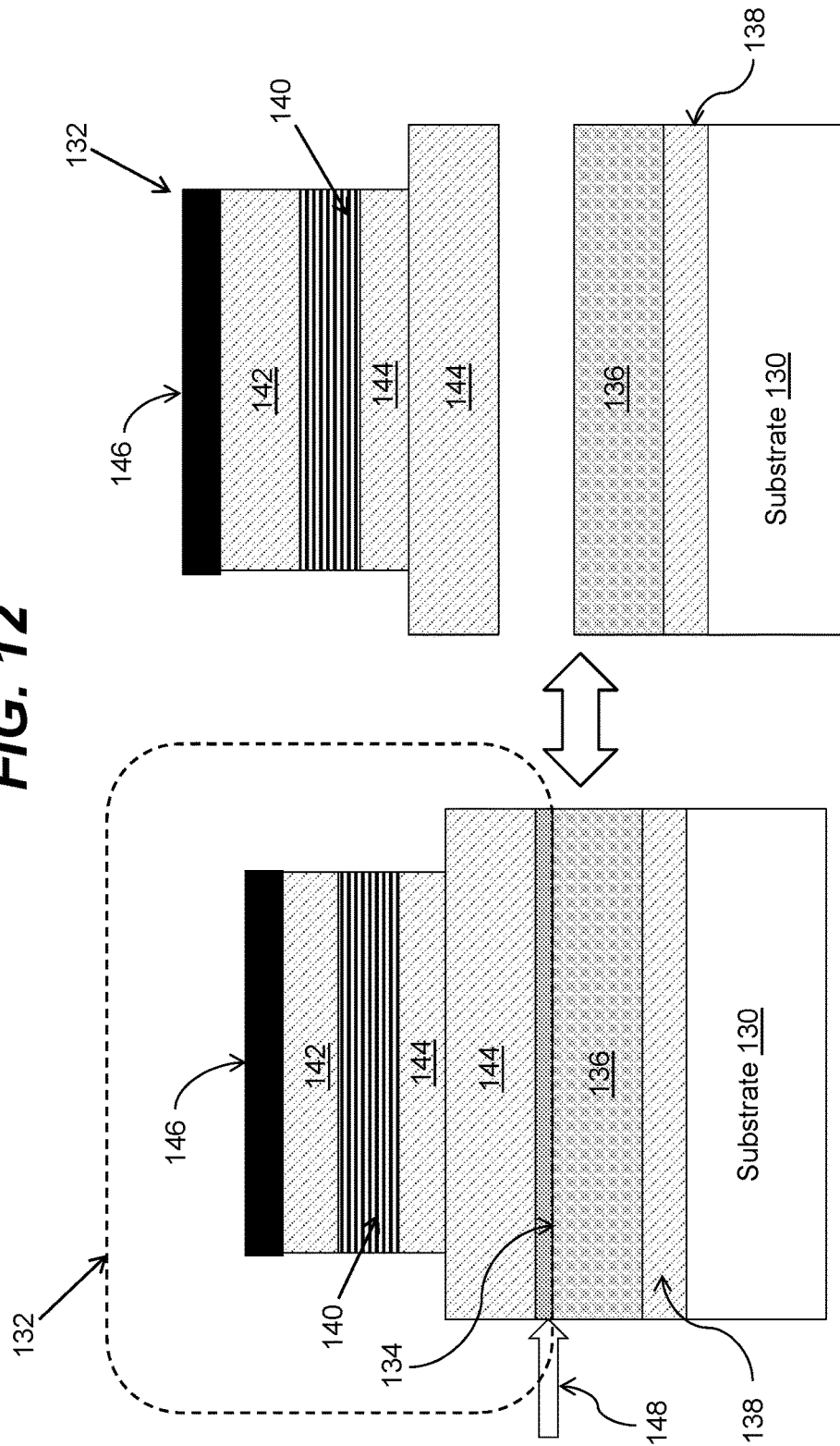


FIG. 13A

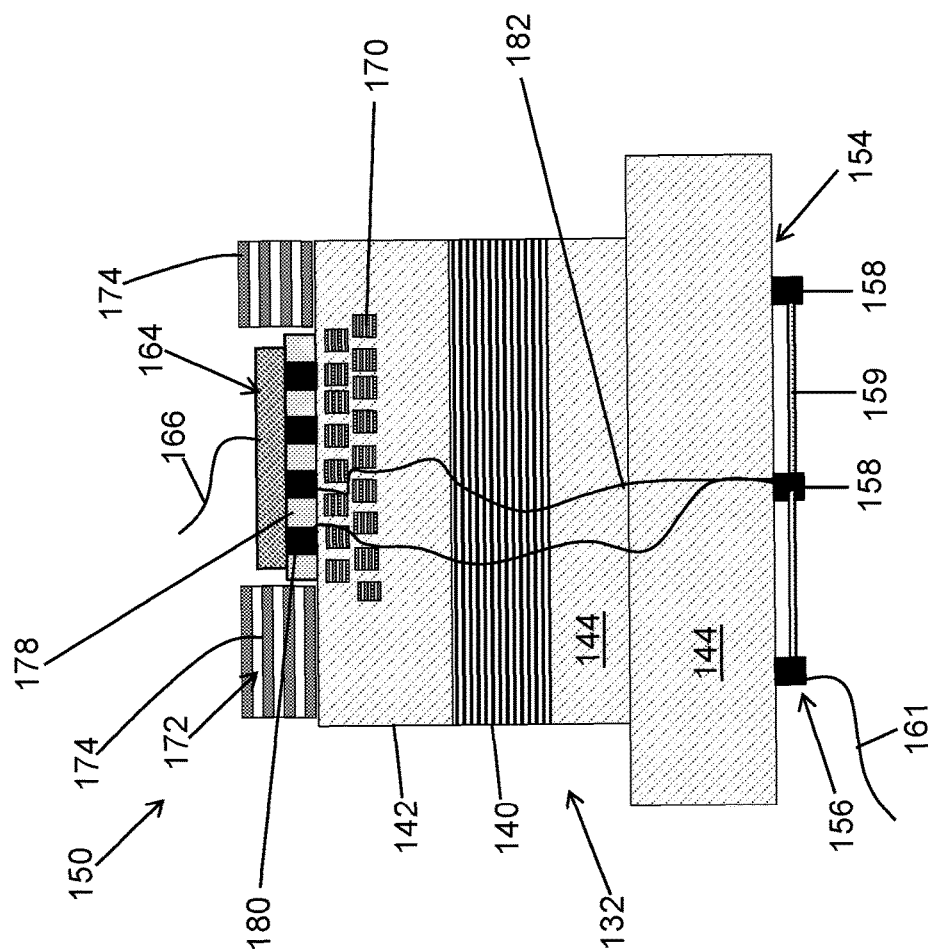


FIG. 13B

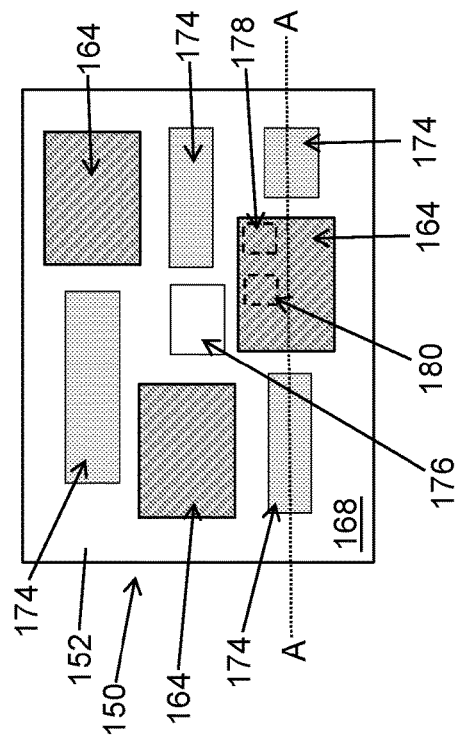


FIG. 13C

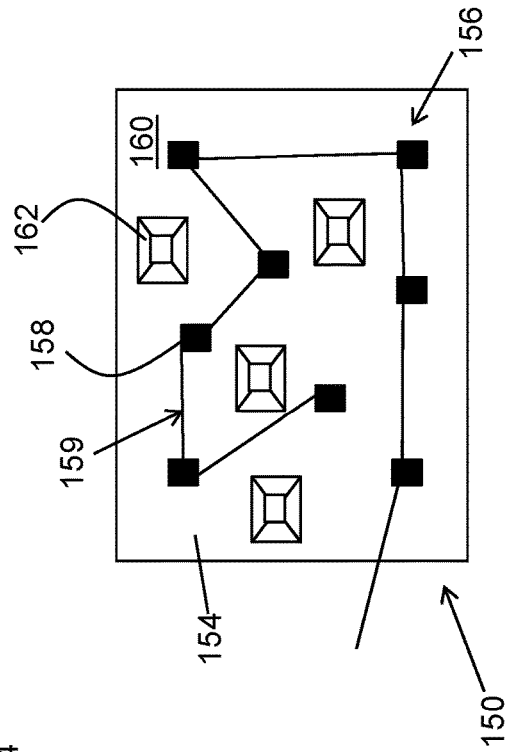
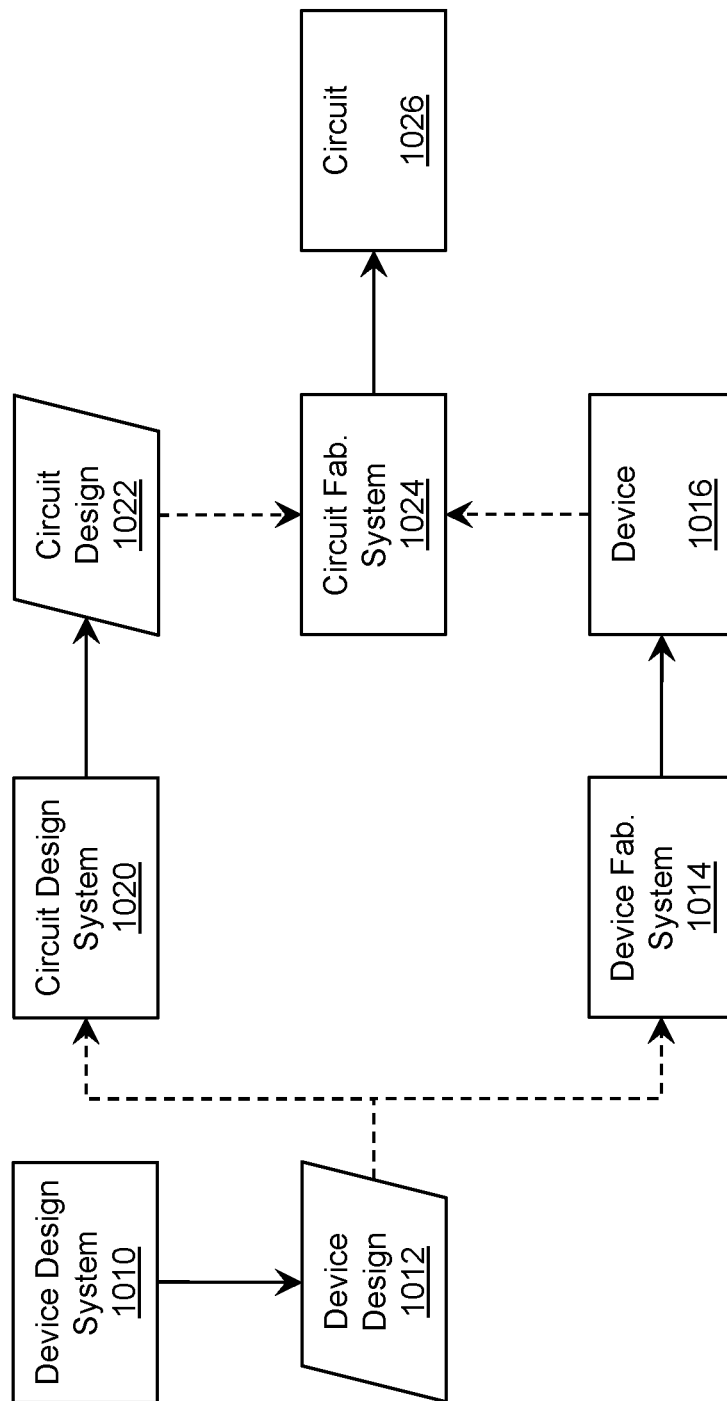


FIG. 14



1

SEMICONDUCTOR STRUCTURE WITH INHOMOGENEOUS REGIONS

REFERENCE TO RELATED APPLICATIONS

The present patent application is a continuation-in-part application of U.S. application Ser. No. 14/189,012, entitled "Semiconductor Structure with Inhomogeneous Regions," which was filed on 25 Feb. 2014, now pending, which claims the benefit of U.S. Provisional Application No. 61/768,581, entitled "Reflective, Transparent, Conductive Semiconductor Structure, Optoelectronic Device With The Same, and Method of Making The Same," which was filed on 25 Feb. 2013, each of which is hereby incorporated by reference in its entirety to provide continuity of disclosure.

TECHNICAL FIELD

The disclosure relates generally to semiconductor devices, and more particularly, to emitting semiconductor devices, such as deep ultraviolet light emitting devices.

BACKGROUND ART

Semiconductor emitting devices, such as light emitting diodes (LEDs) and laser diodes (LDs), include, but are not limited to, solid state emitting devices composed of group III-V semiconductors. A subset of group III-V semiconductors includes group III-Nitride alloys, which can include binary, ternary and quaternary alloys of indium (In), aluminum (Al), gallium (Ga), and nitrogen (N). Illustrative group III-Nitride based LEDs and LDs can be of the form $\text{In}_x\text{Al}_y\text{Ga}_{1-x-y}\text{N}$, where x and y indicate the molar fraction of a given element, $0 \leq x, y \leq 1$, and $0 \leq x+y \leq 1$. Other illustrative group III-Nitride based LEDs and LDs are based on boron (B) nitride (BN) and can be of the form $\text{Ga}_z\text{In}_y\text{Al}_x\text{B}_{1-x-y-z}\text{N}$, where $0 \leq x, y, z \leq 1$, and $0 \leq x+y+z \leq 1$.

An LED is typically composed of semiconducting layers. During operation of the LED, a voltage bias applied across doped layers leads to injection of electrons and holes into an active layer where electron-hole recombination leads to light generation. Light is generated in the active layer with uniform angular distribution and escapes the LED die by traversing semiconductor layers in all directions. Each semiconducting layer has a particular combination of molar fractions for the various elements (e.g., given values of x, y, and/or z), which influences the optical properties of the semiconducting layer. In particular, a refractive index and absorption characteristics of a semiconducting layer are sensitive to the molar fractions of the semiconductor alloy forming the layer.

Current state of the art deep ultraviolet LEDs (DUV LEDs) have a low efficiency due to light trapping within the device, light absorption in the semiconductor layers, as well as light absorption in the contact regions. To improve light extraction efficiency for the DUV LEDs, one approach proposes a design using ultraviolet transparent p-type cladding and contact layers, an ultraviolet reflecting ohmic contact, and chip encapsulation having an optimized shape and refractive index.

SUMMARY OF THE INVENTION

This Summary Of The Invention introduces a selection of certain concepts in a brief form that are further described below in the Detailed Description Of The Invention. It is not intended to exclusively identify key features or essential

2

features of the claimed subject matter set forth in the Claims, nor is it intended as an aid in determining the scope of the claimed subject matter.

Aspects of the invention provide a semiconductor layer including a plurality of inhomogeneous regions. Each inhomogeneous region has one or more attributes that differ from a material forming the semiconductor layer. The inhomogeneous regions can include one or more regions configured based on radiation having a target wavelength. These regions can include transparent and/or reflective regions. The inhomogeneous regions also can include one or more regions having a higher conductivity than a conductivity of the radiation-based regions, e.g., at least ten percent higher. In one embodiment, the semiconductor layer can be used to form an optoelectronic device.

