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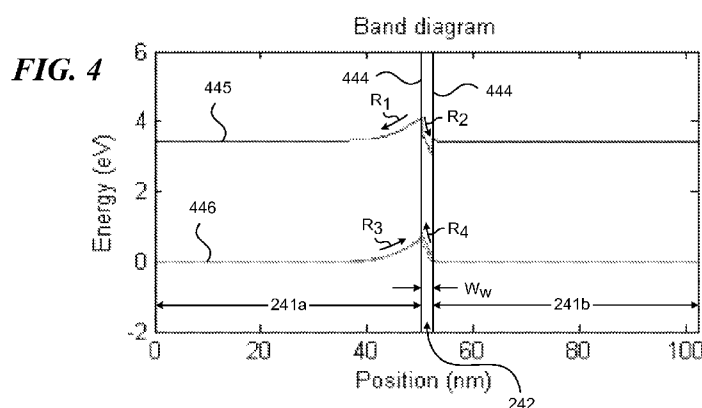
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(54) Title: WAVELENGTH CONVERTERS, INCLUDING POLARIZATION-ENHANCED CARRIER CAPTURE CONVERTERS, FOR SOLID STATE LIGHTING DEVICES, AND ASSOCIATED SYSTEMS AND METHODS



(57) **Abstract:** Wavelength converters, including polarization-enhanced carrier capture converters, for solid state lighting devices, and associated systems and methods are disclosed. A solid state radiative semiconductor structure in accordance with a particular embodiment includes a first region having a first value of a material characteristic and being positioned to receive radiation at a first wavelength. The structure can further include a second region positioned adjacent to the first region to emit radiation at a second wavelength different than the first wavelength. The second region has a second value of the material characteristic that is different than the first value, with the first and second values of the characteristic forming a potential gradient to drive electrons, holes, or both electrons and holes in the radiative structure from the first region to the second region. In a further particular embodiment, the material characteristic includes material polarization. Accordingly, the first region has a first material polarization value and the second region has a second material polarization value different than the first material polarization value, with the differences between the first and second material polarization values forming an electric field at an interface between the first and second regions.

WAVELENGTH CONVERTERS, INCLUDING POLARIZATION-
ENHANCED CARRIER CAPTURE CONVERTERS, FOR SOLID STATE
LIGHTING DEVICES, AND ASSOCIATED SYSTEMS AND METHODS

TECHNICAL FIELD

[0001] The present technology is directed generally to wavelength converters, including polarization-enhanced carrier capture converters, for solid state lighting devices, and associated systems and methods. Wavelength converters in accordance with the present technology are suitable for LEDs and other radiation emitting devices.

BACKGROUND

[0002] Solid state lighting ("SSL") devices are used in a wide variety of products and applications. For example, mobile phones, personal digital assistants ("PDAs"), digital cameras, MP3 players, and other portable electronic devices utilize SSL devices (e.g., LEDs) for backlighting and other purposes. SSL devices are also used for signage, indoor lighting, outdoor lighting, and other types of general illumination. Figure 1A is a cross-sectional view of a conventional SSL device 10a with lateral contacts. As shown in Figure 1A, the SSL device 10a includes a substrate 20 carrying an LED structure 11 having an active region 14, e.g., containing gallium nitride/indium gallium nitride (GaN/InGaN) multiple quantum wells ("MQWs"), positioned between N-type GaN 15 and P-type GaN 16. The SSL device 10a also includes a first contact 17 on the P-type GaN 16 and a second contact 19 on the N-type GaN 15. The first contact 17 typically includes a transparent and conductive material (e.g., indium tin oxide ("ITO")) to allow light to escape from the LED structure 11. In operation, electrical power is provided to the SSL device 10a via the contacts 17, 19, causing the active region 14 to emit light.

[0003] Figure 1B is a cross-sectional view of another conventional LED device 10b in which the first and second contacts 17 and 19 are opposite each other, e.g., in a vertical rather than lateral configuration. During formation of the LED device 10b, a growth substrate, similar to the substrate 20 shown in Figure 1A, initially carries an N-type GaN 15, an active region 14 and a P-type GaN 16. The first contact 17 is disposed on the P-type GaN 16, and a carrier 21 is

attached to the first contact 17. The substrate 20 is removed, allowing the second contact 19 to be disposed on the N-type GaN 15. The structure is then inverted to produce the orientation shown in Figure 1B. In the LED device 10b, the first contact 17 typically includes a reflective and conductive material (e.g., silver or aluminum) to direct light toward the N-type GaN 15.

[0004] One drawback with existing LEDs is that they do not emit white light. Instead, LEDs typically emit light within only a narrow wavelength range. For human eyes to perceive the color white, a broad range of wavelengths is needed. Accordingly, one conventional technique for emulating white light with LEDs is to deposit a converter material (e.g., a phosphor) on an LED die. Figure 1C shows a conventional SSL device 10c that includes a support 2 carrying an LED die 4 and a converter material 6. In operation, an electrical voltage is applied to the die 4 via contacts having an arrangement generally similar to that shown in either Figure 1A or Figure 1B. In response to the applied voltage, the active region of the LED die 4 produces a first emission (e.g., a blue light) that stimulates the converter material 6 to emit a second emission (e.g., a yellow light). The combination of the first and second emissions appears white to human eyes if matched appropriately. As discussed in more detail below, using phosphor converter materials to "convert" blue light into white light has certain drawbacks. Accordingly, there is a need for light emitting devices that can produce light at a particular wavelength without phosphor converter materials.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale. Instead, emphasis is placed on clearly illustrating the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0006] Figure 1A is a partially schematic, cross-sectional diagram of an SSL device having a lateral arrangement in accordance with the prior art.

[0007] Figure 1B is a partially schematic, cross-sectional diagram of another SSL device having a vertical arrangement in accordance with the prior art.

[0008] Figure 1C is a partially schematic, cross-sectional diagram of a light emitting device having a phosphor converter material positioned in accordance with the prior art.

[0009] Figure 2 is a partially schematic, cross-sectional illustration of a system that includes a light source and a radiative structure configured in accordance with an embodiment of the presently disclosed technology.

[0010] Figures 3A-3F are schematic, perspective views of various crystal planes in a GaN/InGaN material in accordance with embodiments of the presently disclosed technology.

[0011] Figure 4 is a band diagram illustrating interfaces between materials having different material polarizations in accordance with an embodiment of the presently disclosed technology.

[0012] Figure 5 is a partially schematic illustration of a portion of a radiative structure having quantum wells and barriers alternating in accordance with an embodiment of the presently disclosed technology.

[0013] Figure 6 is a band diagram illustrating the behavior expected of a representative structure shown in Figure 5, in accordance with an embodiment of the presently disclosed technology.

[0014] Figures 7A and 7B are band diagrams comparing band gap energies for simulated structures having non-polar characteristics (Figure 7A) and polar characteristics (Figure 7B) in accordance with embodiments of the presently disclosed technology.

