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(54) **Title**: PHOTONIC CRYSTAL PHOSPHOR LIGHT CONVERSION STRUCTURES FOR LIGHT EMITTING DEVICES

(57) **Abstract**: Solid state light emitting devices include a solid state light emitting die and a photonic crystal phosphor light conversion structure. The photonic crystal phosphor light conversion structure may include a solid phosphor layer that includes dielectric nanostructures therein and may be on a light emitting surface of the solid state light emitting die. The photonic crystal phosphor light conversion structure may be attached to the light emitting surface of the solid state light emitting die via an adhesive layer. The photonic crystal phosphor light conversion structure may also be directly on a light emitting surface of the solid state light emitting die. Related methods are also disclosed.

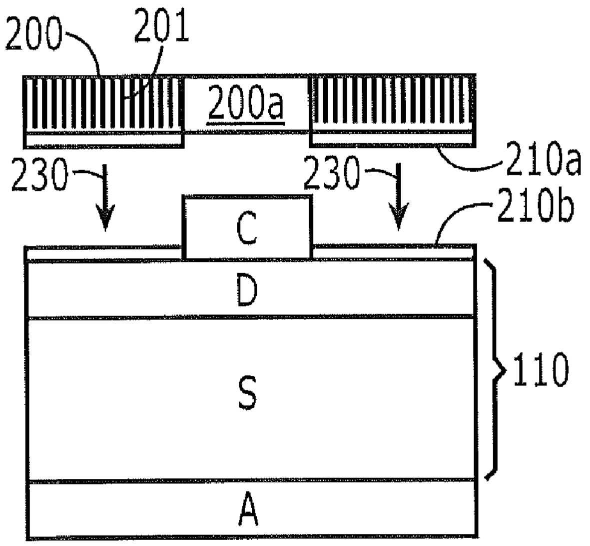

FIG. 2A

PHOTONIC CRYSTAL PHOSPHOR LIGHT CONVERSION STRUCTURES FOR LIGHT EMITTING DEVICES

FIELD OF THE INVENTION

[0001] This invention relates to solid state light emitting devices and fabrication methods therefor, and more particularly, to light conversion structures that may be used in solid state light emitting devices.

BACKGROUND OF THE INVENTION

[0002] Light emitting diodes and laser diodes are well known solid state lighting elements capable of generating light upon application of a sufficient voltage. Light emitting diodes and laser diodes may be generally referred to as light emitting devices ("LEDs"). Light emitting devices generally include a p-n junction formed in an epitaxial layer grown on a substrate such as sapphire, silicon, silicon carbide, gallium arsenide and the like. The wavelength distribution of the light generated by the LED generally depends on the material from which the p-n junction is fabricated and the structure of the thin epitaxial layers that make up the active region of the device

[0003] It is often desirable to incorporate phosphor as part of a solid state light emitting device to enhance the emitted radiation in a particular frequency band and/or to convert at least some of the radiation to another frequency band. The term "phosphor" may be used herein to refer to any materials that absorb light at one wavelength and re-emit light at a different wavelength, regardless of the delay between absorption and re-emission and regardless of the wavelengths involved. Accordingly, the term "phosphor" may be used herein to refer to materials that are sometimes called fluorescent and/or phosphorescent. In general, phosphors absorb light having shorter wavelengths and re-emit light having longer wavelengths. As such, some or all of the light emitted by the LED at a first wavelength may be absorbed by the phosphor particles, which may responsively emit light at a second wavelength(s). For example, a single blue emitting LED may be surrounded with a yellow phosphor, such as cerium-doped yttrium aluminum garnet (YAG). The resulting light, which is a combination of blue light and yellow light, may appear white to an observer.

SUMMARY OF THE INVENTION

[0004] Provided according to some embodiments of the present invention are photonic crystal phosphors that include a solid phosphor layer that includes dielectric nanostructures therein. In some embodiments, such dielectric nanostructures are configured such that the solid phosphor layer acts as a photonic crystal. In some embodiments of the invention, the solid phosphor layer is a discrete single phosphor, and in some embodiments, the solid phosphor layer is substantially a discrete single crystal phosphor.

[0005] Further provided according to some embodiments of the invention are solid state light emitting devices. Such devices may include a primary solid state light emitting die that is configured to emit light upon energization thereof; and a light conversion structure that includes a photonic crystal phosphor according to an embodiment of the invention on a light emitting surface of the primary solid state light emitting die.

[0006] In some embodiments, the solid state light emitting device may also include an adhesive layer that attaches the light conversion structure to the light emitting surface of the primary solid state light emitting die. Furthermore, in some embodiments, the light conversion structure may be sized to fit the light emitting surface of the primary solid state light emitting die. In some embodiments, the light conversion structure is directly on a light emitting surface of the primary solid state light emitting die. In some embodiments, the light conversion structure acts as a substrate for the primary solid state light emitting die. In some embodiments, the solid phosphor layer is spatially separated from the primary solid state light emitting die. In addition, in some embodiments, the solid state light emitting device includes one or more additional solid state light emitting dice configured to emit light upon energization thereof. In some embodiments, a first portion of the dielectric nanostructures are configured to interact with the primary solid state light emitting die and a second portion of the dielectric nanostructures are configured to interact with at least one of the additional solid state light emitting dice.

[0007] The photonic crystal phosphor may include a solid phosphor layer having dielectric nanostructures therein, and in some embodiments, the dielectric nanostructures may include holes within the solid phosphor layer. In some embodiments, the solid phosphor layer includes cerium, for example, at a concentration in a range of about 0.1 to about 20 weight percent. In some embodiments, the solid phosphor layer includes $Y_3Al_5O_{12}$ doped with Ce^{3+} (Ce:YAG). In some embodiments, the solid phosphor layer includes $Ca_xSr_yMg_{1-x-y}AlSiN_3$ doped with cerium or strontium thio-gallate doped with cerium. In some embodiments of the invention, the solid phosphor layer includes europium, for example, at a concentration in a range of about 0.5 to about 20 weight percent. In some embodiments, the solid phosphor layer includes $Sr_{2-x}Ba_xSiO_4$ doped with Eu^{2+} (BOSE) and in some embodiments, the solid phosphor layer includes a europium doped material, such as europium-doped $Ca_xSr_{1-x}AlSiN_3$, strontium thio-gallate, alpha-SiAlON, silicon garnet, Y_2O_2S or La_2O_2S. In some embodiments, the solid phosphor layer has a thickness in a range of about 1 μm to about 200 μm. Further, in some embodiments, a surface of the photonic crystal phosphor light conversion structure is texturized, roughened, etched and/or featured.

[0008] According to some embodiments of the invention, provided are methods of fabricating solid state light emitting devices that include placing a light conversion structure that includes a photonic crystal phosphor according to an embodiment of the invention on a light emitting surface of a solid state light emitting die. In some embodiments, placing the light conversion structure on the light emitting surface includes adhesively attaching the light conversion structure to the light emitting surface of the solid state light emitting die.

[0009] Also provided according to some embodiments of the invention are methods of fabricating solid state light emitting devices that include placing a light conversion structure comprising a solid phosphor layer on a light emitting surface of a solid state light emitting die, and forming dielectric nanostructures in the solid phosphor layer. In some embodiments, placing the light conversion structure on the light emitting surface includes adhesively attaching the solid phosphor layer to the light emitting surface of the solid state light emitting die. In some embodiments, placing the light conversion structure on the light emitting surface includes growing a solid phosphor layer on the surface of the solid state light emitting die via a thin film deposition technique.

[0010] Further, according to some embodiments, of the invention, provided are methods of fabricating solid state light emitting devices that include growing a solid state light emitting die on a surface of a light conversion structure that includes a solid phosphor layer having dielectric nanostructures defined therein. In some embodiments, the surface of the light conversion structure may be polished before the solid state light emitting die is grown thereon.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figures 1A-1F are cross-sectional views of various configurations of conventional light emitting diodes.