A first aspect of the invention provides a semiconductor heterostructure comprising: an active region; a metallic contact; a group III nitride semiconductor layer located between the active region and the metallic contact, the semiconductor layer including a plurality of inhomogeneous regions arranged within multiple levels of the semiconductor layer, wherein some of the inhomogeneous regions in a first level of the semiconductor layer are vertically offset from inhomogeneous regions in a second level of the semiconductor layer, and wherein the plurality of inhomogeneous regions include one or more of a set of transparent regions, a set of reflective regions and/or a set of conductive regions, each of the inhomogeneous regions having a set of attributes differing from a group III nitride material forming the semiconductor layer.

A second aspect of the invention provides a method, comprising: fabricating a semiconductor heterostructure, wherein the semiconductor heterostructure comprises: an active region; a metallic contact; a group III nitride semiconductor layer located between the active region and the metallic contact, the semiconductor layer including a plurality of inhomogeneous regions arranged within multiple levels of the semiconductor layer, wherein some of the inhomogeneous regions in a first level of the semiconductor layer are vertically offset from inhomogeneous regions in a second level of the semiconductor layer, and wherein the plurality of inhomogeneous regions include one or more of a set of transparent regions, a set of reflective regions and/or a set of conductive regions, each of the inhomogeneous regions having a set of attributes differing from a group III nitride material forming the semiconductor layer.

A third aspect of the invention provides an optoelectronic device, comprising: a semiconductor heterostructure, obtained through laser lift-off, having a first side and a second side, the semiconductor heterostructure including: a group III nitride semiconductor layer including a plurality of inhomogeneous regions, each inhomogeneous region having a set of attributes differing from a group III nitride material forming the semiconductor layer, wherein the plurality of inhomogeneous regions include: a set of first inhomogeneous regions configured based on radiation having a target wavelength, wherein the set of first inhomogeneous regions are at least one of: transparent to the radiation or reflective of the radiation; and a set of second inhomogeneous regions having a conductivity at least ten percent higher than a conductivity of the set of first inhomogeneous regions, wherein each of the sets of inhomogeneous regions occupy at least five percent of at least one of: a lateral planar area of the semiconductor layer or a volume of the semiconductor layer, and wherein at least some of the sets of inhomogeneous regions do not fully overlap.

The illustrative aspects of the invention are designed to solve one or more of the problems herein described and/or one or more other problems not discussed.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features of the disclosure will be more readily understood from the following detailed description of the various aspects of the invention taken in conjunction with the accompanying drawings that depict various aspects of the invention.

FIG. 1 shows a typical design of a flip-chip emitting device according to an embodiment.

FIG. 2 shows a typical design of an emitting device including a mesa structure according to an embodiment.

FIG. 3A shows a layer including a plurality of reflective regions, while FIG. 3B shows an illustrative reflective region according to embodiments.

FIG. 4 shows an illustrative semiconductor structure according to an embodiment.

FIG. 5 shows a structure for an illustrative Fabry-Perot interference filter according to an embodiment.

FIG. 6 shows a band diagram of an illustrative embodiment of a horizontally conductive material according to an embodiment.