DETAILED DESCRIPTION

[0015] Embodiments of the presently disclosed technology are directed generally to wavelength converters for solid state lighting (“SSL”) devices, and associated systems and methods. As used hereinafter, the term “SSL device” generally refers to devices with light emitting diodes (“LEDs”), organic light emitting diodes (“OLEDs”), laser diodes (“LDs”), polymer light emitting diodes (“PLEDs”), and/or other suitable sources of illumination, other than electrical filaments, a plasma, or a gas. Briefly described, a radiation system in accordance with a particular embodiment of the disclosed technology includes a solid state radiative semiconductor structure that has a first region and a second region. The first region has a first value of a material characteristic, and the second region has a second value of the material characteristic that is different than the first value. The first region is positioned to receive radiation at a first wavelength, and the second region is positioned adjacent to the first region to emit radiation at a second wavelength different than the first wavelength. The first and second

values of the characteristic form a potential gradient to drive electrons, holes, or both electrons and holes in the radiative structure from the first region to the second region. Accordingly, the second region can receive optically generated carriers from the first region and emit radiation at the second wavelength. In particular embodiments, the radiative semiconductor structure can be positioned proximate to an energy source that directs radiation at the first wavelength toward the first region of the semiconductor structure. In further particular embodiments, the energy source can include a solid state lighting device, for example, an LED.

[0016] Other systems, methods, features, and advantages of the presently disclosed technology will become apparent to one of ordinary skill in the art. Several details describing structures or processes that are well-known and often associated with such systems and methods, but that may unnecessarily obscure some significant aspects of the disclosure, are not set forth in the following description for purposes of clarity. Moreover, although the following disclosure sets forth several embodiments of different aspects of the technology disclosed herein, several other embodiments can include different configurations or different components than those described in this section. Accordingly, the disclosed technology may have other embodiments with additional elements, and/or without several of the elements described below with reference to Figures 2-7.

[0017] Figure 2 is a partially schematic, cross-sectional illustration of a system 200 that receives or absorbs energy at one wavelength and re-radiates or emits energy at another wavelength. In a particular embodiment, the system 200 includes a support 230 carrying a light source 250. The light source 250 can include an LED or other SSL device, or another device (e.g., a laser) that emits first radiation at a first wavelength A. The system 200 further includes a radiative structure 240 positioned to receive and absorb the first radiation and emit second radiation at a different wavelength E. The radiative structure 240 can include one or more first regions 241 (e.g., absorptive regions) and one or more second regions 242 (e.g., emissive regions). For example, in the embodiment shown in Figure 2, the radiative structure 240 includes two absorptive regions 241, shown as a first absorptive region 241a and a second absorptive region 241b, positioned on opposite sides of a single emissive region 242. As used herein, the term “absorptive region” refers generally to a region having suitable (e.g., strong) absorptive characteristics at the first wavelength A emitted by the light source 250. The term “emissive region” refers generally to a region having suitable (e.g., strong) emissive characteristics at the second wavelength E. In any of these embodiments, the radiative structure

240 can replace conventional phosphor structures and can accordingly modify the spectrum of light emitted by overall system 200 without the use of phosphors, or with a reduced use of phosphors. Further features and advantages of representative systems are described below with reference to Figures 3A-7.

[0018] Particular embodiments of the presently disclosed technology are described below in the context of radiative structures having different regions with different material polarizations, resulting, for example, from a difference in material composition or strain of the materials forming the regions and a particular crystal orientation. In other embodiments, the material characteristics of the regions can have other differing characteristics. For example, the regions can have different compositions that produce different bandgap energies. Particular embodiments are disclosed in co-pending U.S. Application No. 13/215,998, titled "Wavelength Converters for Solid State Lighting Devices, and Associated Systems and Methods", filed August 23, 2011, and incorporated herein by reference.

[0019] Figures 3A-3F are schematic perspective views of various crystal planes in a portion of a GaN/InGaN material. In Figures 3A-3F, Ga (or Ga/In) and N atoms are schematically shown as large and small spheres, respectively. As shown in Figures 3A-3F, the GaN/InGaN material has a wurtzite crystal structure with various lattice planes or facets as represented by corresponding Miller indices. A discussion of the Miller index can be found in the *Handbook of Semiconductor Silicon Technology* by William C. O'Mara.

[0020] As used hereinafter, a "polar plane" generally refers to a crystal plane in a crystal structure that contains only one type of atom. For example, as shown in Figure 2A, the polar plane denoted as the "*c*-plane" in the wurtzite crystal structure with a Miller index of (0001) contains only Ga atoms. Similarly, other polar planes in the wurtzite crystal structure may contain only N atoms and/or other suitable type of atoms.

[0021] As used hereinafter, a "non-polar plane" generally refers to a crystal plane in a crystal structure that is generally perpendicular to a polar plane (e.g., to the *c*-plane). For example, Figure 3B shows a non-polar plane denoted as the "*a*-plane" in the wurtzite crystal structure with a Miller index of (11 $\bar{2}$ 0). Figure 3C shows another non-polar plane denoted as the "*m*-plane" in the wurtzite crystal structure with a Miller index of (10 $\bar{1}$ 0). Both the *a*-plane and the *m*-plane are generally perpendicular to the *c*-plane shown in Figure 3A.

[0022] As used hereinafter, a "semi-polar plane" generally refers to a crystal plane in a crystal structure that is canted relative to a polar plane (e.g., to the *c*-plane) without being perpendicular to the polar plane. For example, as shown in Figures 3D-3F, each of the semi-polar planes in the wurtzite crystal structure with Miller indices of $(10\bar{1}\bar{3})$, $(10\bar{1}1)$, and $(11\bar{2}2)$ form an angle with the *c*-plane shown in Figure 3A. The angle is greater than 0° but less than 90° . Only particular examples of crystal planes are illustrated in Figures 3A-3F. Accordingly, the polar, non-polar, and semi-polar planes can also include other crystal planes not specifically illustrated in Figures 3A-3F. In general, the designer can select the material polarization of the materials forming wavelength converters in accordance with embodiments of the present disclosure by selecting the angle along which a corresponding epitaxial substrate is cut. This in turn determines the material polarization of the subsequent epitaxially grown layers. In general, different layers will have the same crystal orientation (as individual layers are grown epitaxially on the layer below), but will have different material polarizations, e.g. due to different concentrations of particular constituents, such as indium.

[0023] As described above with reference to Figure 2, wavelength converters in accordance with the present technology can include one or more first or absorptive regions, and one or more second or emissive regions. The emissive regions can receive carriers from adjacent absorptive regions and can accordingly form quantum wells. Figure 4 is a representative band diagram illustrating a conduction band 445 and a valance band 446 for a second region 242 (e.g., a quantum well) surrounded by corresponding first regions 241a, 241b. In a particular aspect of this embodiment, the second region 242 is a single, 2nm-wide gallium indium nitride structure grown along the *c*-axis. In still a further particular embodiment, the composition of the second region 242 is $\text{Ga}_{0.78}\text{In}_{0.22}\text{N}$. In other embodiments, the second region 242 can include other gallium indium nitride structures, other III-nitride heterostructures, and/or other non-Group III heterostructures (e.g., Group II or Group VI heterostructures). In any of these embodiments, the second region 242 can form interfaces (e.g., heterointerfaces) 444 at the junctions between the second region 242 and the surrounding first regions 241a, 241b. The heterointerfaces 444 may be graded or abrupt, depending upon the particular embodiment. In general, based on the different material polarizations in the first and second regions, the heterointerfaces create electric fields that assist in the transport of optically generated electron-hole pairs from the first regions 241a, 241b to the second region 242.

[0024] In a particular aspect of an embodiment shown in Figure 4, the discontinuity in the polarization field between the second region 242 and the adjacent first regions 241a, 241b creates a negative sheet charge to the left of the second region 242. This negative sheet charge repels electrons and pushes the edge of the conduction band 445 upwards. To the right of the second region 242 is a positive sheet charge which attracts electrons and pulls the conduction band edge 445 down. The electric field to the left of the second region 242 pushes electrons to the left, as indicated by arrow R1. In the second region 242, an electric field pushes the electrons to the right, as indicated by arrow R2. Holes are pushed in the opposite direction: to the right in the first region 241a (as indicated by arrow R3) and to the left in the second region (as indicated by arrow R4).