[0012] Figure 1G is a cross-sectional view of a conventional packaged light emitting diode.

[0013] Figures 2A-2F are cross-sectional views of solid state light emitting devices according to various embodiments of the present invention during intermediate fabrication thereof.

[0014] Figures 3A-3F are cross-sectional views of solid state light emitting devices after attachment of the photonic crystal phosphor light conversion structure, according to various embodiments of the present invention.

[0015] Figure 3G is a cross-sectional view of a packaged device of Figure 3F, according to various embodiments of the present invention.

[0016] Figures 3H-3M are cross-sectional views of solid state light emitting devices after attachment of the photonic crystal phosphor light conversion structure, according to various embodiments of the present invention.

[0017] Figure 3N is a cross-sectional view of a packaged device of Figure 3M, according to various embodiments of the present invention.

[0018] Figure 4 is a flowchart of operations that may be performed to fabricate solid state light emitting devices according to various embodiments of the present invention.

[0019] Figures 5A and 5B are cross-sectional views of packaged devices according to various embodiments of the present invention.

[0020] Figures 6A-6F are cross-sectional views of solid state light emitting devices according to other embodiments of the present invention.

[0021] Figures 7A-7F are cross-sectional views of solid state light emitting devices according to yet other embodiments of the present invention.

[0022] Figures 8A-8F are cross-sectional views of solid state light emitting devices according to still other embodiments of the present invention.

[0023] Figures 9A-9F are cross-sectional views of solid state light emitting devices according to further embodiments of the present invention.

[0024] Figures 10A and 10B are cross-sectional views of solid state light emitting devices according to various embodiments of the present invention during intermediate fabrication thereof.

[0025] Figures 11A-11E are cross-sectional views of solid state light emitting devices according to embodiments of the present invention.

[0026] Figure 12 is a flowchart of operations that may be performed to fabricate a single crystal light conversion structure according to various embodiments of the present invention.

[0027] Figure 13 is a cross-sectional view of a large area preform that is configured to attach to multiple solid state light emitting dice according to various embodiments of the present invention.

[0028] Figures 14 is a flowchart of operations that may be performed to fabricate solid state light emitting devices according to various embodiments of the present invention.

[0029] Figure 15 is a flowchart of operations that may be performed to fabricate solid state light emitting devices according to various embodiments of the present invention.

[0030] Figure 16 is a schematic illustration of a display unit having a backlight including a light emitting device according to some embodiments of the invention.

[0031] Figure 17 is a schematic illustration of a solid state luminaire including a light emitting device according to some embodiments of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0032] The invention will be described more fully hereinafter with reference to the accompanying drawings, in which example embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the example embodiments set forth herein. Rather, the disclosed embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, the size and relative sizes of layers and regions may be exaggerated for clarity. Moreover, each embodiment described and illustrated herein includes its complementary conductivity type embodiment as well. Like numbers refer to like elements throughout.

[0033] It will be understood that when an element or layer is referred to as being “on,” "connected to," "coupled to" or "responsive to" (and/or variants thereof) another element, it can be directly on or directly connected, coupled or responsive to the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly on,” "directly connected to," "directly coupled to" or "directly responsive to" (and/or variants thereof) another element, there are no intervening elements present. Like numbers refer to like elements throughout. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items and may be abbreviated as "/".

[0034] It will be understood that, although the terms first, second, third, etc. may be used herein to describe various elements, components, regions, layers and/or sections, these elements, components, regions, layers and/or sections should not be limited by these terms. These terms are only used to distinguish one element, component, region, layer or section from another region, layer or section. Thus, a first element, component, region, layer or section discussed below could be termed a second element, component, region, layer or section without departing from the teachings of the present invention.

[0035] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a," "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising" (and/or variants thereof), when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. In contrast, the term "consisting of" (and/or variants thereof) when used in this specification, specifies the stated number of features, integers, steps, operations, elements, and/or components, and precludes additional features, integers, steps, operations, elements, and/or components. Moreover, the term "consisting essentially of" when used in the specification, specifies the stated number of features, integers, steps, operations, elements and/or components, and precludes additional features, integers, steps, operations, elements and/or components, except for insubstantial amounts of impurities or other materials that do not materially affect the basic and novel characteristics of the stated features, integers, steps, operations, elements and/or components.

[0036] The present invention is described below with reference to block diagrams and/or flowchart illustrations of methods and/or apparatus (systems) according to embodiments of the invention. It is understood that a block of the block diagrams and/or flowchart illustrations, and combinations of blocks in the block diagrams and/or flowchart illustrations, can embody apparatus/systems (structure), means (function) and/or steps (methods) for implementing the functions/acts specified in the block diagrams and/or flowchart block or blocks.

[0037] It should also be noted that in some alternate implementations, the functions/acts noted in the blocks may occur out of the order noted in the flowcharts. For example, two blocks shown in succession may in fact be executed substantially concurrently or the blocks may sometimes be executed in the reverse order, depending upon the functionality/acts involved. Moreover, the functionality of a given block of the flowcharts and/or block diagrams may be separated into multiple blocks and/or the functionality of two or more blocks of the flowcharts and/or block diagrams may be at least partially integrated.

[0038] Furthermore, relative terms, such as "lower" or "bottom" and "upper" or "top," may be used herein to describe one element's relationship to another element as illustrated in the Figures. It will be understood that relative terms are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures. For example, if the device in one of the figures is turned over, elements described as being on the "lower" side of other elements would then be oriented on "upper" sides of the other elements. The exemplary term "lower", can therefore, encompasses both an orientation of "lower" and "upper," depending of the particular orientation of the figure. Similarly, if the device in one of the figures is turned over, elements described as "below" or "beneath" other elements would then be oriented "above" the other elements. The exemplary terms "below" or "beneath" can, therefore, encompass both an orientation of above and below.

[0039] Example embodiments of the invention are described herein with reference to cross-section illustrations that are schematic illustrations of idealized embodiments (and intermediate structures) of the invention. As such, variations from the shapes of the illustrations as a result, for example, of manufacturing techniques and/or tolerances, may be expected. Thus, the disclosed example embodiments of the invention should not be construed as limited to the particular shapes of regions illustrated herein unless expressly so defined herein, but are to include deviations in shapes that result, for example, from manufacturing. For example, an implanted region illustrated as a rectangle will, typically, have rounded or curved features and/or a gradient of implant concentration at its edges rather than a binary change from implanted to non-implanted region. Likewise, a buried region formed by implantation may result in some implantation in the region between the buried region and the surface through which the implantation takes place. Thus, the regions illustrated in the figures are schematic in nature and their shapes are not intended to illustrate the actual shape of a region of a device and are not intended to limit the scope of the invention, unless expressly so defined herein.

[0040] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the present invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and the present application, and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0041] According to some embodiments of the present invention, provided are photonic crystal phosphors. In some embodiments, such photonic crystal phosphors include a solid phosphor layer that includes dielectric nanostructures therein that are configured such that the solid phosphor layer acts as a photonic crystal. In some embodiments of the invention, the solid phosphor layer is a discrete single phosphor, and in some embodiments, the solid phosphor layer is substantially a discrete single crystal phosphor. In some embodiments, the solid phosphor layer is a solid polycrystalline phosphor, such as a solid polycrystalline phosphor having a grain size in a range of about 100 μm to about 1 mm.