FIGS. 7A-7C show illustrative arrangements of reflective regions according to embodiments.

FIGS. 8A and 8B show illustrative reflective regions comprising omnidirectional mirrors according to embodiments.

FIG. 9 shows an illustrative multilayered metallic contact according to an embodiment.

FIG. 10 shows an illustrative interface between a semiconductor layer and a metallic contact according to an embodiment.

FIGS. 11A-11C show illustrative n-type contact layers including reflective regions according to embodiments.

FIG. 12 shows a schematic of a laser lift-off method to lift a semiconductor structure such as any of the structures described herein from a substrate according to an embodiment.

FIGS. 13A-13C show multiple views of an optoelectronic device formed from a semiconductor heterostructure lifted off from a substrate according to an embodiment.

FIG. 14 shows an illustrative flow diagram for fabricating a circuit according to an embodiment.

It is noted that the drawings may not be to scale. The drawings are intended to depict only typical aspects of the invention, and therefore should not be considered as limiting the scope of the invention. In the drawings, like numbering represents like elements between the drawings.

DETAILED DESCRIPTION OF THE INVENTION

As indicated above, aspects of the invention provide a semiconductor layer including a plurality of inhomogeneous regions. Each inhomogeneous region has one or more attributes that differ from a material forming the semiconductor layer. The inhomogeneous regions can include one or more regions configured based on radiation having a target wavelength. These regions can include transparent and/or reflective regions. The inhomogeneous regions also can include one or more regions having a higher conductivity than a conductivity of the radiation-based regions, e.g., at least ten percent higher. As used herein, unless otherwise noted, the

term “set” means one or more (i.e., at least one) and the phrase “any solution” means any now known or later developed solution.

Aspects of the invention provide a semiconductor structure (e.g., a semiconductor layer) that can be incorporated into an optoelectronic device, such as a light emitting diode (LED), a vertical LED, a light emitting laser, a light sensor, a photodetector, an avalanche diode, and/or the like, after removing the semiconductor structure from a substrate using a technique, such as, for example, a laser lift off technique. The semiconductor structure can include inhomogeneous regions formed by one or more of: patterning, masking, epitaxial growth, epitaxial overgrowth, deposition techniques, and/or the like. Deposition techniques can include thermal evaporation, magnetron sputtering, ion-beam deposition, laser beam evaporation, and/or the like. In a more particular embodiment, the semiconductor structure comprises a group III nitride semiconductor layer. The inhomogeneous regions can include various types of inhomogeneous regions and can be located within the semiconductor structure in various arrangements. Aspects of the invention are further described in conjunction with emitting devices, such as group III nitride-based emitting devices, including an active region configured to generate radiation during operation of the device. However, it is understood that the invention can be applied to other types of optoelectronic devices.

Flip-chip technology is frequently utilized to control light extraction and thermal management of a LED, such as a deep ultraviolet (DUV) LED. Turning to the drawings, FIG. 1 shows a typical design of a flip-chip emitting device 10 according to an embodiment, while FIG. 2 shows a typical design of an emitting device 10 including a mesa structure according to an embodiment. In general, each emitting device 10 includes a semiconductor heterostructure having multiple semiconductor layers. Each semiconductor layer typically has lateral dimensions significantly larger than the layer height. Such a semiconductor layer is referred to herein as a planar layer and the discussion distinguishes between two directions: a direction in plane (e.g., extending right to left and into and out of the page in the drawing) and a direction perpendicular to the plane (e.g., extending top to bottom in the drawing). In a typical embodiment, the lateral dimensions of a layer can reach several square millimeters, whereas the height of the layer is typically measured in micrometers and nanometers. A planar area of the layer is typically referred to as the area of the layer or the area of the semiconductor structure. A lateral planar area is defined as an area of a surface of the semiconductor layer and is parallel to the surface of the substrate used for epitaxial growth.

As illustrated, each emitting device 10 includes a heterostructure comprising a substrate 12, a buffer layer 14 adjacent to the substrate 12, an n-type contact layer 16 (e.g., an electron supply layer) adjacent to the buffer layer 14, and an active region 18 having an n-type side 19A adjacent to the n-type cladding layer 16. Furthermore, the heterostructure of each emitting device 10 includes a p-type contact layer 22 (e.g., a hole supply layer) adjacent to a p-type side 19B of the active region 18. It is understood that the emitting devices 10 are only illustrative of various configurations of heterostructures. To this extent, a heterostructure can include one or more additional layers, which are not shown.

In a more particular illustrative embodiment, an emitting device 10 is a group III-V materials based device, in which some or all of the various layers are formed of elements selected from the group III-V materials system. In a still

5

more particular illustrative embodiment, the various layers of the emitting device **10** are formed of group III nitride based materials. Group III nitride materials comprise one or more group III elements (e.g., boron (B), aluminum (Al), gallium (Ga), and indium (In)) and nitrogen (N), such that $B_W Al_X Ga_Y In_Z N$, where $0 \leq W, X, Y, Z \leq 1$, and $W+X+Y+Z=1$. Illustrative group III nitride materials include AlN, GaN, InN, BN, AlGaIn, AlInN, AlBN, AlGaInN, AlGaBN, AlInBN, and AlGaInBN with any molar fraction of group III elements.

An illustrative embodiment of a group III nitride based emitting device **10** includes an active region **18** (e.g., a series of alternating quantum wells and barriers) composed of $In_x Al_x Ga_{1-x-y} N$, $Ga_z In_y Al_{1-x-y-z} N$, an $Al_x Ga_{1-x} N$ semiconductor alloy, or the like. Similarly, both the n-type contact layer **16** and the p-type contact layer **22** can be composed of an $In_x Al_x Ga_{1-x-y} N$ alloy, a $Ga_z In_y Al_{1-x-y-z} N$ alloy, or the like. The molar fractions given by x, y, and z can vary between the various layers **16**, **18**, and **22**. The substrate **12** can be sapphire, silicon carbide (SiC), silicon (Si), GaN, AlGaIn, AlON, LiGaO₂, or another suitable material, and the buffer layer **14** can be composed of AlN, an AlGaIn/AlN superlattice, and/or the like.

A p-type metal **24** can be attached to the p-type contact layer **22** and a n-type metal **28** can be attached to the n-type contact layer **16**. The p-type metal **24** and the n-type metal **28** can form ohmic contacts to the corresponding layers **22**, **16**, respectively. As shown with respect to the emitting device **10** of FIG. 1, a p-type metallic contact **26** can be attached to the p-type metal **24** and an n-type metallic contact **30** can be attached to the n-type metal **28**. In an embodiment, the p-type metal **24** and the n-type metal **28** each comprise several conductive and reflective metal layers, while the n-type metallic contact **30** and the p-type metallic contact **26** each comprise highly conductive metal.

In an embodiment, an emitting device **10** includes one or more layers, such as the n-type contact layer **16** and/or the p-type contact layer **22**, formed of a semiconductor structure having one or more inhomogeneous regions located therein. The inhomogeneous regions can include one or more regions configured based on radiation having a target wavelength and/or one or more regions configured based on a desired conductivity. To this extent, the inhomogeneous regions can include one or more of: a set of transparent regions, a set of reflective regions, and/or a set of conductive regions. As used herein, a region is a transparent region when the region allows at least ten percent of radiation having a target wavelength, which is radiated at a normal incidence to an interface of the region, to pass there through. Furthermore, as used herein, a region is a reflective region when the region reflects at least ten percent of radiation having a target wavelength, which is radiated at a normal incidence to an interface of the region. In an embodiment, the target wavelength of the radiation corresponds to a wavelength of radiation emitted or sensed by the active region **18** during operation of the device **10**. For a given layer, the wavelength can be measured in a material of consideration and can depend on a refractive index of the material.

A conductive region can be configured to promote conductivity of carriers in the semiconductor structure. A conductive region can have a higher concentration of carriers due to, for example, a locally reduced band gap of the semiconductor layer, a local high doping of the semiconductor layer, and/or the like. In an illustrative embodiment, the conductive region is formed of a group III nitride semiconductor material. In this case, a high local level of

6

doping can be achieved by locally reducing an aluminum content, by polarization doping resulting in graded layers, and/or the like. Regardless, the improved conductivity can maintain an overall conductivity of the semiconductor structure. In an embodiment, a conductive region has a conductivity at least ten percent higher than a conductivity of a transparent region and a conductivity of a reflective region and a higher conductivity than a base semiconductor material for the layer.

A conductive region described herein can be anisotropic in the layer normal and/or lateral directions. For example, one or more of the conductive regions can have a high conductivity in a layer normal direction but not in the layer lateral direction, while one or more other conductive regions can have a high conductivity in the layer lateral direction but not in the layer normal direction. The conductive regions with high conductivity in the layer normal direction are referred to as regions with vertical conductivity, while conductive regions with high conductivity in the layer lateral direction are referred to as regions with horizontal conductivity. Similar to an isotropic conductive region, an anisotropic conductive region can have a conductivity in the preferred semiconductor direction that is at least ten percent higher than a conductivity of the reflective and transparent regions in the preferred direction.