[0025] As described further below with reference to Figures 5-7B, radiative structures can be designed with multiple quantum wells separated by corresponding barriers in such a way that the polarization mismatches at the heterointerfaces between these structures create electric fields that funnel carriers (e.g., holes and/or electrons) into the adjacent layers, so as to produce emitted light at a target wavelength.

[0026] Figure 5 is a schematic illustration of a representative radiative structure 540 that includes multiple quantum wells 542 (four are shown in Figure 5), interleaved with multiple barriers 543 (four are shown in Figure 5), and sandwiched between corresponding first regions 541a, 541b. Embodiments of the present disclosure are not limited to those shown in Figure 5. For example, other embodiments can include any suitable number of quantum wells and barriers, depending on device characteristics. In particular embodiments, the first regions 541a, 541b can include N-GaN. In the illustrated embodiment, the lower first region 541a can provide a substrate for epitaxial growth of the barriers 543 and the quantum wells 542. The upper first region 541b can be eliminated in some embodiments. However, an advantage of the upper first region 541b is that it can separate the quantum wells 542 from the outermost surface of the structure 540, thus reducing or eliminating surface charges that can adversely affect the performance of the structure 540. The quantum well composition can be $\text{Ga}_{0.78}\text{In}_{0.22}\text{N}$, and the barrier composition can be $\text{Ga}_{0.9}\text{In}_{0.1}\text{N}$, in particular embodiments, and can have other compositions in other embodiments. The doping concentration can be $5 \times 10^{18} \text{ cm}^{-3}$ in the N-GaN and in the barriers 543, and can have other values in other embodiments. The quantum wells 542 and corresponding barriers 543 are stacked (e.g., grown) generally perpendicular to the c-axis, as shown in Figure 5. In other embodiments, the barriers 543 can be N-GaN without

indium. However, an advantage of including indium (or another suitable element) is that it is expected to increase the absorptivity of the barriers 543, and therefore the wavelength conversion efficiency of the structure 540. In still further embodiments, materials other than GaInN can be used for the quantum wells 542 and the barriers 543. Suitable materials include zinc oxide or other materials having a wurtzite crystal structure.

[0027] Figure 6 illustrates a band diagram corresponding to the structure described above with reference to Figure 5. Each of the quantum wells 542 has a well width W_w of approximately 2 nanometers, and each barrier 543 has a barrier width W_B of approximately 10 nanometers. Accordingly, the total absorption thickness (e.g., the thickness of material absorbing incident radiation at a first wavelength) is 48 nanometers, while the total quantum well thickness is 8 nanometers. Both the barriers 543 and the quantum wells 542 absorb incident light. As the light is absorbed, it generates electrons and holes (e.g., optically generated carriers). When the electrons and holes are located in the quantum wells 542, they are at an electropotential minimum (or relative minimum) and are accordingly confined. When electrons are located in the barriers 543, they experience an electric field, which pushes the electron toward a nearby quantum well 542. For example, in the left-most barrier 543 shown in Figure 6, electrons are pushed to the right, as indicated by arrow R5. In the next three barriers 543, the electrons are pushed to the left, as indicated by arrows R6. In a generally similar manner, holes located in a barrier are pushed toward a corresponding quantum well by the field resulting from the difference in polarization between the barrier 543 and the quantum well 542. For example, holes in the right-most three barriers 543 are forced to the right as indicated by arrows R7 and into the adjacent quantum wells 542. Holes in the leftmost barrier 543 are pushed into the adjacent first region 541a as indicated by arrow R8. In this manner, the polarization-induced fields act to funnel electrons and holes into the adjacent quantum wells 542, where they may combine efficiently and emit light (or other radiation) at the target wavelength.

[0028] Figures 7A and 7B illustrate the results of a numerical simulation conducted to demonstrate the efficacy of structures having characteristics generally similar to those described above with reference to Figures 2-6. In this particular simulation, the structures include a stack of nine quantum wells 542, each having a width of approximately 3 nanometers and a composition of $\text{Ga}_{0.8}\text{In}_{0.2}\text{N}$. Neighboring quantum wells 542 are separated by barriers 543 having a width of approximately 100 nanometers and a composition of $\text{Ga}_{0.9}\text{In}_{0.1}\text{N}$. The outermost quantum wells are positioned adjacent to layers of gallium nitride 541a, 541b. The

silicon doping concentration is $5 \times 10^{18} \text{ cm}^{-3}$ in the gallium nitride 541a, 541b and $1 \times 10^{18} \text{ cm}^{-3}$ in the barriers 543. Non-radiative recombination lifetimes in the barriers are assumed to be 5 nanoseconds for both electrons and holes. Figure 7A illustrates a simulation for which the polarization within the structure is zero. This case is analogous to potential wavelength conversion structures with non-polar semiconductors, or with polar semiconductors, but along non-polar directions. Figure 7B illustrates the results when the polarization within the structure is the predicted amount for c-plane gallium indium nitride heterostructures. In both simulations, all layers are assumed to be pseudomorphic (e.g., strained).

[0029] The simulation method solves the Poisson equation and continuity equations for electrons and holes self-consistently. The boundary condition for the simulation is that no current flows in or out of the structure, which is the case if the structure is not connected to an electrical circuit. An undepleted optical pump is assumed to generate electron-hole pairs uniformly within both the quantum wells 542 and the barriers 543. This pump corresponds to an LED or other light source that generates the optical energy absorbed by the radiative structure and reemitted at a different wavelength. The total number of generated carriers is assumed to be equal for the results shown in both Figures 7A and 7B, and the carriers are permitted to move freely through drift and diffusion processes and recombine either non-radiatively (through Shockley-Reed-Hall recombination or Auger recombination) or radiatively, thereby generating light.

[0030] Still referring to Figures 7A and 7B, the steady state band diagrams of the two structures in the presence of optical excitation are shown. The electron and hole quasi-Fermi levels are separated, as expected. The differences between the two cases are clearly shown. In Figure 7B, the polarization produces electric fields that exist in the barriers 543 and that act to direct carriers toward the quantum wells 542 where they accumulate to sufficiently high densities to recombine efficiently. This is not the case for the structure without polarization (shown in Figure 7A), where the lifetime of the carriers generated in the barriers 543 will be longer.

[0031] The ultimate output of the calculation based on the foregoing simulations is the relative rate of radiative and non-radiative recombination. In the structure represented by Figure 7B, the Shockley-Reed-Hall recombination rate was reduced by 30.9%, while the radiative rate was increased by 17.6%. Accordingly, Figures 7A and 7B demonstrate the

efficiency enhancement that maybe obtained by taking advantage of polarization-enhanced carrier capture.

[0032] One feature of at least some of the foregoing embodiments described above with reference to Figures 2-7B is that the disclosed technology can include structures that are selected based on crystal-based material polarization to concentrate carriers in regions selected to emit radiation at particular wavelengths. These structures can more efficiently convert energy received at one wavelength to energy emitted at a second wavelength. An advantage of this arrangement is that it can reduce power consumed by the device, and/or increase the light output by the device, when compared with conventional wavelength converters, for example, phosphor coatings and the like. In particular, the radiative structure can be manufactured and operated with a phosphor.