[0042] According to some embodiments of the present invention, provided are solid state light emitting devices that include a solid state light emitting die that is configured to emit light upon energization thereof and a photonic crystal phosphor light conversion structure on a light emitting surface of the solid state light emitting die. The photonic crystal phosphor light conversion structure may include a solid phosphor layer that includes dielectric nanostructures therein configured such that the solid phosphor layer acts as a photonic crystal. In some embodiments, the solid phosphor layer may be formed on the light emitting surface of the solid state light emitting die by thin film vapor deposition technique, such as MOCVD, MBE, LPE, and the like, as described in further detail below. In such a case, the array of nanostructures in the solid phosphor layer may be formed during or after deposition of the solid phosphor layer on the surface of the solid state light emitting die. In other embodiments, the solid phosphor layer may be grown externally (*e.g.*, via a Czochralksi-type method), which may also be referred to as a preform, optionally sized to fit the light emitting surface of the die, and then attached to the light emitting surface, as described in further detail below. In such cases, the dielectric nanostructures in the solid phosphor layer may be formed either before or after the preform is attached to the solid state light emitting surface of the die. The preform may be adhesively attached to the light emitting die in some embodiments. Furthermore, in some embodiments, the photonic crystal phosphor light conversion structure may act as a substrate for the solid state light emitting die.

[0043] A “light conversion structure” is a structure in an LED that includes a solid phosphor layer that may absorb light at one wavelength and re-emit light at another wavelength(s).

[0044] A “photonic crystal” is a crystalline material having dielectric nanostructures defined therein. The dielectric nanostructures may be any dielectric nanostructures known to those of skill in the art, including holes of any suitable cross-sectional shape, including regular shapes such as circular, square, hexagonal, and the like, or irregular shapes and cross-section as might, for example, be formed by the intersection of nano-rods arranged at different angles in a so-called woodpile arrangement. Such dielectric nanostructures may be filled with air or another material, such as silicon oxides (SiOx) or aerogels. The dielectric nanostructures may be in any suitable configuration, but in some embodiments, the dielectric nanostructures are present in a periodic array, and in some embodiments, the periodicity is on the same length scale as half the wavelength of the electromagnetic waves propagated therethrough. The configuration, shape, width and depth of the nanostructures will depend on several factors, such as the solid state light emitting die used, the chemical nature of the phosphor layer, the thickness of the solid phosphor layer and the type of photonic effect desired, as will be discussed in further detail below. However, for the dielectric nanostructures, at least one dimension of the nanostructure (e.g., length, width, spacing, etc.) is nanoscale, i.e., less than 1um.

[0045] A “solid phosphor layer” is a phosphor layer having a defined shape and volume sufficient to support the formation of the dielectric nanostructures without substantial change in shape or volume (except for the formed nanostructures). In some embodiments, the solid phosphor layer consists of a discrete single crystal phosphor, meaning that the solid phosphor layer is one continuous single crystal. In some embodiments, the solid phosphor layer is substantially a discrete single crystal phosphor, meaning that the solid phosphor layer is substantially a continuous single crystal, but may have defects and/or minor regions of impurities. In some embodiments, the solid phosphor layer is a solid polycrystalline phosphor, such as a solid polycrystalline phosphor having a grain size in a range of about 100 μm to about 1 mm.

[0046] The phrase "adhesively attaching" means bonding two elements to one another. The bonding may be direct via a single adhesive layer or via one or more intermediate adhesive and/or other layers/structures, to form a unitary structure of the solid state light emitting die and the photonic crystal phosphor preform that is adhesively attached thereto, such that this unitary structure may be placed on a submount or other packaging element.

[0047] Finally, the term "transparent" means that optical radiation from the solid state light emitting device can pass through the material without being totally absorbed or totally reflected.

[0048] The use of a photonic crystal phosphor light conversion structure, according to various embodiments of the invention, may provide many potential advantages. For example, it is often desirable to incorporate phosphor and/or other optical elements into the solid state light emitting device. However, when coating a phosphor layer, the coating may be unduly thick and/or undesirably nonuniform. Moreover, a phosphor layer that is incorporated into a dome or shell also may be too thick and/or nonuniform. In addition, typically, phosphors are generally provided to the LED as a polycrystalline powder, wherein the size and quality of the phosphor particles may significantly affect the quantum efficiency of the phosphor. In addition, the phosphor particles may be applied to the chip in silicone or other polymeric matrix. The correlated color temperature (CCT) of the light emitted from the phosphor particles may be altered by varying the quantity of the phosphor particles in the polymer matrix, or by varying the thickness of the polymer matrix. However, it may be difficult to cut, shape and/or handle some polymeric light conversion structures in order to place them accurately on the chip. Furthermore, although the polymer is only present in the light conversion structure to act as an inert matrix for the phosphor particles, its absorption may become an issue if relatively thick preforms are used. Thus, in practice, relatively thin structures may be used, which may result in handling difficulties, especially in mass production. In addition, the photonic crystal nature of the light conversion structures described herein may allow for directionality of the light emitted from the phosphor, and may allow for the use of relatively thin phosphor layers due to the increased light extraction.

[0049] The photonic crystal phosphor light conversion structure may be formed from any suitable phosphor material that may be formed into a solid layer. For example, the phosphor material may be a cerium (Ce) doped phosphor, such as $Y_3Al_5O_{12}$ (Ce:YAG), in some embodiments. In other embodiments, other phosphors, such as Ce and/or europium (Eu) doped (Ca, Sr, Mg)$AlSiN_3$; Eu doped $Sr_{2-x}Ba_xSiO_4$ (BOSE); Ce or Eu doped strontium thio-gallate; or Eu doped alpha-SiAlON, Y_2O_2S, La_2O_2S, silicon garnet, Y_2O_2S or La_2O_2S may be used. In addition, in some embodiments, the phosphors described in European Patent Publication No. 1,696,016, U.S. Patent Publication No. 2007/0075629 and U.S. Patent Application No. 12/250,828, entitled *Cerium and Europium-Doped Phosphor Compositions and Light Emitting Devices Including the Same*, filed on October 14, 2008 may also be used. The phosphor may also be doped at any suitable level. In some embodiments, Ce and/or Eu is doped into the solid phosphor layer such that the dopant concentration is in a range of about 0.1 to about 20 weight %.

[0050] Since the light conversion structures of the invention are formed from photonic crystals, extraction efficiency may be increased relative to traditionally used light conversion structures. Moreover, in some embodiments, the photonic crystal phosphor light conversion structure may be relatively thin, for example, in a range of about 1 μm to about 10 μm, and in other embodiments, in a range of about 5 μm to500 μm, and in some embodiments, in a range of about 2 μm to about 100 μm.

[0051] Internal absorption or bounce seen in polymeric light conversion structures may also be reduced by using a photonic crystal phosphor light conversion structure. Also, in some embodiments, the photonic crystal phosphor light conversion structure is a preform that can be formed separately from the solid state light emitting die, and so it can be fabricated and tested without impacting the reliability and/or yield of the solid state light emitting die. Finally, the solid phosphor layer of the photonic crystal phosphor may allow for more efficient and effective texturization, roughening, etching and/or featuring of the light conversion structure.

[0052] Figures 1A-1E are cross-sectional views of various configurations of conventional light emitting diodes (LEDs) that may be used with photonic crystal phosphor light conversion structures, optionally in combination with other optical elements, according to various embodiments of the present invention. As shown in Figures 1A-1E, a solid state light emitting device **100** includes a solid state light emitting die **110** that may comprise a diode region **D** and a substrate **S**. The diode region **D** is configured to emit light upon energization thereof, by applying a voltage between an anode contact **A** and a cathode contact **C**. The diode region **D** may comprise organic and/or inorganic materials. In inorganic devices, the substrate **S** may comprise silicon carbide, sapphire and/or any other single element and/or compound semiconductor material, and the diode region **D** may comprise silicon carbide, gallium nitride, gallium arsenide, zinc oxide and/or any other single element or compound semiconductor material, which may be the same as or different from the substrate **S**. The substrate **S** may be between about 100 μm and about 250 μm thick, although thinner and thicker substrates may be used or the substrate may not be used at all. The cathode **C** and anode **A** contacts may be formed of metal and/or other conductors, and may be at least partially transparent and/or reflective. The design and fabrication of organic and inorganic LEDs are well known to those having skill in the art and need not be described in detail herein. LEDs such as depicted in Figures 1A-1E may be marketed by Cree, Inc., the assignee of the present application, for example under the designators XThin®, MegaBright®, EZBright™, UltraThin™, RazerThin®, XBright®, XLamp® and/or other designators, and by others.