Regions of each type (transparent, reflective, and conductive) can be incorporated into the semiconductor structure (e.g., a layer in the emitting device **10**) and have an area that is a fraction of the area of the entire semiconductor structure. In an embodiment, the area of the region is approximately a few percent of the area of the semiconductor structure or more (e.g., greater than or equal to approximately three percent of the area of the semiconductor structure). Additionally, a region can have a height that is smaller than a height of the corresponding semiconductor structure. For example, a region can have a height that is fifty percent or ten percent of the height of the semiconductor layer. A region can be located anywhere within the semiconductor structure, including completely within the semiconductor structure or located adjacent to either planar side of the semiconductor structure. In an embodiment, the semiconductor structure includes multiple regions of the same type, which can be located in various portions of the semiconductor structure and can be present at different levels along a height of the semiconductor structure. To this extent, two or more of the regions of the same type can at least partially overlap with one another. In an embodiment, regions of the same type occupy at least five percent of the volume of the semiconductor structure. In another embodiment, regions of the same type occupy at least five percent of the lateral planar area of the semiconductor structure.

A semiconductor structure can include regions of one or more types. When regions of multiple types are included, the regions of different types can be located anywhere within the semiconductor structure with respect to one another. For example, a transparent region can be located adjacent to a reflective region, a conductive region can be located adjacent to a transparent region and/or a reflective region, and/or the like. Additionally, a single region can comprise both a transparent region, by allowing at least ten percent of radiation of a target wavelength to pass there through, and a reflective region, by reflecting at least ten percent of the radiation.

A reflective region can be formed of one or more composite mirrors. A composite mirror includes any structure having multiple sublayers of dielectric or metallic material. Such a composite mirror can be an omnidirectional mirror,

which comprises a layer of material having a low index of refraction followed by a metallic reflector or a Bragg mirror. To this extent, FIG. 3A shows a layer including a plurality of reflective regions while FIG. 3B shows an illustrative reflective region according to embodiments. In FIG. 3A, the layer can correspond to a p-type contact layer 22, which is located adjacent to a p-type metal 24. However, it is understood that this is only illustrative. The p-type contact layer 22 is shown including three reflective regions 40A-40C located therein. As illustrated, each reflective region 40A-40C is located adjacent to a planar side of the p-type contact layer 22. However, it is understood that the number of and relative locations of the reflective regions 40A-40C are also only illustrative of various possible configurations.

As illustrated, a reflective region 40A-40C can be formed of a composite mirror having alternating sublayers of low index of refraction material 42 and relatively high index of refraction material 44 (e.g., a metallic reflector or a Bragg mirror). Furthermore, a sublayer of the reflective region 40A-40C closest to the p-type side 19B of the active region can be formed of a low index of refraction material 42. In an embodiment shown in FIG. 3B, a reflective region 40 (e.g., a Bragg mirror) can be epitaxially grown, and include a superlattice of group III nitride semiconductor sublayers 42, 44 of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}/\text{Al}_{x'}\text{In}_{y'}\text{Ga}_{1-x'-y'}\text{N}$, where x , y , x' , and y' are chosen such that a refractive index of one sublayer is different from a refractive index of another sublayer by at least two percent (five percent in another embodiment). In a more particular embodiment, the refractive index of a group III nitride semiconductor alloy varies between values of 2.2 and 2.7 by adjusting a molar fraction of aluminum and/or indium. In an illustrative embodiment, x (the molar fraction of aluminum in one of the sublayers) is greater than 0.4. Only values with relatively high molar fractions are important in order to have Bragg mirrors with low absorption characteristics. Typical Bragg mirrors are designed to have alternative sublayers of low and high refractive index, with sublayer thicknesses being a quarter of a target wavelength (λ), wherein the target wavelength corresponds to a wavelength of radiation measured in the semiconductor material. In an embodiment, the Bragg mirror includes at least ten layers.

In an embodiment, a semiconductor structure, such as the p-type contact layer 22, includes a sufficient number and configuration of reflective regions 40A-40C (e.g., Bragg mirrors) to provide at least a ten percent reflectivity for the entire semiconductor structure 22. In another embodiment, the reflective regions 40A-40C also can serve as transparent regions, which concurrently transmit and reflect at least ten percent of the radiation. In still another embodiment, such a transparent and reflective region can reflect at least twenty percent of radiation having a target wavelength at the normal direction to the region surface.

A reflective region 40 can be formed using another deposition solution, such as thermal evaporation, magnetron sputtering, ion-beam deposition, laser beam evaporation, and/or the like. A reflective region 40 formed using an alternative solution to epitaxial growth can utilize one or more of a larger selection of materials for the sublayers. For example, a reflective region 40 can include sublayers of a low index of refraction material, such as silicon dioxide (SiO_2), magnesium oxide (MgO), magnesium fluoride (MgF_2), and/or the like, and sublayers of a high index of refraction material such as aluminum oxide (Al_2O_3), scandium oxide (Sc_2O_3), magnesium aluminum oxide (MgAl_2O_3), and a group III nitride (e.g., $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$). As a result, a larger variability in the refractive indices of the

sublayers is possible. For example, the refractive index of one sublayer can differ from the refractive index of another sublayer by at least three percent (ten percent in a more particular embodiment). In an embodiment, a sublayer with a low index of refraction can be deposited followed by either a metallic reflector or a Bragg mirror. Similar to Bragg mirrors grown epitaxially, a thickness of each sublayer can be chosen to be a quarter of a target wavelength, where the target wavelength is the wavelength of the radiation measured in the sublayer material.

A semiconductor structure (e.g., the p-type contact layer 22) including transparent, reflective, and/or conductive regions can be fabricated using patterning. For example, an initial group III nitride semiconductor layer can be epitaxially grown on a surface, followed by deposition of transparent, reflective, and/or conductive (vertically and/or horizontally) region(s) over the semiconductor layer by means of thermal evaporation, magnetron sputtering, ion-beam deposition, laser beam evaporation, and/or the like. Alternatively, one or more of the regions can be epitaxially grown above the group III nitride semiconductor layer. The deposited region(s) can be patterned, e.g., using photolithography, which includes depositing a photoresist, exposing patterned areas to high intensity light, and etching the exposed areas. Some portions of the deposited region(s) can be etched, and a group III nitride semiconductor layer is overgrown in the etched regions. The process of patterning can be repeated, again depositing a next layer of transparent, reflective, and/or conductive region(s). More complicated deposition and patterning are also possible, which can result in various arrangements of transparent, reflective, and/or conductive regions. For example, after etching portions of the deposited region(s), a second set of region(s) of a different type can be deposited in the etched regions (e.g., to form laterally adjacent regions of different types).

FIG. 4 shows an illustrative semiconductor structure 50 according to an embodiment. The semiconductor structure 50 includes a vertically conductive region 52 and a background base semiconductor structure 54 and is located adjacent to a metallic contact 60. In an embodiment, the background base semiconductor structure 54 comprises a group III nitride semiconductor layer, a structure composed of group III nitride semiconductor layers, or the like. In a more particular embodiment, the background base semiconductor structure 54 comprises a superlattice comprising $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}/\text{Al}_{x'}\text{In}_{y'}\text{Ga}_{1-x'-y'}\text{N}$ sublayers. In this case, the superlattice can have an enhanced horizontal conductivity. The semiconductor structure 50 further includes reflective regions 56 (e.g., composite mirrors) and transparent regions 58. As illustrated, the transparent regions 58 can be located at several different levels within the semiconductor structure 50. Similarly, while not shown in FIG. 4, the reflective regions 56 can be located at different levels. A size of the regions 56, 58 can vary, e.g., based on a method utilized for fabricating such regions 56, 58. For example, regions 56, 58 formed using epitaxial growth can be ten to one thousand nanometers, whereas regions 56, 58 produced through patterning can result in a region size of several micrometers or larger.

In an embodiment, a semiconductor structure can include transparent regions and reflective regions interspersed with vertically conductive regions such that any lateral cross section of the semiconductor structure contains at least one transparent or reflective region and at least one vertically conductive region. For example, the semiconductor structure 50 can include a sufficient number of reflective regions 56 and transparent regions 58 arranged in conjunction with

the vertically conductive region **52** to meet such a condition. Still further, an illustrative arrangement of regions can include regions of two or more types laterally adjacent to one another (e.g., joined). For example, a semiconductor structure can include an arrangement in which transparent or reflective regions are laterally adjacent to vertically conductive regions.

In an embodiment, a transparent region, such as one or more of the transparent regions **58**, comprises an $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}/\text{Al}_x\text{In}_y\text{Ga}_{1-x'-y'}\text{N}$ superlattice with x , y , x' and y' chosen such that the transparency of the superlattice is at least ten percent for a target wavelength of radiation. In another embodiment, the transparent region can be configured to form a Fabry-Perot interference filter for a target wavelength of radiation. For example, FIG. **5** shows a structure for an illustrative Fabry-Perot interference filter **62** according to an embodiment. In this case, the filter **62** comprises a superlattice including a series of alternating layers of $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}/\text{Al}_x\text{In}_y\text{Ga}_{1-x'-y'}\text{N}$, where x and x' molar fractions are larger than 0.35. The molar fractions x , x' are chosen to improve a transparency of the layers within the superlattice to radiation having a target wavelength. In an embodiment, y and y' are both zero (i.e., the layers do not include indium). Each layer in the superlattice has a thickness of approximately one quarter the target wavelength (λ), except for a middle layer having a thickness of approximately one half the target wavelength. In this manner, the filter **62** only transmits radiation having the target wavelength. In another embodiment, the transparent region **58** includes aluminum oxide (Al_2O_3), fused silica, aluminum nitride, or the like which can be deposited by means of thermal evaporation, magnetron sputtering, ion-beam deposition, or laser beam evaporation, and/or the like.