[0033] From the foregoing, it will be appreciated that specific embodiments of the disclosed technology have been described herein for purposes of illustration, but that various modifications may be made without deviating from the disclosed technology. For example, materials having different material polarizations can be combined based on isotropic and/or anisotropic material polarizations. The material polarizations of adjacent elements in a wavelength converter structure can change abruptly at the hetero interfaces, as was generally shown above, or gradually, e.g., by gradually varying the concentration of indium at the hetero interfaces between GaInN barriers and quantum wells. Certain embodiments of the technology were described in the context of particular materials (e.g., gallium nitride and gallium indium nitride), but in other embodiments, other materials can be used to produce similar results. Certain embodiments of the technology were described above in the context of shifting the wavelength of visible light. In other embodiments similar structures and methods can be used to shift energy at other wavelengths.

[0034] Certain aspects of the technology described in the context of particular embodiments may be combined or eliminated in other embodiments. For example, particular embodiments can include more or fewer barriers and quantum wells than described above with reference to Figures 5-7B. The wavelength conversion structure can include a single first region rather than two, e.g., if the first region is properly doped. The structures described above can be combined with additional structures (e.g., lenses, power sources controllers, and/or other devices) depending upon the functions the structures are intended to perform. Further, while advantages associated with certain embodiments have been described in the context of those

embodiments, other embodiments may also exhibit such advantages, and not all embodiments need necessarily exhibit such advantages to fall within the scope of the present technology. Accordingly, the present disclosure and associated technology can encompass other embodiments not expressly shown or described herein.

CLAIMS

I/We claim:

1. A method for forming a radiation system, comprising:
selecting a radiative structure having a first region and a second region, the first region having a first value of a material characteristic, the second region having a second value of the material characteristic, with the first and second values producing a potential gradient to drive at least one of electrons and holes in the radiative structure from the first region to the second region; and
positioning the radiative structure with the first region proximate to a radiation source to absorb radiation at a first wavelength, and with the second region positioned to receive energy from the first region and emit the energy at a second wavelength different than the first wavelength.
2. The method of claim 1 wherein the material characteristic includes material polarization, and wherein selecting a radiative structure includes selecting a radiative structure with the first region having a first material polarization value and the second region having a second material polarization value different than the first material polarization value, with the differences between the first and second material polarization values forming an electric field at an interface between the first and second regions.
3. The method of claim 1, further comprising:
selecting a first material for the first region based at least in part on the first value of the material characteristic; and
selecting a second material for the second region based at least in part on the second value of the material characteristic.
4. The method of claim 3, further comprising disposing the first and second materials adjacent to and fixed relative to each other.

5. The method of claim 1 wherein selecting the first material includes selecting the first material to include gallium nitride, and wherein selecting the second material includes selecting the second material to include gallium indium nitride.

6. The method of claim 1 wherein selecting the first material includes selecting the first material to include gallium indium nitride with a first concentration of indium, and wherein selecting the second material includes selecting the second material to include gallium indium nitride with a second concentration of indium different than the first.

7. The method of claim 1, further comprising selecting both the first and second materials to have wurtzite crystal structures.

8. The method of claim 1, further comprising selecting both the first and second materials to have the same crystal orientation.

9. A method for forming a radiative system, comprising:
selecting a first material to have a first material polarization and to have stronger absorption than emission at a first wavelength;
selecting a second material to have a second material polarization different than the first material polarization and to have stronger absorption than emission at a second wavelength different than the first wavelength; and
disposing the first and second materials adjacent to each other to produce an electric field at an interface between the two materials, the electric field being oriented to drive electrons, holes, or both electrons and holes from the first material to the second material.

10. The method of claim 9, further comprising fixing the first and second materials relative to each other.

11. The method of claim 9 wherein the electric field includes a first electric field, and wherein the first material includes a first region of the first material and a second region of the first material, and wherein disposing the first and second materials includes disposing the first and second materials with the second material positioned between the first and second regions of

the first material to produce the first electric field at an interface between the second material and the first region, and to produce a second electric field at an interface between the second material and the second region, the first electric field being oriented to drive electrons from the first region to the second material, the second electric field being oriented to drive holes from the second region to the second material.

12. The method of claim 9, further comprising selecting the first and second materials to include a common constituent, with the constituent having a first concentration in the first material and a second concentration different than the first concentration in the second material.

13. The method of claim 12, further comprising selecting the first and second materials to include alloys of gallium nitride.

14. The method of claim 9 wherein disposing the first and second materials includes forming an alternating stack of barriers and quantum wells.

15. A radiation system, comprising:

a solid state radiative semiconductor structure, having:

- a first region positioned to receive radiation at a first wavelength, the first region having a first value of a material characteristic; and
- a second region positioned adjacent to the first region to emit radiation at a second wavelength different than the first wavelength, the second region having a second value of the material characteristic that is different than the first value, with the first and second values of the characteristic forming a potential gradient to drive electrons, holes, or both electrons and holes in the radiative structure from the first region to the second region.

16. The system of claim 15 wherein the material characteristic includes material polarization, and wherein the first region has a first material polarization value and the second region has a second material polarization value different than the first material polarization

value, with the differences between the first and second material polarization values forming an electric field at an interface between the first and second regions.

17. The system of claim 15 wherein the first material includes gallium nitride and the second material includes gallium indium nitride.

18. The system of claim 15 wherein the first material includes gallium indium nitride with a first concentration of indium, and the second material includes gallium indium nitride with a second concentration of indium different than the first.

19. The system of claim 15 wherein both the first and second materials have wurtzite crystal structures.

20. The system of claim 15 wherein both the first and second materials have the same crystal orientation.

21. The system of claim 15 wherein the first region includes a barrier and the second region includes a quantum well, and wherein the system includes a stack of alternating barriers and quantum wells.

22. A radiation system, comprising:

a solid state radiative semiconductor structure, having:

a first region positioned to receive radiation at a first wavelength, the first region having a first material polarization; and

a second region positioned adjacent to the first region to emit radiation at a second wavelength different than the first wavelength, the second region having a second material polarization different than the first material polarization, with the first and second material polarizations forming a potential gradient to drive electrons, holes, or both electrons and holes in the radiative structure from the first region to the second region.

23. The system of claim 22 wherein a composition of the semiconductor structure has a step change at an interface between the first and second regions.

24. The system of claim 22, further comprising an energy source positioned to direct radiation at the first wavelength toward the first region of the semiconductor structure.

25. The system of claim 22 wherein the first and second regions are polar regions and wherein an interface between the first and second regions is at a c-plane of at least one of the first and second regions.

26. The system of claim 22 wherein the first and second regions are semi-polar regions.

27. The system of claim 22 wherein the first region includes a barrier and the second region includes a quantum well, and wherein the system includes a stack of alternating barriers and quantum wells, with individual barriers comprising indium gallium nitride with a first concentration of indium, and with individual quantum well comprising indium gallium nitride with a second concentration of indium greater than the first, and wherein the quantum wells and the barriers have the same wurtzite crystal orientation.

28. A solid state lighting (SSL) system, comprising:
a solid state radiative semiconductor structure, having:

an alternating arrangement of first and second regions, with individual first regions positioned between consecutive second regions, and with individual second regions positioned between consecutive first regions;
wherein

individual first regions are positioned to receive light at a first wavelength, the individual first regions comprising a first material having a first material polarization and a stronger absorptivity than emissivity at the first wavelength;

individual second regions are positioned to receive (a) electrons from one immediately adjacent first region on one side of the individual second region and (b) holes from another immediately adjacent first region on an opposite side of the individual second region due to electrical potential gradients at the interfaces between the individual second region and the immediately adjacent first regions, the individual second regions

comprising a second material different than the first material, the second material having a second material polarization different than the first material polarization and a stronger emissivity than absorptivity at a second wavelength different than the first wavelength.