[0053] In Figure 1A, light emission may take place directly from the diode region **D**. In contrast, in embodiments of Figure 1B, emission may take place from diode region **D** through the substrate **S**. In Figures 1C and 1D, the substrate **S** may be shaped to enhance emission from sidewalls of the substrate **S** and/or to provide other desirable effects. Finally, in Figure 1E, the substrate itself may be thinned considerably or eliminated entirely, so that only a diode region **D** is present. Moreover, in all of the above embodiments, the anode **A** and cathode **C** contacts may be of various configurations and may be provided on opposite sides of the solid state light emitting die **110**, as illustrated, or on the same side of the solid state light emitting die **110**. Multiple contacts of a given type also may be provided.

[0054] Figure 1F provides a generalization of Figures 1A-1E, by providing a solid state light emitting device **100** that comprises a solid state light emitting die **110** that includes a diode region **D** of Figures 1A-1E and also may include substrates of Figures 1A-1E, and that is configured to emit light upon energization thereof via one or more contacts **120a**, **120b**, which may include the anode **A** and cathode **C** of Figures 1A-1E.

[0055] Figure 1G illustrates a solid state light emitting device **100** of Figure 1F that is packaged by mounting the device **100** on the submount **130** that provides external electrical connections **132** using one or more wire bonds **134** and also provides a protective dome or cover **140**. Many other packaging techniques may be employed to package a solid state light emitting die, as is well known to those having skill in the art, and need not be described further herein. For example, packaging techniques are described in U.S. Patent Nos. 6,791,119, issued September 14, 2004 to Slater, Jr. et al., entitled *Light Emitting Diodes Including Modifications for Light Extraction*; 6,888,167, issued May 3, 2005 to Slater, Jr. et al., entitled *Flip-Chip Bonding of Light Emitting Devices and Light Emitting Devices Suitable for Flip-Chip Bonding*; 6,740,906, issued May 24, 2004 to Slater, Jr. et al., entitled *Light Emitting Diodes Including Modifications for Submount Bonding*; 6,853,010, issued February 8, 2005 to Slater, Jr. et al., entitled *Phosphor-Coated Light Emitting Diodes Including Tapered Sidewalls, and Fabrication Methods Therefor*; 6,885,033, issued April 26, 2005 to Andrews, entitled *Light Emitting Devices for Light Conversion and Methods and Semiconductor Chips for Fabricating the Same*; and 7,029,935, issued April 18, 2006 to Negley et al., entitled *Transmissive Optical Elements Including Transparent Plastic Shell Having a Phosphor Dispersed Therein, and Methods of Fabricating Same*; U.S. Patent Application Publications Nos. 2005/0051789, published March 10, 2005 to Negley et al., *Solid Metal Block Mounting Substrates for Semiconductor Light Emitting Devices, and Oxidizing Methods for Fabricating Same*; 2005/0212405, published September 29, 2005 to Negley, *Semiconductor Light Emitting Devices Including Flexible Film Having Therein an Optical Element, and Methods of Assembling Same*; 2006/0018122, published January 26, 2006 to Negley, *Reflective Optical Elements for Semiconductor Light Emitting Devices*; 2006/0061259, published March 23, 2006 to Negley, *Semiconductor Light Emitting Devices Including Patternable Films Comprising Transparent Silicone and Phosphor, and Methods of Manufacturing Same*; 2006/0097385, published May 11, 2006 to Negley, *Solid Metal Block Semiconductor Light Emitting Device Mounting Substrates and Packages Including Cavities and Heat Sinks, and Methods of Packaging Same*; 2006/0124953, published June 15, 2006 to Negley et al., *Semiconductor Light Emitting Device Mounting Substrates and Packages Including Cavities and Cover Plates, and Methods of Packaging Same*; and 2006/0139945, published June 29, 2006 to Negley et al., *Light Emitting Diode Arrays for Direct Backlighting of Liquid Crystal Displays*; and U.S. Application Serial Number 11/408,767, filed April 21, 2006 for Villard, *Multiple Thermal Path Packaging For Solid State Light Emitting Apparatus And Associated Assembling Methods*, all assigned to the assignee of the present invention, the disclosures of which are hereby incorporated herein by reference in their entirety as if set forth fully herein.

[0056] Figures 2A-2F are cross-sectional views, according to various embodiments of the present invention, of the intermediate fabrication of a solid state light emitting device including a photonic crystal phosphor light conversion structure that is formed, for example, by growing, externally and then attached to the solid state light emitting device (also referred to herein as a "preform"). The respective solid state light emitting devices of Figures 2A-2F employ the respective solid state light emitting dice of Figures 1A-1F. As described below, the photonic crystal phosphor light conversion structure may be optionally modified, *e.g.*, by cutting, polishing, texturing, and the like, before or after being attached to the solid state light emitting die.

[0057] As shown in Figure 2A, a photonic crystal phosphor light conversion structure **200** may be sufficiently thin so as to allow at least some light that is emitted from the solid state light emitting die **110** to pass therethrough. A layer **210a**, **210b**, such as an adhesive layer, also may be provided on the photonic crystal phosphor light conversion structure **200** and/or on the die **110** that attaches, such as adhesively attaches, the photonic crystal phosphor light conversion structure **200** and the solid state light emitting die **110** to one another as shown by arrows **230** and also optically couples the photonic crystal phosphor light conversion structure **200,** and the solid state light emitting die **110** to one another. The photonic crystal phosphor light conversion structure **200** is an optical element that can modify at least some of the light that is emitted from the solid state light emitting die **110**. The photonic crystal phosphor light conversion structure **200** includes dielectric nanostructures **201** defined therein. Such dielectric nanostructures may be in any suitable configuration in the photonic crystal phosphor light conversion structure **200**, as will be discussed in further detail below. Additionally, as described below, other optical elements may be used in combination with the photonic crystal phosphor light conversion structure **200** according to some embodiments of the invention. It will also be understood that, in some embodiments, the layer **210a**, **210b** may be provided only on the photonic crystal phosphor light conversion structure **200** or only on the die **110**. The layer **210a**, **210b** may be transparent epoxy, such as a thermoset silicone gel or rubber, that is available from Dow Corning, Shin-Etsu, NuSil, GE and others, and/or any other transparent epoxy.

[0058] As also shown in Figure 2A, the photonic crystal phosphor light conversion structure **200** may be relatively rigid compared to silicone-based photonic crystal phosphor light conversion structures. In some embodiments, the photonic crystal phosphor light conversion structure may be the approximate size of a face of an LED die, for example about 1000 μm × 1000 μm, and may have a thickness of between about 1 μm and about 100 μm. However, other dimensions may be provided in other embodiments.

[0059] As also shown in Figure 2A, the solid state light emitting die may include an external contact pad, such as cathode **C**, and the photonic crystal phosphor light conversion structure **200** may include a notch, hole and/or other void **200a** that is configured so as to expose the external contact pad **C**. In embodiments of Figure 2A, the photonic crystal phosphor light conversion structure **200** is planar and may be of uniform thickness. Moreover, the photonic crystal phosphor light conversion structure **200** of Figure 2A may be of a same size and shape as a surface of the solid state light emitting die **110**, except for a void, notch or other surface feature **200a** that may be provided to expose an external contact **C**. It may also be desirable to provide one or more features in the photonic crystal phosphor light conversion structure to facilitate alignment of the photonic crystal phosphor light conversion structure **200** to the die **110**.