As discussed herein, a semiconductor structure can include a material having an enhanced horizontal conductivity (e.g., the background base semiconductor structure **54** of FIG. **4**). FIG. **6** shows a band diagram **64** of an illustrative embodiment of a horizontally conductive material according to an embodiment. In this case, the material comprises an $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}/\text{Al}_x\text{In}_y\text{Ga}_{1-x'-y'}\text{N}$ superlattice having barriers and quantum wells alternating along a height of the material. Regions **66** and **68** correspond to localized concentration of electrons and holes, respectively, and result in the formation of two dimensional carrier gases. In particular, region **66** results in the formation of a two dimensional electron gas (2DEG), while region **68** results in the formation of a two dimensional hole gas (2DHG). The carrier gases have a high mobility in the lateral direction, which results in a horizontally conductive layer. In general, higher changes in band gap produce larger polarization fields, which can lead to an increase concentration of the carrier gases. In an illustrative example, a superlattice including layers of $\text{GaN}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ provides a horizontally conductive material superlattice. In another embodiment, more than a two percent change in band gap is desired for formation of 2DEG.

As discussed herein, regions of any of the types (e.g., reflective, transparent, or conductive), can be located in various arrangements within a semiconductor structure. To this extent, FIGS. **7A-7C** show illustrative arrangements of reflective regions according to embodiments. In FIG. **7A**, a semiconductor base layer **70** is located adjacent to a metal contact **72** and includes two levels **74A**, **74B** of reflective regions. Each level **74A**, **74B** of reflective regions is immersed in the semiconductor base layer **70**. Additionally, reflective regions located in level **74B** are laterally offset (staggered) from reflective regions located in level **74A**.

FIG. **7C** shows a top view of an embodiment in which the levels **74A**, **74B** of reflective regions can be staggered in a manner that forms a checkerboard arrangement. In FIG. **7B**, a first level **76A** of reflective regions is located adjacent to an interface of the semiconductor base layer **70**, while a second level **76B** of reflective regions penetrates the metal contact **72**. It is understood that these arrangements are only illustrative of various possible arrangements of regions.

FIGS. **8A** and **8B** show illustrative reflective regions **80A**, **80B** comprising omnidirectional mirrors according to embodiments. The mirror for each reflective region **80A**, **80B** comprises a low refractive index layer **82** located within a contact layer, such as the p-type contact layer **22**. Additionally, each reflective region **80A**, **80B** comprises a highly reflective layer **84** located adjacent to an opposite side of the low refractive index layer **82** as the active region **18**. Reflective region **80B** further includes a distributed dielectric mirror **86** located between the low refractive index layer **82** and the highly reflective layer **84**. The reflective regions **80A**, **80B** can further include a set of conductive regions **88**, each of which can extend from the contact layer **22** to the highly reflective layer **84**. The conductive regions **88** can comprise metallic or other conductive material regions. In an embodiment, the conductive regions **88** can be fabricated by etching the low refractive index layer **82** and distributed dielectric mirror **86** to access the contact layer **22** located underneath.

A semiconductor structure can include any combination and/or arrangement of the various types of regions, which can be selected based on a set of performance requirements for the semiconductor structure and/or the corresponding device. In an embodiment, the semiconductor structure can include vertically and horizontally conductive regions arranged to form an interconnected network of conductive paths through the semiconductor structure. The term "interconnected" network does not necessarily imply that all the conductive regions form a single network. As used herein, the term is applied loosely and includes clusters of overlapping conductive regions disconnected by gaps. In an embodiment, a typical cluster size and cluster density is chosen to match a conductivity requirement of the semiconductor structure. For example, for a semiconductor structure formed adjacent to a p-type contact, the cluster density and cluster size can be chosen to provide such conductivity of the p-type contact that a voltage drop across the p-type contact is ten percent or less than a voltage drop across the entire device.

As discussed herein, an embodiment of the semiconductor structure can be included in an optoelectronic device, such as a light emitting diode, a deep ultraviolet light emitting diode, a light sensor, other types of optoelectronic solid state devices, and/or the like. In a more specific embodiment, the semiconductor structure is incorporated in such a device to improve light extraction characteristics of the corresponding device. Returning to FIGS. **1** and **2**, a semiconductor structure described herein can be incorporated as some or all of the p-type contact layer **22** and/or n-type contact layer **16**.

In an embodiment of the device **10** shown in FIG. **1** or FIG. **2**, a metallic contact **24** and/or a metallic contact **28** can comprise a multilayered structure. For example, the metallic contact **24**, **28** can include an ohmic layer adjacent to the corresponding contact layer **22**, **16**, respectively, followed by a reflective layer located adjacent to the ohmic layer. The ohmic layer can be transparent to radiation having a target wavelength as described herein, while the reflective layer can be reflective to radiation having the target wavelength. In a more specific embodiment, the ohmic layer allows at

least twenty percent of radiation having a target wavelength, which is radiated at a normal incidence to an interface of the ohmic layer, to pass there through. In another more specific embodiment, the reflective layer reflects at least fifty percent of radiation having the target wavelength, which is radiated at a normal incidence to an interface of the reflective layer. In an embodiment, the target wavelength corresponds to ultraviolet light, e.g., within a range of wavelengths between approximately 260 and approximately 360 nanometers.

A metallic contact **24** and/or a metallic contact **28** can include one or more additional layers, e.g., to improve stability, reflectivity, and/or conductive properties of the ohmic contact. For example, FIG. 9 shows an illustrative multilayered metallic contact **90** according to an embodiment. In this case, the contact **90** includes an ohmic layer **92**, an ohmic protective layer **94**, a reflective layer **96**, a reflective protective layer **98**, and a conductive metallic layer **100**. Each layer **92**, **94**, **96**, **98**, **100** can be formed of any suitable material and can be fabricated using any solution. For example, the ohmic contact layer **92** can be one of: cobalt (Co), nickel (Ni), palladium (Pd), iron (Fe), platinum (Pt), or the like. Additionally, the ohmic contact layer **92** can include one or sub-layers of metals. Such a sub-layer can include the above metals as well as: Pd, rhodium (Rh), ruthenium (Ru), osmium (Os), iridium (Ir), thorium (Th), and boron (B), and can incorporate one or more of: calcium (Ca), magnesium (Mg), beryllium (Be), manganese (Mn), or tin (Sn), with a maximum concentration up to approximately 10^{21} cm⁻³. For example, the ohmic layer **92** can include: a sub-layer of Co/Mg/Ni having a thickness of approximately one to two nanometers, which can act as an adhesive; a two to five nanometer sub-layer of palladium, which can provide a good ohmic contact; and a sub-layer of rhodium having a thickness of approximately 150 Angstroms. The ohmic protective layer **94** can comprise: Pt, rhenium (Re), Pd, Rh, Ru, Os, Ir, or the like; an oxide, such as indium tin oxide (ITO), zinc oxide (ZnO), or the like; and/or the like. The ohmic protective layer **94** can be as thick as few tens of nanometers. The reflective layer **96** can comprise Al, and be relatively thick (e.g., as much as a few hundred nanometers). A reflective protective layer **98** can comprise titanium (Ti), zirconium (Zr), hafnium (Hf), molybdenum (Mo), tungsten (W), Pd, Rh, Ru, Os, Ir, vanadium (V), chromium (Cr), Pt, or their alloys. A conductive metallic layer **100** can comprise a layer of any type of material having a high electrical conductivity, including copper (Cu), silver (Ag), gold (Au), nickel (Ni), or their alloys.

An ohmic layer and/or reflective layer of a metallic contact **24** and/or a metallic contact **28** can be discontinuous. For example, a layer can comprise a plurality of island formations. The island formations can have a characteristic size of between ten to two thousand nanometers (up to one hundred thousand nanometers in another embodiment) and can be separated from one another by a characteristic distance of approximately the same order as the characteristic size of the islands. In an embodiment, the ohmic and reflective islands are interspersed with each other. Similarly, a semiconductor layer located adjacent to a metallic contact **24** and/or a metallic contact **28** can have a laterally inhomogeneous structure.

For example, FIG. 10 shows an illustrative interface between a semiconductor layer **102** and a metallic contact **110** according to an embodiment. The semiconductor layer **102** is shown including laterally adjacent regions **104**, **106**, which can have distinct properties. In an embodiment, a first set of regions **104** comprise conductive regions, while a second set of regions **106** comprise transparent or reflective

regions. The metallic contact **110** is shown having an ohmic layer formed of a plurality of ohmic islands **112A-112F**, over which a reflective layer **114** can be located. The ohmic islands **112A-112F** can be randomly located or patterned. Furthermore, an alignment of the ohmic islands **112A-112F** with respect to the regions **104**, **106** of the semiconductor layer **102** can be random or predetermined. In the latter case, any solution can be utilized for the alignment including for example, semiconductor layer patterning and overgrowth, ohmic layer patterning, and/or the like. As illustrated, a characteristic distance *D* between the ohmic islands **112A-112F** can be comparable to a characteristic lateral size of the ohmic islands **112A-112F**.

FIGS. 11A-11C show illustrative n-type contact layers **116A-116C**, respectively, including reflective regions **118** according to embodiments. The reflective regions **118** can comprise, for example, superlattices of Al_xIn_yGa_{1-x-y}N/Al_xIn_yGa_{1-x-y}N layers, which can be grown epitaxially. Since the n-type contact layers **116A**, **116B** can have thicknesses of several microns, relatively thick composite reflective regions **118** can be utilized which can lead to a higher degree of reflection. As illustrated in FIG. 11A, inclusion of the reflective regions **118** in the n-type contact layer **116A** can provide a more efficient reflection of radiation towards the p-type contact **24**. For an efficient extraction of radiation from the device **111**, the p-type contact **24** and the p-type contact layer **22** should be transparent to the radiation generated by the active region **18** (e.g., transmitting at least thirty percent of the radiation of a target wavelength in an embodiment).