29. The system of claim 28 wherein individual barriers comprise indium gallium nitride with a first concentration of indium, and individual quantum wells comprise indium gallium nitride with a second concentration of indium greater than the first, and wherein the quantum wells and the barriers have the same wurtzite crystal orientation.

30. The system of claims 28, further comprising an SSL device that includes an active region positioned adjacent to an N-type material and a P-type material, the active region being positioned to emit light at the first wavelength directed to the solid state radiative semiconductor structure.

31. A method for operating a radiative structure, comprising:
receiving radiation of a first wavelength at a first region of a solid state radiative semiconductor structure, the first region having a first material polarization and a first density of electrons and holes;
transmitting electrons from the first region to a second region of the solid state radiative semiconductor structure to increase a density of the electrons at the second region to a second density higher than the first density, the second region having a second material polarization different than the first material polarization; and
combining electrons with holes at the second region to radiate energy at a second wavelength different than the first wavelength.

32. The method of claim 31 wherein the first region is one of a plurality of first regions, and the second region is one of a plurality of second regions, and wherein individual second regions are positioned between consecutive first regions, and wherein transmitting electrons includes transmitting electrons from a first region on one side of the second region, and wherein the method further comprises transmitting holes to the second region from a first region on an opposite side of the second region.

33. The method of claim 31 wherein radiating energy at the second wavelength includes radiating energy at the second wavelength in the visible spectrum, without radiating the energy from a phosphor.

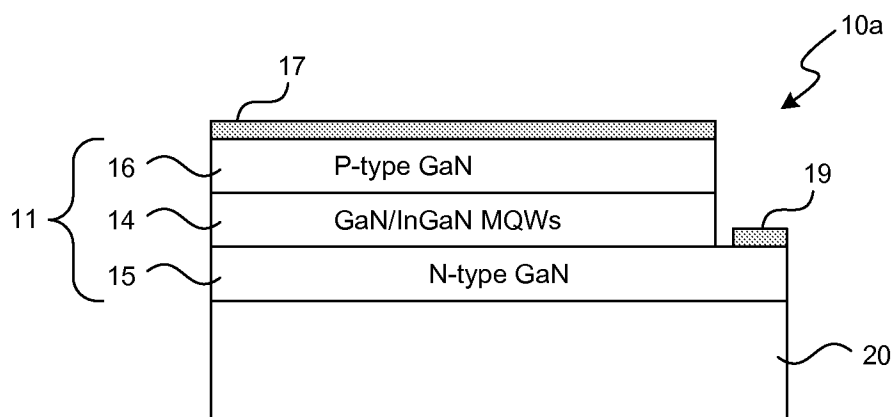


FIG. 1A
(Prior Art)

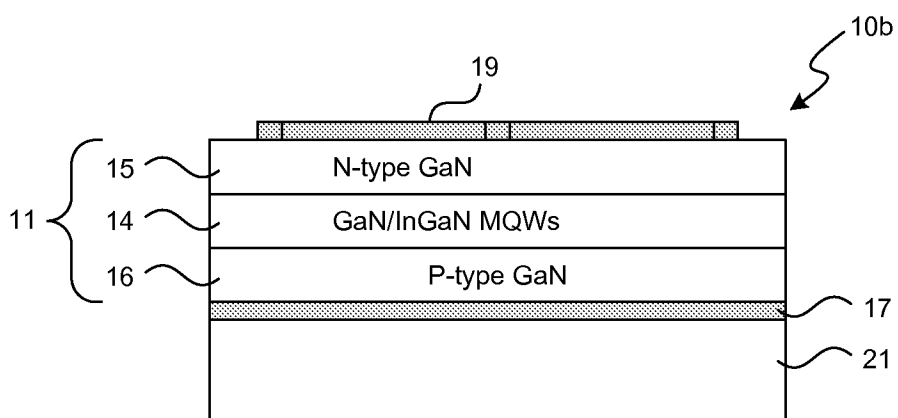


FIG. 1B
(Prior Art)

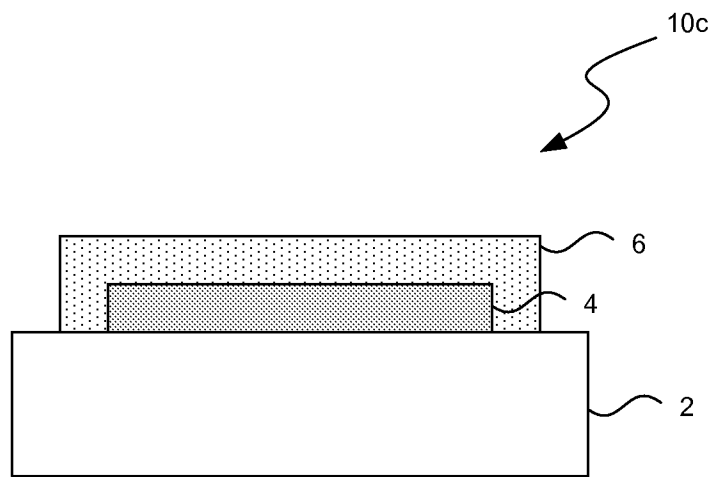


FIG. 1C
(Prior Art)