[0060] Figure 2B illustrates other embodiments of the present invention, wherein the photonic crystal phosphor light conversion structure **200** is nonplanar and may include, for example, a sidewall **202** that is configured to extend along a sidewall of the solid state light emitting die **110**. Radiation that is emitted from the sidewall of the solid state light emitting die may thereby pass through the photonic crystal phosphor light conversion structure **200**, as well as radiation that is emitted from the major surface to which the photonic crystal phosphor light conversion structure **200** is attached. The sidewall **202** may extend partway or fully along the sidewall of the die. Moreover, in some embodiments, the photonic crystal phosphor light conversion structure **200** may extend all the way around the die, including on the sidewalls and the opposing faces of the die. The layer **210b** may be located on the die as shown in Figure 2B, and may also be provided on the photonic crystal phosphor light conversion structure **200** including on the sidewall **202** of the photonic crystal phosphor light conversion structure **200** and/or on the sidewall of the die **110**.

[0061] Figure 2C illustrates other embodiments of the present invention, wherein the photonic crystal phosphor light conversion structure extends beyond a surface of the die **110**. Accordingly, as shown in Figure 2C, the photonic crystal phosphor light conversion structure **200** overhangs a surface of the solid state light emitting die **110**. By providing an overhang, radiation from a sidewall of the device may pass through the photonic crystal phosphor light conversion structure **200**. The overhang **204** may be thicker than the remaining portion of the photonic crystal phosphor light conversion structure **200**. Moreover, the overhang **204** may extend a large distance beyond the die and may extend to a sidewall of a cavity in which the die **110** is mounted, so that substantially all light that is emitted from the cavity passes through the photonic crystal phosphor light conversion structure **200**.

[0062] Figure 2D illustrates other embodiments, wherein a uniform thickness photonic crystal phosphor light conversion structure **200** may include an overhang **204**. Again, the overhang **204** may extend a large distance beyond the die and may extend to a sidewall of a cavity in which the die **110** is mounted, so that substantially all light that is emitted from the cavity passes through the photonic crystal phosphor light conversion structure. Figure 2E illustrates the use of a photonic crystal phosphor light conversion structure of Figure 2B along with coupling/adhesive layer **210c** that extends along the sidewall of the LED die **110**, as well as on the top surface thereof. Finally, Figure 2F generically illustrates the use of a photonic crystal phosphor light conversion structure **200** and a coupling/adhesive layer **210a/210b** that attaches the photonic crystal phosphor light conversion structure **200** and a light emitting die to one another, as shown by arrows **230** and couples the photonic crystal phosphor light conversion structure **200** and the light emitting die **110** to one another. It will be understood by those having skill in the art that embodiments of Figures 2A-2F may be combined in various permutations and combinations. Thus, for example, a photonic crystal phosphor light conversion structure of Figure 2D may be used with the solid state light emitting die of Figure 2C and a photonic crystal phosphor light conversion structure of Figure 2E may be used with a solid state light emitting die of Figure 2D.

[0063] Figures 3A-3F correspond to Figures 2A-2F, but illustrate the photonic crystal phosphor light conversion structure **200** attached to the light emitting die **110** by a layer **210** that may comprise a coupling/adhesive layer **210a** and/or **210b** of Figure 2A. Accordingly, after attachment of the photonic crystal phosphor light conversion structure **200** and die **110**, a unitary structure **300** of the solid state light emitting die **110** and the photonic crystal phosphor light conversion structure **200** is provided. This unitary structure **300** may then be mounted on a submount **130** and further packaged, as shown in Figure 3G.

[0064] Figures 3H-3N correspond to Figures 3A-3G, but illustrate the use of a low profile wire bond **334** that does not pass through the photonic crystal phosphor light conversion structure **200** itself but, rather, passes through the layer **210**. In these embodiments, the wire **334** may be bonded to the anode **A** or cathode **C**, before placing the adhesive/coupling layer **210** and the photonic crystal phosphor light conversion structure **200** on the die **110**. Low profile wire bonding embodiments of Figures 3H-3N may obviate the need for a cutout in the photonic crystal phosphor light conversion structure **200**, which can facilitate fabrication of the LEDs and can make alignment of the photonic crystal phosphor light conversion structure easier during assembly. Moreover, in these embodiments, it may be desirable to provide a thicker layer **210** to accommodate the wire **334** therein. Thicknesses of between about 35 μm and about 70 μm may be used in some embodiments of the present invention.

[0065] The layer **210** may be a liquid epoxy, as described above. The liquid epoxy may be dispensed onto the photonic crystal phosphor light conversion structure **200** and/or solid state light emitting die **110** prior to attachment of the photonic crystal phosphor light conversion structure **200** to the die **110**, and then cured after attachment of the photonic crystal phosphor light conversion structure **200** to the die **110**. For example, the above-described silicone-based liquid epoxy may be dispensed at room temperature and spread using the pick and place force of the photonic crystal phosphor light conversion structure **200** placement. Curing may then take place by heating in an oven. Adhesive layers of thickness of about 0.1 μm to about 50 μm may be used in some embodiments. Moreover, in other embodiments, a "wicking" adhesive/optical coupling fluid may be applied after placing the photonic crystal phosphor light conversion structure **200** on the die **110**, to provide a thin layer **210**.

[0066] Light conversion structures may be configured, as was illustrated in Figures 2A-2F and 3A-3N, to provide various potential advantages according to some embodiments of the invention. For example, in Figures 2B, 2E, 3B, 3E, 3I and 3L, the photonic crystal phosphor light conversion structure **200** includes a sidewall **202** that extends at least partially along or adjacent a sidewall of the solid state light emitting die **110**. It has been found, according to some embodiments of the present invention, that although light may be primarily emitted from the top surface of the die **110**, some low angle sidewall emission may take place. This sidewall emission may adversely impact the desired Correlated Color Temperature (CCT) uniformity of the solid state light emitting device. However, by providing a three-dimensional (nonplanar) photonic crystal phosphor light conversion structure **200**, side emissions may also be "captured" by the photonic crystal phosphor light conversion structure **200**. Back emissions may also be captured, in some embodiments, by providing the photonic crystal phosphor light conversion structure on the opposing faces and the sidewalls of the die.

[0067] In another example, as illustrated in Figures 2C, 2D, 3C, 3D, 3J and 3K, the photonic crystal phosphor light conversion structure may include an overhang **204** that is the same thickness as, or is of different thickness than, the remainder of the photonic crystal phosphor light conversion structure **200**. The overhang **204** may capture radiation that is emitted from the sidewall of the solid state light emitting die **110**. Moreover, by providing a thicker overhang, the photonic crystal phosphor light conversion structure can convert, for example, a non-Lambertian radiation pattern to a more desirable Lambertian radiation pattern or can convert a somewhat Lambertian radiation pattern to a more Lambertian radiation pattern, in some embodiments. It will be understood by those having skill in the art that the thicker portions of the photonic crystal phosphor light conversion structure of Figures 2C, 3C and 3J may extend toward the solid state light emitting die **110** as shown in Figures 2C, 3C and 3J and/or away from the solid state light emitting die.

[0068] Figure 4 is a flowchart of operations that may be performed to fabricate solid state light emitting devices according to various embodiments of the present invention. Referring to Figure 4, at Block **410**, the solid state light emitting die, such as the die **110**, is fabricated using conventional techniques. At Block **420**, a photonic crystal phosphor light conversion structure, such as the photonic crystal phosphor light conversion structure **200**, is fabricated using techniques that will be described in detail below and/or using other photonic crystal phosphor light conversion structure fabrication techniques. It will be understood that the dice and photonic crystal phosphor light conversion structures may be fabricated out of the order shown in Figure 4 and/or at least partially overlapping in time.