As shown in FIGS. 11B and 11C, a n-type metal contact **120A-120C** can include metallic protrusions **122** extending into the n-type contact layer **116B**, **116C**. Furthermore, as shown in FIG. 11C, a n-type contact layer **116C** can include conductive regions **124A**, **124B** having high horizontal conductivity in a location of the protrusions **122**. The protrusions **122** can deliver the current to the horizontally conductive regions **124A**, **124B**, which can spread the current horizontally to other regions having a high vertical conductivity (e.g., the background base semiconductor structure of the n-type contact layer **116C**). Furthermore, a n-type metal contact, such as the metal contact **120C**, can be adjacent to region(s) of high vertical conductivity. The metal contact **120C** provides a vertical design for the n-type contact structure and can be included alone or in combination with the horizontal designed metal contacts **120A**, **120B**. In an embodiment, the metal contact **120C** is formed by removing a substrate used for epitaxial growth of the semiconductor layer(s) and depositing the n-type metal contact **120C** on the exposed surface of the semiconductor layer.

Any of the semiconductor structures described herein, as well as other structures that include any of the concepts of the various embodiments described herein can be incorporated into an optoelectronic device such as one of those devices listed above. FIG. 12 shows a schematic of a laser lift-off method to lift a semiconductor structure, such as any of the structures described herein, from a substrate **130** according to an embodiment. As shown on the left-hand side of FIG. 12, a semiconductor heterostructure **132** can be formed on the substrate **130** via a sacrificial layer **134**, a semiconductor layer **136** and a buffer layer **138**.

The semiconductor heterostructure **132** can include an active region **140**, a p-type contact layer **142** located on a first side of the active region **140**, and a n-type contact layer **144** located on a second side of the active region **140** opposite the first side. A p-type metal layer **146** can be

13

formed on the p-type contact layer 142. Any of the aforementioned materials are suitable for use with the active region 140, the p-type contact layer 142, the n-type contact layer 144 and the p-type metal layer 146. A semiconductor heterostructure formed from group III nitride layers is one example of materials that can be used since these layers can grow over the substrate 130, the sacrificial layer 134, the semiconductor layer 136 and the buffer layer 138.

Although not shown in FIG. 12, either one or both of the p-type contact layer 142 and the n-type contact layer 144 can include a group III nitride semiconductor layer having a plurality of inhomogeneous regions that can take the form of any of the previously described embodiments. In this manner, each inhomogeneous region in either the p-type contact layer 142 and the n-type contact layer 144 can have a set of attributes that differ from the group III nitride material forming the semiconductor layer. In one embodiment, the plurality of inhomogeneous regions can include a set of first inhomogeneous regions configured based on radiation having a target wavelength, wherein the set of first inhomogeneous regions are at least one of: transparent to the radiation or reflective of the radiation: The plurality of inhomogeneous regions can further include a set of second inhomogeneous regions having a conductivity that is at least ten percent higher than a conductivity of the set of first inhomogeneous regions. Each of the sets of inhomogeneous regions can occupy at least five percent of at least one of: a lateral planar area of the semiconductor layer or a volume of the semiconductor layer. In one embodiment, at least some of the sets of inhomogeneous regions do not fully overlap with each other.

The substrate 130 can include any substrate that is well-known for growing semiconductor layers thereon. One example of a substrate can include sapphire, but other substrates are possible. The buffer layer 138 can be a semiconductor layer that provides some separation from the semiconductor heterostructure 132. The buffer layer 138 can include, but is not limited to, aluminum nitride or gallium nitride. In some embodiments, the buffer layer 138 can comprise an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer, with $x > 0.8$.

The semiconductor layer 136 can serve to improve the subsequent heterostructure by reducing the number of dislocations present in the heterostructure. In an embodiment, the semiconductor layer 136 comprises an AlN layer grown under conditions allowing for reduction of dislocations. For example, the semiconductor layer 136 can be grown to have a variable V/III ratio or a presence of one or more AlGaIn interlayers. In other cases, the semiconductor layer 136 can contain an $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{Al}_y\text{Ga}_{1-y}\text{N}$ superlattice, in which x and y differ by at least 5%. In one embodiment, the semiconductor layer 136 can include $\text{Al}_x\text{In}_y\text{B}_z\text{Ga}_{1-x-y-z}\text{N}$. For an embodiment in which an optoelectronic device is an ultraviolet light emitting diode, for which the described technology is preferential, the semiconductor layer 136 can include AlN having a thickness that is chosen to minimize the number of dislocations in subsequent layers. In one embodiment, a typical thickness for a semiconductor layer 136 including AlN can range from about 1 micrometers to about 10 micrometers.

The sacrificial layer 134 can include a material that is capable of being grown over the semiconductor heterostructure 132 with the semiconductor layer 136, the buffer layer 138 and the substrate layer 130 coupled thereto. In one embodiment, the sacrificial layer 134 can be suitable for use in lift-off techniques where the semiconductor heterostructure 132 is removed from the substrate 130, including the sacrificial layer 134, the semiconductor layer 136, and the

14

buffer layer 138, using laser radiation and subsequent fabrication of an optoelectronic device. In one embodiment, the sacrificial layer 134 can include a group III nitride semiconductor layer with a bandgap value that is lower than the bandgap value of any layer in the semiconductor heterostructure 132. For example, the sacrificial layer 134 can include GaN. In another embodiment, the sacrificial layer 134 can include columnar structures comprising group III nitride semiconductors epitaxially grown over a masked region that has holes or openings for growing sacrificial layer material. For example, the sacrificial layer 134 can include alternating GaN/AlN layers of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{Al}_y\text{Ga}_{1-y}\text{N}$ layers having a difference between molar fractions of x and y that is at least 0.1 and preferably greater than 0.5. In one embodiment, the sacrificial layer 134 can include a large number of compositional lateral fluctuations. For example, the sacrificial layer 134 can include compositional fluctuations in $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{N}$ alloy with fluctuations both in aluminum and indium molar fractions. In another embodiment, the sacrificial layer 134 can include a semiconductor layer containing holes, vacancies, or a set of disjoint columnar structures. In one embodiment, the sacrificial layer 134 can include combinations of any of the aforementioned sacrificial layers. Also, the sacrificial layer 134 can include tensile and compressive layers

The thickness of the sacrificial layer 134 can be selected to result in maximum stresses and strains within the layer without significantly altering the number of dislocations within the layer. In one embodiment, the thickness of the sacrificial layer 134 can range from about 10 nanometers (nm) to about 500 nanometers (nm). The exact optimal thickness of the sacrificial layer 134 can be determined by growing the sacrificial layer with different thicknesses and determining the limiting thickness that leads to the onset of dislocations. In one embodiment, the optimal thickness of the sacrificial layer 134 can be selected to be about 10% lower than the maximum allowable thickness before the onset of dislocations. U.S. Provisional Application 62/187,707, entitled "A method of releasing group III nitride semiconductor heterostructure," which was filed on 1 Jul. 2015 provides further details of a sacrificial layer and is incorporated herein by reference.

In one embodiment, the semiconductor heterostructure 132 can be separated from the substrate 130 by irradiating the semiconductor layers that can form the heterostructure from the substrate side to decompose the sacrificial layer, thus separating the semiconductor heterostructure 132 from the substrate 130, the semiconductor layer 136 and the buffer layer 138. A laser lift-off is one example of a laser radiation technique that can be used to lift semiconductor layers such as a semiconductor heterostructure from a substrate. A laser lift-off is a well-known technique in the art that is used to separate semiconductor layers from a substrate, which can result in improved characteristics of a subsequently fabricated optoelectronic device. U.S. Provisional Application 62/187,707 provides further details of several laser-lift off techniques that can be used to irradiate group III nitride semiconductor layers from the substrate side to decompose a sacrificial layer. As shown in the right-hand side of FIG. 12, the semiconductor heterostructure 132 is lifted off the substrate 130, the semiconductor layer 136 and the buffer layer 138 upon the application of a laser emission 148 (left-hand side of FIG. 12). In particular, the laser emission at a specified wavelength is absorbed by the sacrificial layer 134, causing it to decompose, separating the semiconductor heterostructure 132 from the substrate 130.

15

FIGS. 13A-13C show multiple views of an optoelectronic device 150 formed from the semiconductor heterostructure 132 depicted in FIG. 12 after a laser lifted off from the substrate 130 according to an embodiment. In particular, FIG. 13A shows a cross-sectional view of the optoelectronic device 150 taken from a cut line AA in FIG. 13B, which shows a top plan view of a top surface 152 of the optoelectronic device 150, while FIG. 13C shows a bottom plan view of a bottom surface 154 of the optoelectronic device 150.

As shown in FIGS. 13A and 13C, the bottom surface 154 of the optoelectronic device 150 can have a metallic n-type contact 156 having a plurality of metallic domains 158 connected by electrical contacts 159. In particular, the metallic n-type contact 156 and connected metallic domains 158 can be formed on a first side 160 of the n-type contact layer 144 with an electrical contact 161, such as an n-type electrical contact, coupled to the metallic n-type contact 156. The metallic n-type contact 156 and connected metallic domains 158 can serve to conduct electrical current through the device 150 and/or scatter or reflect the light generated by the device 150. In one embodiment, the metallic n-type contact 156 and connected metallic domains 158 can be made from materials that can include, but are not limited to, titanium, nickel, chromium, a combination of two or more of the materials, and/or the like. It is noted that the electrical contacts 159 that connect the metallic domains 158 can be made sufficiently thin to not pose a significant obstruction to the emitted light from the optoelectronic device 150. The metallic domains 158, which can be n-type domains, can also cover a small fraction of the area of the first side 160 of the metallic n-type contact 156 as not to pose a significant obstruction to the emitted light.