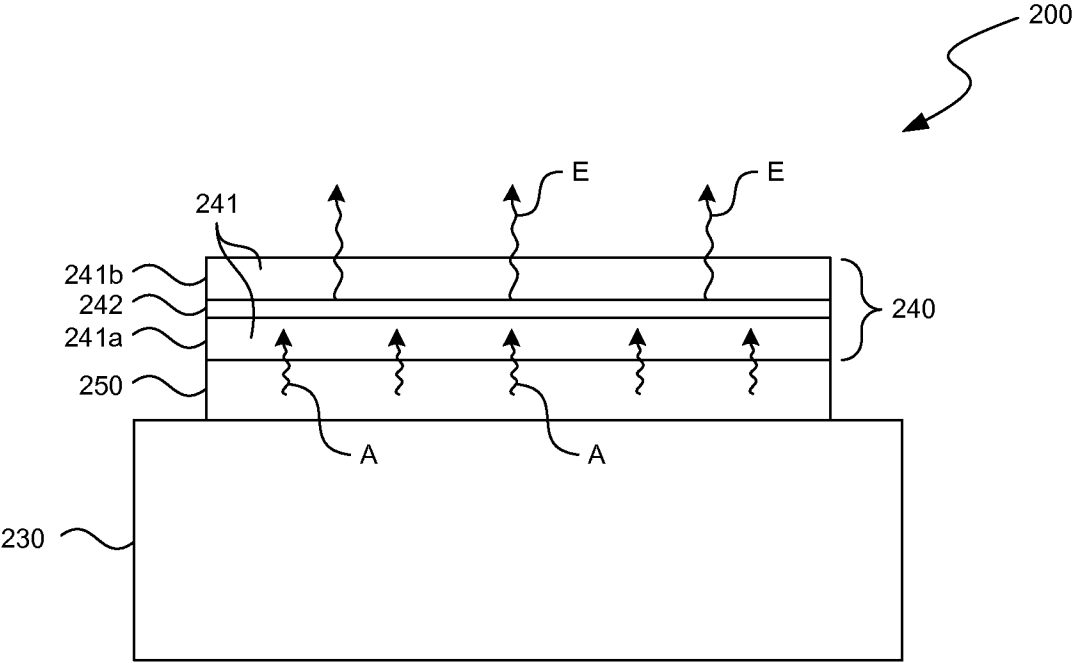


FIG. 2

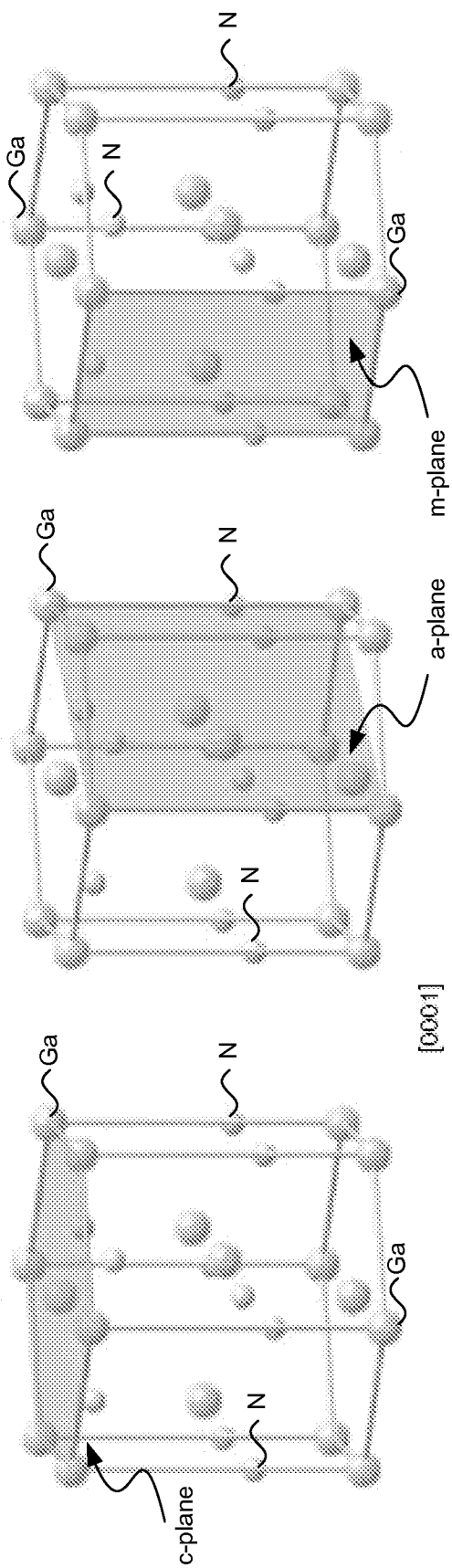


FIG. 3B

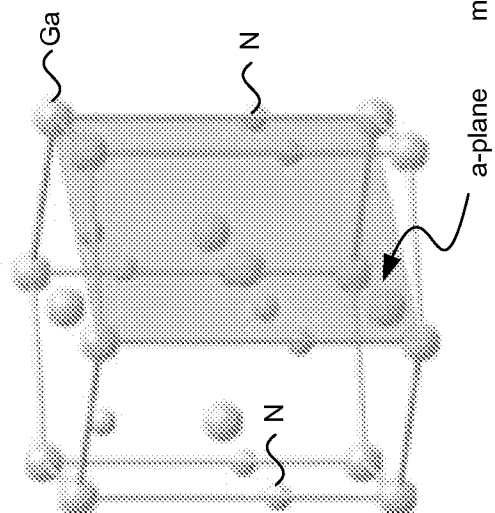


FIG. 3C

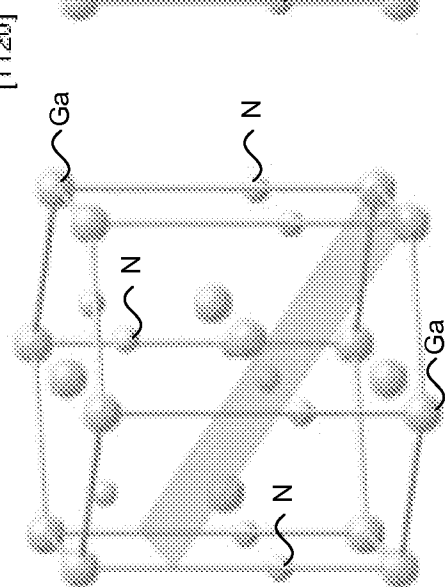
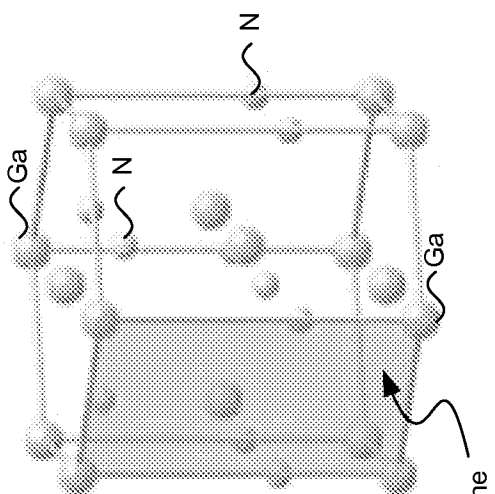