[0069] Then, at Block **430**, adhesive, such as coupling/adhesive layer **210**, is applied to the die **110** and/or the photonic crystal phosphor light conversion structure **200**. The photonic crystal phosphor light conversion structure and the die are then attached to one another at Block **440**. If needed, the adhesive is cured at Block **450**. Subsequent packaging may then take place at Block **460**, for example, by bonding the unitary structure of the die **110** and photonic crystal phosphor light conversion structure **200** to a submount and/or other packaging substrate. It will also be understood that a wire bond may be attached to the die before or after performing the attaching step at Block **440**.

[0070] While the photonic crystal phosphor light conversion structure may be extremely stable at high temperatures, and thus, can be put directly on or next to the light emitting surface, the efficiency of the phosphor is generally inversely related to the temperature of the photonic crystal phosphor light conversion structure **200**. The die **110** may be relatively warm, *e.g.*, at about 110 °C, and so raising or separating the photonic crystal phosphor light conversion structure **200** from the die **110** may reduce or minimize heating of the photonic crystal phosphor light conversion structure **200**, thereby improving quantum efficiency.

[0071] Referring to Figure 5A, according to some embodiments of the invention, the photonic crystal phosphor light conversion structure **200** is placed over the die **110** and on the submount **130**, whereby the photonic crystal phosphor light conversion structure **200** is attached to die **110** via a transparent substrate **500.** In other embodiments, the transparent substrate **500** is not present and so the photonic crystal phosphor light conversion structure **200** is not attached to the die **110** via the transparent substrate **500**, but instead an empty space is present between the die **110** and the photonic crystal phosphor light conversion structure **200**. Referring to Figure 5B, in some embodiments that may be referred to as "remote phosphor," the photonic crystal phosphor light conversion structure **200** may be raised above the submount

130 via sidewalls **510** and attached to the die **110** via a transparent substrate **500**. In some embodiments, the transparent substrate **500** is not present and so the photonic crystal phosphor light conversion structure **200** is not attached to the die **110** via a transparent substrate **500** but is supported by the sidewalls **510**. Thus, an empty space is provided between the die **110** and the photonic crystal phosphor light conversion structure **200.** The sidewalls **510** may be formed from a reflective surface (*e.g.*, aluminum) and/or coated with a reflective material, in order to more efficiently irradiate the photonic crystal phosphor light conversion structure **200**. It will be understood that the distance between the die **110** and the photonic crystal phosphor light conversion structure **200** may be varied according to the configuration of the die **110**, submount **130** and transparent substrate **500**.

[0072] Many other optical elements may be provided in combination with the photonic crystal phosphor light conversion structure, according to various embodiments of the present invention. In general, the optical element may be configured to modify at least some of the light that is emitted from the solid state light emitting die **110**, by changing its amplitude, frequency and/or direction. These optical elements may include an additional light conversion structure including polycrystalline phosphor particles, an optical refracting element such as a lens, an optical filtering element such as a color filter, an optical scattering element such as optical scattering particles, an optical diffusing element such as a textured surface and/or an optical reflecting element such as a reflective surface, that is included in and/or on the photonic crystal phosphor light conversion structure. Combinations of these and/or other embodiments may be provided. Moreover, two or more photonic crystal phosphor light conversion structures may be provided, wherein each photonic crystal phosphor light conversion structure can perform a different optical processing function, the same optical processing function or overlapping processing functions, depending upon the desired functionality of the solid state light emitting device. Many other examples will now be described in detail.

[0073] For example, as shown in Figures 6A-6F, a second light conversion structure **600** that includes scattering particles **620** therein may be attached/coupled by a second layer **610**, to separate the functionalities of light conversion and light scattering into two different light conversion structures **200**, **600**. The second layer **610** may be the same as, or different from, the first layer **210**. It will be understood that the order of the first and second light conversion structures **200** and **600** relative to the solid state light emitting die **110** may be reversed from that shown in Figures 6A-6F. Moreover, the first and second light conversion structures need not be congruent to one another or of the same thickness. Finally, from a fabrication standpoint, the first and second light conversion structures **200**, **600** may be fabricated and then attached to one another before attaching the assembly of the first and second light conversion structures **200/600** to the solid state light emitting die **110**. Alternatively, one of the light conversion structures may be attached to the solid state light emitting die **110** and then the other light conversion structure may be attached to the light conversion structure that is already attached to the solid state light emitting die **110**. Three or more light conversion structures also may be used in other embodiments of the present invention.

[0074] As another example, embodiments that are illustrated in Figures 7A-7F provide an optical element, such as polycrystalline phosphor particles **720**, on the photonic crystal phosphor light conversion structure **200**. The coating may be provided by coating a photonic crystal phosphor light conversion structure at any point during its fabrication and then by attaching a coated photonic crystal phosphor light conversion structure to the solid state light emitting die. However, in other embodiments, coating may be performed after the photonic crystal phosphor light conversion structure is attached to the die.

[0075] Figures 8A-8F illustrate other embodiments of the present invention, wherein a reflector **820** is provided on the photonic crystal phosphor light conversion structure **200**, for example on a sidewall of the photonic crystal phosphor light conversion structure **200**. The reflector **820** may change the radiation pattern of the light emitting die by reflecting stray side radiation back into a main radiation path. The reflector **820** may be created by selectively metallizing the photonic crystal phosphor light conversion structure **200** before attachment to the solid state light emitting die. In other embodiments, the photonic crystal phosphor light conversion structure **200** may be metallized after it is attached. It will be understood that mirrors and/or other reflectors **820** may be combined with any of the other embodiments described herein. It will also be understood that the metallization also may be used to provide electrical traces, wiring and/or contacts, so as to provide an electrical element in and/or on the photonic crystal phosphor light conversion structure.

[0076] Figures 9A-9F illustrate other embodiments of the present invention, wherein the optical element is a diffuser **920** that is formed by texturing a surface of the photonic crystal phosphor light conversion structure **200**. The relative rigidity of the solid phosphor layer may facilitate the effective texturization of the surface. Etching, molding, sandblasting and/or other techniques for texturing are well known to those having skill in the art. As is also well known, texturing can provide diffusion of emitted radiation that can allow more uniform CCT. It will also be understood that texturing may be provided on a separate photonic crystal phosphor light conversion structure, and may be combined with any of the other embodiments of the invention that are described herein. Moreover, rather than texturing, a die-scale lens and/or an array of microlenses also may be provided on the surface of the photonic crystal phosphor light conversion structure **200**, to provide further optical processing.

[0077] It will be understood by those having skill in the art that the surface of a solid state light emitting die itself may be textured by etching the semiconductor material. Unfortunately, this etching may decrease the yield and/or reliability of the solid state light emitting die. In sharp contrast, embodiments of the present invention can texture a separate photonic crystal phosphor light conversion structure using conventional etching techniques, and then use this textured photonic crystal phosphor light conversion structure to reduce or obviate the need to texture the solid state light emitting die itself. This can be done but may change the photonic crystal's light emission properties. The texturing may increase scattering which may in turn increase the amount of light reflected back into the crystal. Conversly, it may however, depending of the length scale of the texture, improve coupling from the photonic phosphor crystal into the surrounding medium.

[0078] Figures 10A and 10B illustrate some embodiments of the invention wherein a photonic crystal phosphor light conversion structure provides a substrate for the epitaxial growth of a solid state light emitting die. Figure 10A depicts a photonic crystal phosphor light conversion structure **200** according to some embodiments of the invention. As with other embodiments of the invention, any suitable phosphor material may be used, including the specific phosphor materials described herein. Figure 10B depicts the photonic crystal phosphor light conversion structure **200** acting as a substrate for the solid state light emitting die **110**. Generally, the solid state light emitting die **110** is grown on a surface of the photonic crystal phosphor light conversion structure **200** that does not have dielectric nanostructures **201** therein (*e.g.*, on a face opposite dielectric nanostructures **201** that do not traverse entirely through the structure). Any suitable solid state light emitting material may be used, but in some embodiments, Group III nitrides, such as GaN or InGaN, and in some embodiments, materials such as ZnO or GaP, may be used. As with other embodiments described herein, many different configurations may be used, and the configurations may be used in combination with other optical elements, such as the optical elements described herein. These embodiments can use the photonic crystal light conversion structure **200** as a substrate for the epitaxial growth of the solid state light emitting die **110**. In some embodiments, one or more buffer layers may be provided there between. Moreover, in some embodiments, the phosphor layer itself may be formed on another layer or substrate.