FIG. 13C also shows that the bottom surface 154 of the optoelectronic device 150 can have roughness elements 162 to improve light extraction from the device. In particular, the roughness elements 162 are interspersed with the metallic domains 158 of the metallic n-type contact 156. The roughness elements can include, but are not limited to, protrusions within the substrate, externally deposited roughness elements comprising shapes of Al_2O_3 or SiO_2 , and/or the like.

As shown in FIGS. 13A and 13B, the top surface 152 of the optoelectronic device 150 can have metallic contact domains 164 formed thereon with an electrical contact 166 coupled thereto. In one embodiment, the metallic contact domains 164 can be p-type metallic contact domains that are formed on a side 168 of the p-type contact layer 142, and the electrical contact 166 can be a p-type electrical contact. As shown in FIG. 13B, the metallic contact domains 164 can be located on various locations throughout the side 168 of the p-type contact layer 142. Each of these metallic contact domains 164 can be coupled to an electrical contact 166. In one embodiment, the p-type metallic contact domains 164 can be made from materials that can include, but are not limited to, nickel, rhodium, palladium, aluminum, and/or the like. In an embodiment, a metallic contact domain 164 comprises a multi-layer metallic structure with the first metallic layer being nickel. The electrical contact 166, which as noted above can be a p-type electrical contact, can be made from materials that can include, but are not limited to, UV reflective material, aluminum, rhodium or other conductive and partially UV reflective metal, and/or the like.

The optoelectronic device 150 can also include UV reflective elements 170 that can protect the p-type contact layer electrical contact 166 by preventing emitted UV radiation from being absorbed by the p-type contact layer electrical contact 166. In one embodiment, the reflective elements 170 can be incorporated or embedded within the p-type contact

16

layer 142. In one embodiment, the reflective elements 170 can be incorporated in multiple levels of the p-type contact layer 142. As shown in FIG. 13A, the reflective elements 170 in each level can be staggered with reflective elements in an adjacent level such that there is an offset in position between elements in the different levels. It is understood that the two levels depicted in FIG. 13A are illustrative of one example, and that it is possible to have more levels, or only one level.

The reflective elements 170 can include, but are not limited to, a dielectric, metallic reflective islands, Bragg mirrors, omnidirectional reflectors such as combination of metallic and dielectric films, and combinations thereof. In an embodiment where the reflective elements 170 are formed from Bragg mirrors, these elements can include alternating layers of dielectric with at least one of the layers being Hf_2O_3 . In another embodiment, the Bragg mirrors can be formed from alternating layers of one of Hf_2O_3 and Al_2O_3 , H_2O_3 and SiO_2 , and Al_2O_3 and SiO_2 . The alternating layers of H_2O_3 and SiO_2 can have the highest contrast in the index of refraction, and thus, can provide the best reflection. These types of Bragg mirrors can be obtained by depositing alternative sequences of the dielectric material with subsequent patterning. It is understood that several deposition patterning and overgrowth steps may be needed to produce the right combination of reflective domains such that the reflective elements 170 can have the staggered arrangement illustrated in FIG. 13A. The Bragg mirrors can also be combined with a highly reflective layer. As used herein, a highly reflective layer is a layer that is at least 50% reflective to a normal radiation. For example, the highly reflective layer can include a metallic layer such as aluminum. In another embodiment, the highly reflective layer can include a dielectric or a polymer layer that is diffusively reflective such as polytetrafluoroethylene (PTFE), a highly ultraviolet reflective expanded polytetrafluoroethylene (ePTFE) membrane (e.g., GORE® Diffuse Reflector Material), and/or the like.

Although not shown in the figures, the reflective elements 170 can be incorporated within the n-type contact layer 144. In this manner, the reflective elements 170 can aid in improving light extraction of the optoelectronic device 150.

The top surface 152 of the optoelectronic device 150 can further include a p-type metallic contact 172 having p-type metallic domains 174 formed on the side 168 of the p-type contact layer 142. Each of the p-type metallic domains 174 can be separated from adjacent p-type metallic domains 174 by a predetermined spacing. In one embodiment, as shown in FIGS. 13A-13B, the p-type metallic domains 174 can be separated by a p-type metallic contact domain 164. The p-type metallic domains 174 serve to reflect the light, while the domains 164 can be used primarily for delivering current to the semiconductor structure. In one embodiment, the p-type metallic domains 174 can be made from materials that can include, but are not limited to, UV reflective material, such as aluminum or rhodium.

Regions between the p-type metallic contact domain 164 and the p-type metallic domains 174 can include a transparent or reflective domain 176. It is understood for clarity that only one transparent or reflective domain 176 is shown in FIG. 13B, however, it is understood that more of these domains can be deployed on the top surface 152 of the optoelectronic device 150. In one embodiment, the transparent or reflective domain 176 can include either a UV transparent or partially UV transparent material or reflective Bragg mirrors that act as UV reflective domains. In another embodiment, the domain 176 can include omnidirectional

17

mirrors such as a layer of dielectric and a layer of highly reflective metal. In an embodiment the highly reflective metal can be substituted by a highly ultraviolet reflective expanded polytetrafluoroethylene (ePTFE) membrane (e.g., GORE® Diffuse Reflector Material), and/or the like.

The top surface **152** of the optoelectronic device **150** can also have a passivation layer **178** with or without disjoint domains **180**. As shown in FIGS. **13A-13B**, the passivation layer **178** and the disjoint domains **180** can be formed on a surface of the p-type contact layer **142**. In one embodiment, the passivation layer **178** and the disjoint domains **180** can be formed underneath the metallic p-type contact domain **164**. The passivation layer **178** can function to reduce deterioration of the surface, and possible recombination effects at the surface, while the role of the disjoint domains **180** is to reduce absorption of light at the p-type surface. As shown in FIG. **13A**, electrical contacts **182** can connect the disjoint domains **180** to the metallic domains **158** of the metallic n-type contact **156** so that the domains **180** can form an electrical network. In one embodiment, the passivation layer **178** can include, but is not limited to, a dielectric material such as SiO_2 , Al_2O_3 , Si_3N_4 , and/or the like. In one embodiment, the disjoint domains **180** can include, but are not limited to, nickel and rhodium based domains.

It is understood that not all of the elements described for the optoelectronic device **150** as shown in FIGS. **13A-13C** are necessary for use. For example, a regular contact structure can be used in conjunction with the reflective elements **170**. As used herein, a regular contact structure is a continuous metallic layer deposited over a semiconductor layer, which is followed by annealing to form a contact to the semiconductor layer. Alternatively, the reflective elements **170** can be absent from the optoelectronic device **150**. In such an embodiment, the contact structure can utilize the disjoint domains **180**. Alternatively, it is understood that reflective elements **170** that utilize Bragg mirrors do not have to be arranged in a staggered formation and can have other formations. In addition, it is understood that details of the n-type contact layer **144** can also vary. For example, the n-type contact layer **144** can include conductive, partially transparent oxide domains. In addition, the exact position of the roughness elements **162** can also be varied. Furthermore, it is possible that the n-type contact layer **144** can take the form of the structure depicted in FIG. **11A** after using a lift-off technique. In this embodiment, then the entire surface **160** of the n-type contact layer **144** can contain roughness elements. Furthermore, the metallic n-type contact **156** and the connected metallic domains **158** of the n-type contact layer **144** can be partially located on the surface **160**. In this manner, it would be partially deposited as shown in FIG. **11A**.

The optoelectronic device **150** depicted in FIGS. **13A-13C**, which can take the form of a vertical device having reflective, transparent and contacts can have several benefits. A first benefit is that there will be vertical current flow in the device that avoids current crowding, which is due to the location of the metallic p-type contact domains **164** and the n-type contact **156**. This makes the optoelectronic device **150** suited to operate as a vertical light emitting diode having a vertical structure obtained through a laser lift-off technique. A second benefit is that the optoelectronic device **150** can have a larger emitting area as there is no area required for placing the n-type contact.

Various embodiments of the semiconductor structures described herein can be fabricated using any solution, including patterning, masking, epitaxial growth, and/or the like. An illustrative solution for producing a laterally inho-

18

mogeneous semiconductor structure includes depositing group III nitride semiconductor alloys under a faceted and/or three-dimensional growth mode as shown and described in U.S. Pat. No. 7,812,366. This solution is notably different from conventional approaches of growing AlGaIn films and can lead to a surface morphology having large scale faceting evidencing metal droplets. In conventional approaches, the films are typically produced at a very high gallium flux, which results in a surface of the AlGaIn film typically having a smooth morphology. In another embodiment described herein, inhomogeneous regions within a semiconductor structure can be produced using a MOCVD approach, which is distinctly different from the approach described in U.S. Pat. No. 7,812,366.

Ternary and quaternary nitride semiconductor epitaxial layers inherently grow inhomogeneously due to contrasting optimum growth conditions needed for respective binary layers. In an embodiment, inhomogeneity in aluminum-containing nitride layers is further enhanced by intentionally lowering a mobility of aluminum adatoms. For example, aluminum mobility on the growing surface is strongly influenced by growth temperature and V/III molar ratio. In an illustrative embodiment, three dimensional inhomogeneous structures are formed with V/III ratio being above 1000 (e.g., in a range between 1000 and 100000) and growth temperatures being in the range of 500-1300 degrees Celsius. Adjacent semiconductor layers can be grown using such a group V/III ratio and growth temperatures, while varying a molar fraction of one or more of the elements (e.g., a molar fraction of aluminum can differ by at least one percent between adjacent layers).