FIG. 3D

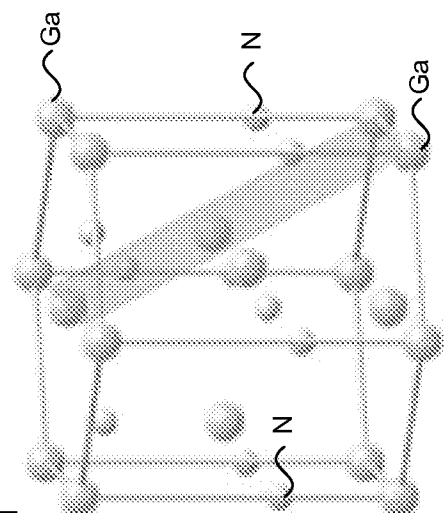


FIG. 3E

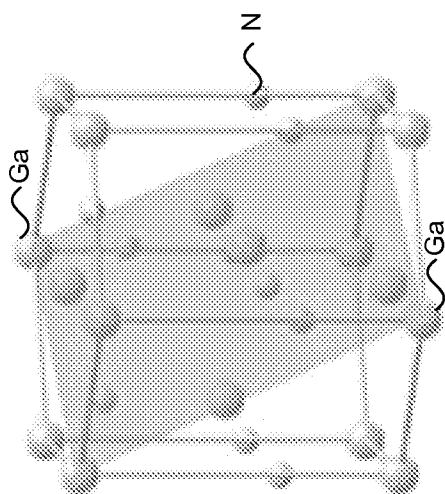
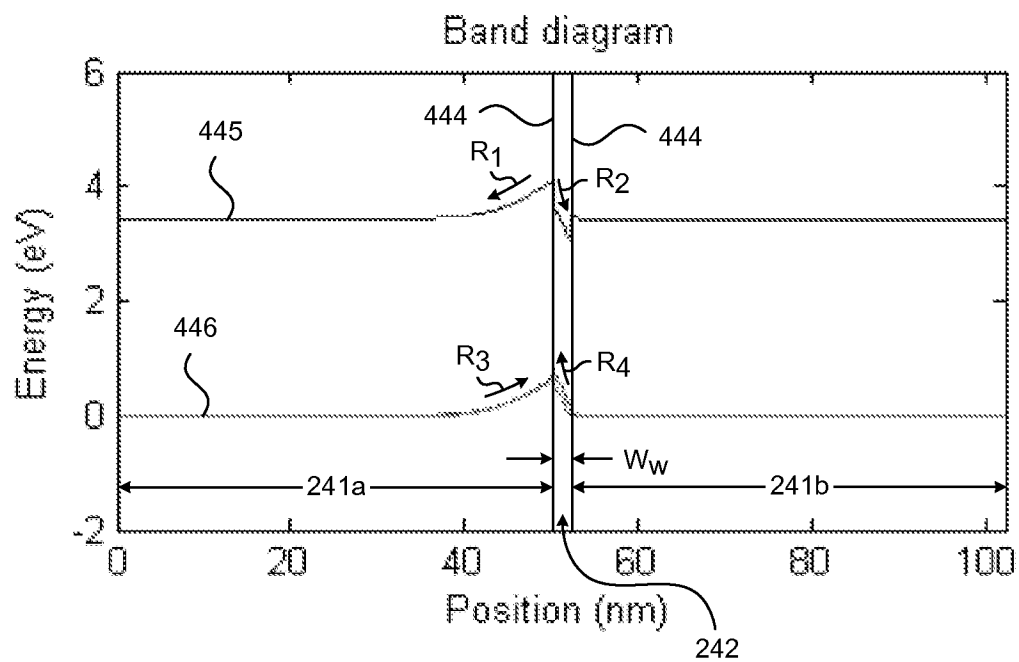
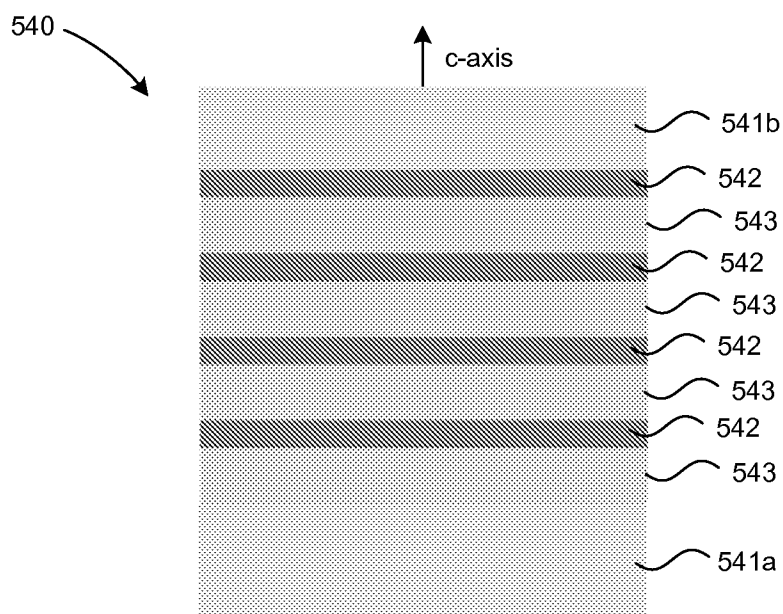