[0079] As was described above, in some embodiments, the photonic crystal phosphor light conversion structures may be planar and may be the same size and shape as a surface of the light emitting die. In other embodiments, the photonic crystal phosphor light conversion structures may be laser or saw cut into a desired shape, to provide, for example, wire bond notches in a square photonic crystal phosphor light conversion structure and/or to allow the photonic crystal phosphor light conversion structure to fit on and around the die surface. In other embodiments, desired shapes may be formed by etching a photonic crystal phosphor light conversion structure after it is formed. Moreover, in some embodiments, three-dimensional preforms may be fabricated that can provide photonic crystal phosphor light conversion structures having a shallow cup shape to allow edge of the die coverage by the photonic crystal phosphor light conversion structure, with appropriate cutouts for wire bonds and/or other features.

[0080] Many different configurations of dielectric nanostructures may be provided. Referring to Figures 11A-11E, the dielectric nanostructures **201** of the photonic crystal phosphor light conversion structure **200** may be present as an array of holes in the solid phosphor layer **1100**. Such holes may be filled with air or another material, such as silicon oxides (SiOx) or aerogels. The holes may be present in any suitable configuration, but in some embodiments, the holes are present in a periodic array such that the periodicity is on the same length scale as half the wavelength of the electromagnetic waves propagated there through. Furthermore, in some embodiments, the holes are spaced between 200 to 500 nm apart. In some embodiments, the holes may traverse through the solid phosphor layer, but in some embodiments, the holes may traverse only 40%, 50%, 60%, 70%, 80%, 90% or 95% of the thickness of solid phosphor layer, such that dielectric nanostructures **201** are only present on one face of the solid phosphor layer, while other faces may not have dielectric nanostructures **201** therein. In some embodiments, the width of the holes is in a range of about 50 nm to about 250 nm. The configuration, shape, width and depth of the holes will depend on several factors, such as the solid state light emitting die used, the chemical nature of the phosphor layer **1100**, the thickness of the solid phosphor layer **1100** and the photonic effect desired. However, at least one dimension of the holes will be in the nanoscale range. In addition, the solid state light emitting die **110** may in any suitable direction with respect to the photonic crystal phosphor light conversion structure **200** and with respect to the dielectric nanostructures **201**.

[0081] As described above, any suitable configuration of the dielectric nanostructures **201** may be used in embodiments of the invention. However, the configuration, shape, width and depth of the dielectric nanostructures **201** that may be formed in the solid phosphor layer **1100** may include those found in "Fabrication of photonic crystals for the visible spectrum by holographic lithography," *Nature*, 404, 53-56 (2 March 2000) by M. Campbell, D. N. Sharp, M. T. Harrison, R. G. Denning and A. J. Turberfield, the relevant portions of which are hereby incorporated by reference.

[0082] Examples of configurations will now be discussed. Referring to Figure 11A, in some embodiments, the photonic crystal phosphor light conversion structure **200** may be on the solid state light emitting die **110**. When the dielectric nanostructures **201** include an array of holes, the holes may be any suitable depth and width, which may depend on several factors, as described above. The radiation emitted from the solid state light emitting die **110** may be modified by the photonic crystal phosphor light conversion structure **200**. In addition, the dielectric nanostructures **201** may allow for the light **1110** from the photonic crystal phosphor light conversion structure **200** to be emitted in a particular direction.

[0083] Referring to Figures 11B and 11C, the dielectric nanostructures **201** may be in any suitable formation or direction. In Figure 11B, the dielectric nanostructures **201** are holes that are tilted from a position perpendicular to a light emitting surface of the solid state light emitting die **110**. Thus, the light **1110** emitted from the photonic crystal phosphor light conversion structure **200** may be directed in a particular direction or pattern. In Figure 11C, the dielectric nanostructures **201** are parallel to the light emitting surface of the solid state light emitting die **110**. Thus, the light **1110** from the photonic crystal phosphor light conversion structure **200** may be directed parallel to the surface of the solid state light emitting die **110**. In other embodiments, the dielectric nanostructures **201** may be randomly or pseudo-randomly oriented so that direction of light is also random or pseudo-random.

[0084] Referring to Figures 11D and 11E, more than one solid state light emitting die **110** may be used in conjunction with the photonic crystal phosphor light conversion structure **200**. The solid state light emitting dice **110** may emit light at the same wavelength or at different wavelengths, and the dielectric nanostructures **201** may interact with each of the solid state light emitting dice **110** in the same manner, or some of the dielectric nanostructures **201** may be configured to interact with the light emitted from one solid state light emitting die **110**, while other dielectric nanostructures **201** may be configured to interact with light emitted from the other solid state light emitting die **110**. Referring to Figure 11E, the size and spacing of the dielectric nanostructures **201** may be varied for interaction with the light emitted from the different solid state light emitting dice **110**. For example, two of the solid state light emitting dice **110A** located on opposite ends of the photonic crystal phosphor light conversion structure **200** may emit red light and another **110B** may emit blue light, and some of the dielectric nanostructures **201** may interact with the solid state light emitting dice **110A**, and some of the dielectric nanostructures **201** may interact with the solid state light emitting die **110B**. For the structures described in Figures 11A-11E, the photonic crystal phosphor light conversion structure **200** is depicted as a planar. However, as one of skill in the art will appreciate, the photonic crystal phosphor light conversion structure **200** may be in any suitable shape, including structures that are non-uniform in thickness and/or overhang the solid state light emitting die **110**, for example, those structures described in Figures 2A-2F.

[0085] Figure 12 is a flowchart of operations that may be performed to fabricate a photonic crystal phosphor light conversion structure, according to various embodiments of the present invention, which may correspond to Block **420** of Figure 4. As shown at Block **1210**, a solid phosphor sheet is fabricated, *e.g.*, by a Czochralski-type method. A Czochralski-type method is a method of producing large single crystals, or boules, by inserting a small seed crystal of an inorganic material into a crucible filled with similar molten material, then slowly pulling the seed up from the melt while rotating it. In some embodiments, the solid phosphor sheet may be grown on a carrier substrate, such as a glass substrate. Once a solid phosphor sheet is fabricated, it may be patterned to create the dielectric nanostructures **201**. Any suitable method for forming a photonic crystal may be used. Such techniques are known in the art, and may include, lithographic, etching and masking techniques. Suitable techniques for forming the dielectric nanostructures **201** include those described in "Fabrication of photonic crystals for the visible spectrum by holographic lithography," *Nature*, 404, 53-56 (2 March 2000) by M. Campbell, D. N. Sharp, M. T. Harrison, R. G. Denning and A. J. Turberfield, the relevant portions of which are hereby incorporated by reference.

[0086] Referring back to Figure 12, at Block **1220**, the solid phosphor sheet is singulated to form individual photonic crystal phosphor light conversion structures. The solid phosphor layer may be patterned to create the dielectric nanostructures **201** before or after singluation. In some embodiments, the solid phosphor sheet is singulated, but an attached substrate is not singulated, while in other embodiments, both the solid phosphor sheet and the attached substrate are singulated. The photonic crystal phosphor light conversion structure may be removed from the substrate using a pick and place and/or conventional mechanism, and attached to the solid state light emitting die, as shown in Block **1230**. Some embodiments of the present invention can allow mass production of photonic crystal phosphor light conversion structures which due to their rigidity may be handled by automated equipment.