In one embodiment, the invention provides a method of designing and/or fabricating a circuit that includes one or more of the devices designed and fabricated as described herein (e.g., including one or more emitting devices including a semiconductor structure described herein). To this extent, FIG. **14** shows an illustrative flow diagram for fabricating a circuit **1026** according to an embodiment. Initially, a user can utilize a device design system **1010** to generate a device design **1012** for a semiconductor device as described herein. The device design **1012** can comprise program code, which can be used by a device fabrication system **1014** to generate a set of physical devices **1016** according to the features defined by the device design **1012**. Similarly, the device design **1012** can be provided to a circuit design system **1020** (e.g., as an available component for use in circuits), which a user can utilize to generate a circuit design **1022** (e.g., by connecting one or more inputs and outputs to various devices included in a circuit). The circuit design **1022** can comprise program code that includes a device designed as described herein. In any event, the circuit design **1022** and/or one or more physical devices **1016** can be provided to a circuit fabrication system **1024**, which can generate a physical circuit **1026** according to the circuit design **1022**. The physical circuit **1026** can include one or more devices **1016** designed as described herein.

In another embodiment, the invention provides a device design system **1010** for designing and/or a device fabrication system **1014** for fabricating a semiconductor device **1016** as described herein. In this case, the system **1010**, **1014** can comprise a general purpose computing device, which is programmed to implement a method of designing and/or fabricating the semiconductor device **1016** as described herein. Similarly, an embodiment of the invention provides a circuit design system **1020** for designing and/or a circuit fabrication system **1024** for fabricating a circuit **1026** that includes at least one device **1016** designed and/or fabricated

19

as described herein. In this case, the system **1020**, **1024** can comprise a general purpose computing device, which is programmed to implement a method of designing and/or fabricating the circuit **1026** including at least one semiconductor device **1016** as described herein.

In still another embodiment, the invention provides a computer program fixed in at least one computer-readable medium, which when executed, enables a computer system to implement a method of designing and/or fabricating a semiconductor device as described herein. For example, the computer program can enable the device design system **1010** to generate the device design **1012** as described herein. To this extent, the computer-readable medium includes program code, which implements some or all of a process described herein when executed by the computer system. It is understood that the term "computer-readable medium" comprises one or more of any type of tangible medium of expression, now known or later developed, from which a stored copy of the program code can be perceived, reproduced, or otherwise communicated by a computing device.

In another embodiment, the invention provides a method of providing a copy of program code, which implements some or all of a process described herein when executed by a computer system. In this case, a computer system can process a copy of the program code to generate and transmit, for reception at a second, distinct location, a set of data signals that has one or more of its characteristics set and/or changed in such a manner as to encode a copy of the program code in the set of data signals. Similarly, an embodiment of the invention provides a method of acquiring a copy of program code that implements some or all of a process described herein, which includes a computer system receiving the set of data signals described herein, and translating the set of data signals into a copy of the computer program fixed in at least one computer-readable medium. In either case, the set of data signals can be transmitted/received using any type of communications link.

In still another embodiment, the invention provides a method of generating a device design system **1010** for designing and/or a device fabrication system **1014** for fabricating a semiconductor device as described herein. In this case, a computer system can be obtained (e.g., created, maintained, made available, etc.) and one or more components for performing a process described herein can be obtained (e.g., created, purchased, used, modified, etc.) and deployed to the computer system. To this extent, the deployment can comprise one or more of: (1) installing program code on a computing device; (2) adding one or more computing and/or I/O devices to the computer system; (3) incorporating and/or modifying the computer system to enable it to perform a process described herein; and/or the like.

The foregoing description of various aspects of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously, many modifications and variations are possible. Such modifications and variations that may be apparent to an individual in the art are included within the scope of the invention as defined by the accompanying claims.

What is claimed is:

1. A semiconductor heterostructure, comprising:

an active region;

a metallic contact;

a group III nitride semiconductor layer located between the active region and the metallic contact, the semiconductor layer including a plurality of inhomogeneous

20

regions arranged within multiple levels of the semiconductor layer along a height direction of the semiconductor layer, wherein some of the inhomogeneous regions in a first level of the semiconductor layer are vertically offset from inhomogeneous regions in a second level of the semiconductor layer, and wherein the plurality of inhomogeneous regions include one or more of a set of transparent regions, a set of reflective regions and/or a set of conductive regions, each of the inhomogeneous regions having a set of attributes differing from a group III nitride material forming the semiconductor layer.

2. The semiconductor heterostructure of claim 1, wherein each of the inhomogeneous regions in the first level and the second level of the semiconductor layer includes a set of reflective regions.

3. The semiconductor heterostructure of claim 1, wherein each of the plurality of inhomogeneous regions in the first level of the semiconductor layer extend into the metallic contact and each of the plurality of inhomogeneous regions in the second level of the semiconductor layer are located at an interface of the semiconductor layer.

4. The semiconductor heterostructure of claim 1, wherein all of the inhomogeneous regions in the first level of the semiconductor layer are staggered with the inhomogeneous regions in the second level of the semiconductor layer to form a checkerboard arrangement of the inhomogeneous regions within the semiconductor layer.

5. The semiconductor heterostructure of claim 1, wherein the inhomogeneous regions in the first level of the semiconductor layer each has a surface contacting the metallic contact, wherein at least one metal protrusion from the metallic contact extends into each inhomogeneous region.

6. The semiconductor heterostructure of claim 5, wherein each of the inhomogeneous regions in the first level of the semiconductor layer comprises a set of conductive regions and each of the inhomogeneous regions in the second level of the semiconductor layer comprises a set of reflective regions.

7. The semiconductor heterostructure of claim 6, wherein each of the inhomogeneous regions in the second level of the semiconductor layer has at least one metal protrusion extending from the metallic contact into the semiconductor layer that is directed to a surface of the inhomogeneous region without contact thereof.

8. A method, comprising:

fabricating a semiconductor heterostructure, wherein the semiconductor heterostructure comprises:

an active region;

a metallic contact;

a single group III nitride semiconductor layer located between the active region and the metallic contact, the semiconductor layer including a plurality of inhomogeneous regions arranged within multiple levels of the semiconductor layer along a height direction of the semiconductor layer, wherein some of the inhomogeneous regions in a first level of the semiconductor layer are vertically offset from inhomogeneous regions in a second level of the semiconductor layer, and wherein the plurality of inhomogeneous regions include one or more of a set of transparent regions, a set of reflective regions and/or a set of conductive regions, each of the inhomogeneous regions having a set of attributes differing from a group III nitride material forming the semiconductor layer.

21

9. The method of claim 8, wherein the fabricating includes:

epitaxially growing a portion of the group III nitride semiconductor layer;

forming at least one of the sets of inhomogeneous regions on a surface of the portion of the group III nitride semiconductor layer; and

epitaxially over-growing the group III nitride semiconductor layer after the forming.

10. The method of claim 9, wherein the forming includes: depositing the at least one of the sets of inhomogeneous regions using one of: thermal evaporation, magnetron sputtering, ion-beam deposition, or laser beam evaporation; and

patterning the at least one of the sets of inhomogeneous regions using photolithography.

11. An optoelectronic device, comprising:

a semiconductor heterostructure having a first side and a second side, the semiconductor heterostructure including:

a group III nitride semiconductor layer including a plurality of inhomogeneous regions, each inhomogeneous region having a set of attributes differing from a group III nitride material forming the semiconductor layer, wherein the plurality of inhomogeneous regions include:

a set of first inhomogeneous regions configured based on radiation having a target wavelength, wherein the set of first inhomogeneous regions are at least one of: transparent to the radiation or reflective of the radiation; and

a set of second inhomogeneous regions having a conductivity at least ten percent higher than a conductivity of the set of first inhomogeneous regions, wherein each of the sets of inhomogeneous regions occupy at least five percent of at least one of: a lateral planar area of the semiconductor layer or a volume of the semiconductor

22

layer, and wherein at least some of the sets of inhomogeneous regions do not fully overlap.

12. The optoelectronic device of claim 11, further comprising a first metallic contact having a plurality of connected metallic domains formed on the first side of the semiconductor heterostructure.

13. The optoelectronic device of claim 11, further comprising a plurality of roughness elements formed on the first side of the semiconductor heterostructure.

14. The optoelectronic device of claim 11, further comprising a plurality of metallic contact domains formed on the second side of the semiconductor heterostructure.

15. The optoelectronic device of claim 11, further comprising a plurality of reflective elements incorporated within the semiconductor heterostructure proximate a surface of the second side of the semiconductor heterostructure.

16. The optoelectronic device of claim 15, wherein the plurality of reflective elements comprise one of dielectrics, metallic reflective islands, Bragg mirrors and combinations thereof.

17. The optoelectronic device of claim 15, wherein the plurality of reflective elements comprise alternating layers of one of Hf_2O_3 and Al_2O_3 , H_2O_3 and SiO_2 , and Al_2O_3 and SiO_2 .

18. The optoelectronic device of claim 11, further comprising a plurality of Bragg domains formed on the second side of the semiconductor heterostructure.

19. The optoelectronic device of claim 11, further comprising a second metallic contact having metallic domains formed on the second side of the semiconductor heterostructure, each of the metallic domains separated from an adjacent metallic domain by a predetermined spacing.

20. The optoelectronic device of claim 11, further comprising a passivation layer formed on the second side of the semiconductor heterostructure and a plurality of disjoint domains interspersed within the passivation layer.

* * * * *