FIG. 3F

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**FIG. 4****FIG. 5**

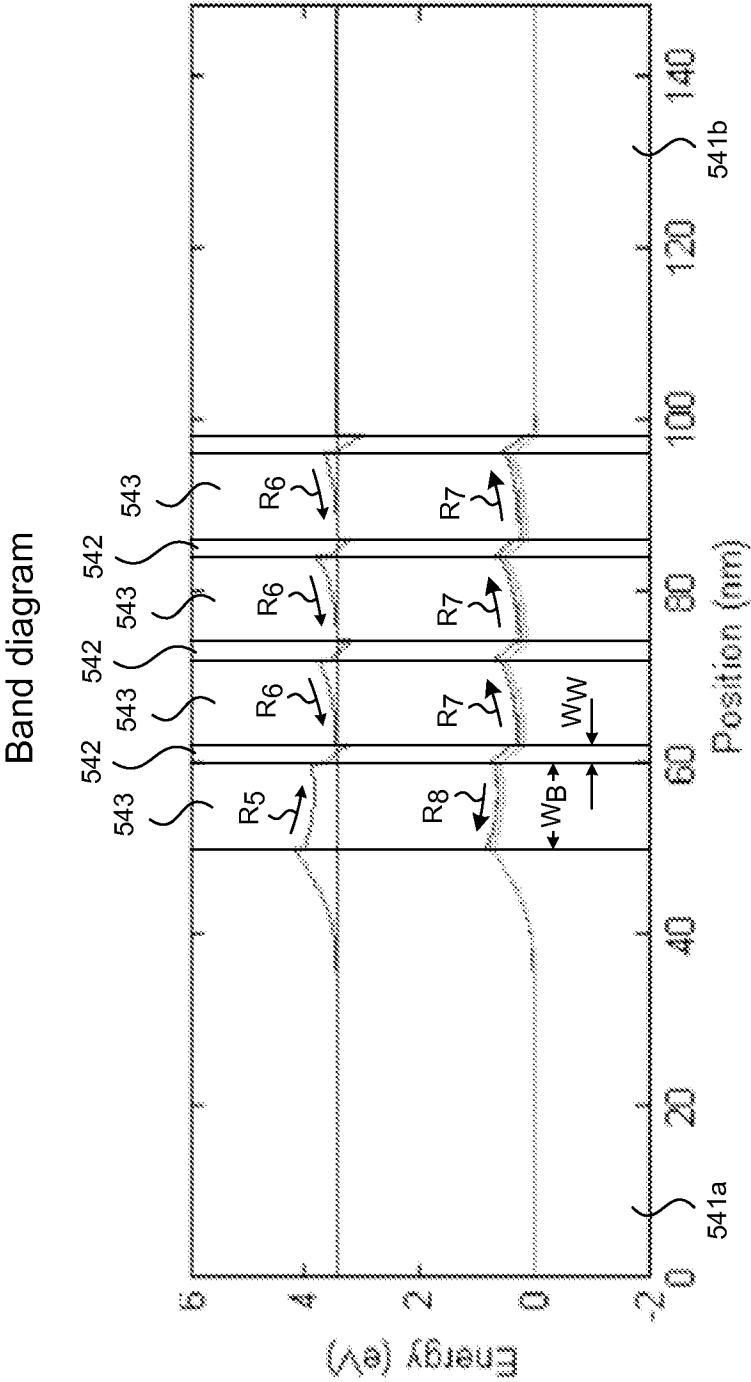


FIG. 6

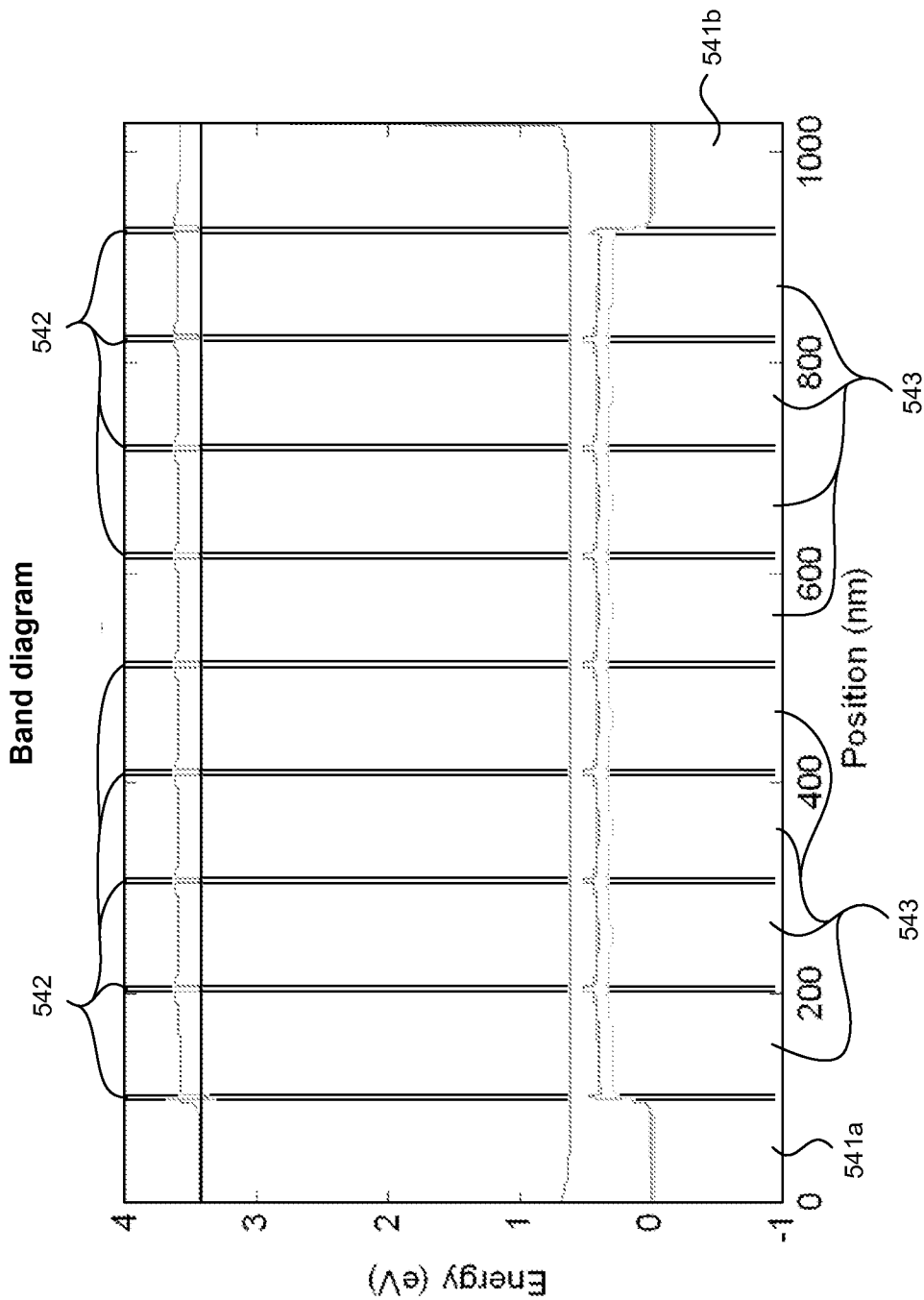


FIG. 7A

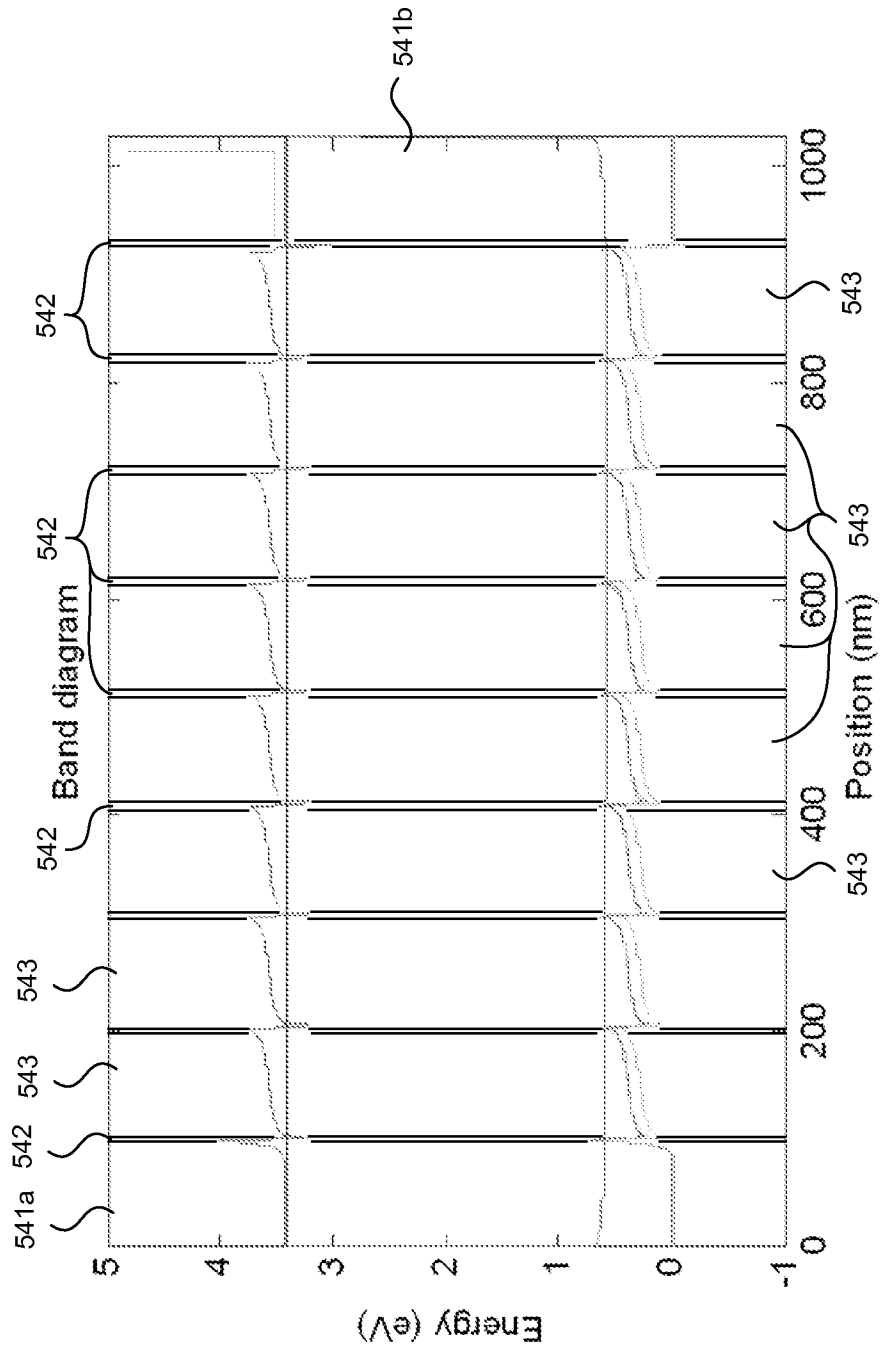


FIG. 7B

A. CLASSIFICATION OF SUBJECT MATTER***H01L 33/04(2010.01)i, H01L 33/32(2010.01)i***

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L 33/04; G02F 2/02; H01L 33/00; H01L 31/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: solid state lighting device, wavelength, convert, polar

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2007-0045609 A1 (ADAM W. SAXLER) 01 March 2007 See abstract, paragraphs [0031]-[0064], and figures 1-12.	1-33
A	US 2011-0101403 A1 (MICHAEL A. HAASE et al.) 05 May 2011 See abstract, paragraphs [0102]-[0114], and figures 8-14.	1-33
A	US 2008-0283822 A1 (KEIICHI YUI) 20 November 2008 See abstract, paragraphs [0026]-[0049], and figures 2A-7.	1-33
A	JP 2005-056973 A (HITACHI CABLE LTD.) 03 March 2005 See abstract, paragraphs [0019]-[0031], and figures 1-3.	1-33
A	US 2011-0121319 A1 (MICHAEL A. HAASE et al.) 26 May 2011 See abstract, paragraphs [0030]-[0044], and figures 1-2F.	1-33



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

31 JANUARY 2013 (31.01.2013)

Date of mailing of the international search report

31 JANUARY 2013 (31.01.2013)

Name and mailing address of the ISA/KR



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Telephone No. 82-42-481-3463



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2012/050161

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