[0087] Embodiments of the present invention have been described above in connection with a photonic crystal phosphor light conversion structure that is a preform that is adhesively attached to a single LED. However, in other embodiments, as illustrated in Figure 13, large photonic crystal phosphor preform sheets **1300** could be used to adhesively attach multiple LED dice **120** in large fixtures. The type of photonic crystal phosphor and the thickness of the sheets **1300** may be altered to make different temperatures of white light, depending on which sheets are used. Different types of light, such as morning sunlight, noonday sunlight, evening light and/or other colors, may then be provided, by changing or adding/subtracting phosphor sheets for emission control.

[0088] Alternatively, the large photonic crystal phosphor preform sheets **1300** could be used in a remote phosphor light fixture. For example, one or more LEDs, dice or packaged, could be provided in a chamber, such as a cylindrical or frusto-conical chamber, and one or more of the perform sheets **1300** provided at an opposing end of the chamber. Such perform sheet **1300** could be spaced as described, for example, in United States Patent No. 7,614,759, the disclosure of which is incorporated herein by reference as if set forth in its entirety.

[0089] Spacing of a phosphor from a light emitter may improve the efficiency of the emitter/phosphor system. While not being limited to a particular theory of operation, it is believed that at least some of this efficiency increase may be the result of reducing absorption by the light emitter of the light generated by the phosphor. As such, improving the light extraction of the phosphor may result in less light to be absorbed by the LED. Thus, the LED and phosphor may be spaced more closely than in systems that do not have photonic crystal phosphors while maintaining efficiency or efficiency may be improved for a given distance between the phosphor and the LED.

[0090] As described above, instead of the photonic crystal phosphor light conversion structures **200** grown externally, in some embodiments of the invention, a solid phosphor layer may be grown on a light emitting surface of a solid state light emitting die and then processed to form the dielectric nanostructures. The term "grown," as used herein, refers to the formation of a phosphor thin film via any thin film deposition technique, such as metal organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), low pressure deposition (LPD), and any other thin film deposition technique known to those of skill in the art. The dielectric nanostructures **201** may be formed after the solid phosphor layer is grown or the dielectric nanostructures **201** may be formed during the growth of the solid phosphor layer, for example, by masking, deposition of sacrificial structures and/or using lithographic techniques.

[0091] As with the phosphor preforms, LEDs including a solid phosphor layer grown directly on the light emitting die may be in many different configurations. For example, any of the configurations illustrated in Figures 3A-3N may be produced by growing a solid phosphor layer on the solid state light emitting die and then processing the solid phosphor layer to form the dielectric nanostructures. In addition, the configurations shown in Figures 5A and 5B could also be achieved by using a phosphor thin film deposition technique with subsequent processing. For example, referring to Figure 5A, a sacrificial layer or other support structure could be provided in the submount **130** in order to allow for the growth of the solid phosphor layer. As another example, referring to Figure 5B, a solid phosphor layer may be grown on the transparent substrate **500**, or as with Figure 5A, a support layer could be provided for the growth of the solid phosphor layer. Referring to Figures 3A-3N, in some embodiments, the solid phosphor layers may be grown directly on the surface of the die **110**. Thus, the coupling/adhesive layer **210** may not necessarily be present in the LED, but in some embodiments, the coupling/adhesive layer **210** could be present, particularly to provide a layer through which a low profile wire bond **334** may be passed through. In addition, in some embodiments, selective growth of the solid phosphor layer and/or the dielectric nanostructures, may be achieved via masking or lithographic techniques known to those of skill in the art. Also according to some embodiments, a support layer and/or a sacrificial layer may be formed on or adjacent to the solid state light emitting die **110** in order to support the formation of various shapes and configurations of solid phosphor layers. It will also be understood that masking and etching processes may be used in combination.

[0092] Figure 14 is a flowchart of operations that may be performed to fabricate solid state light emitting devices according to embodiments of the present invention. Referring to Figure 14, at Block **1410**, the solid state light emitting die, such as the die **110**, is fabricated using conventional techniques. At Block **1420**, a mask, a coupling layer, and/or a temporary layer (such as a sacrificial layer or support layer) may, in some embodiments, be formed on and/or adjacent to the solid state light emitting die. For example, in embodiments illustrated in Figures 3A-3G, the anode or cathode may be masked so as to allow the formation of the photonic crystal phosphor light conversion structure on the die **110** but not the contact **120a**. In addition, configurations such as those depicted in Figures 3B, 3C, 3D 3F, 3I, 3J, 3K and 3L may require temporary supports or sacrificial layers on and/or adjacent to the die **110** in order to provide support for the formation of nonplanar and/or overhanging photonic crystal phosphor light conversion structures. Referring to Block **1430**, a solid phosphor layer (which may be a photonic crystal if dielectric nanostructures **201** are formed in situ during growth of the phosphor) may be grown on a surface of the die **110**. Removal of a mask, a support layer and/or a sacrificial layer may occur in some embodiments at Block **1440**. Subsequent packaging may then take place at Block **1450**, for example, by bonding the unitary structure of the die **110** and the photonic crystal phosphor light conversion structure **200** to a submount and/or other packaging substrate. It will also be understood that a wire bond may be attached to the die before or after depositing step at Block **1430**.

[0093] As with the photonic crystal phosphor light conversion structures grown externally, many other optical elements may be provided in combination with photonic crystal phosphor light conversion structures that are grown directly on the surface of the light emitting die. All of the optical elements and combinations described with reference to photonic crystal phosphor light conversion structures grown externally (preforms) may also be used with photonic crystal phosphor light conversion structures grown on the solid state light emitting die, including photonic crystal phosphor light conversion structures comprising scattering particles, as illustrated in Figures 6A-6F; polycrystalline phosphor particle coatings, as illustrated in Figures 7A-7F; reflectors, as illustrated in Figures 8A-8F; and diffusing elements, as illustrated in Figures 9A-9F.

[0094] Figure 15 is a flowchart of operations that may be performed to fabricate solid state light emitting devices according to other embodiments of the present invention. Referring to Figure 15, at Block **1510**, a solid phosphor layer (which may be a photonic crystal if dielectric nanostructures **201** are formed in situ during growth of the phosphor) may be grown using any suitable technique, such as by any of the techniques described herein. In some embodiments, the solid phosphor layer is grown on another layer or substrate. Moreover, in some embodiments, the solid phosphor layer may be grown on one substrate and transferred to another substrate for further processing. In some embodiments, the dielectric nanostructures **201** may then be formed in the solid phosphor layer. At Block **1520**, a surface of the solid phosphor layer may then be polished, *e.g.*, by using a polishing technique known in art for polishing crystalline layers and/or other inorganic layers. At Block **1530**, a solid state light emitting die may then be epitaxially grown on the polished surface of the solid phosphor layer. Any suitable technique for growing the solid state light emitting die may be used. For example, techniques for growing Group III nitrides, such as GaN or InGaN, on the solid phosphor layer may be similar to those used in growing Group III nitrides on other substrates such as silicon, silicon carbide and sapphire. Particular techniques may be similar to those described in United States Patent Nos. 7,211,833, 7,170,097, 7,125,737, 7,087,936, 7,084,436, 7,042,020, 7,037,742, 7,034,328 and 7,026,659, the contents of each of which are incorporated herein by reference in their entirety. In some embodiments, one or more buffer layers are provided on the solid phosphor layer before the solid state light emitting die is epitaxially grown thereon. At Block **1540**, the resulting solid state light emitting device may be packaged, which may include, *e.g.*, singulation of the solid state light emitting die grown on the solid phosphor layer.

[0095] The light emitting devices provided according to some embodiments of the invention may be used in many applications. For example, referring to Figure 16, a lighting panel **1640** including a plurality of light emitting devices according to some embodiments of the invention may be used as a backlight for a display such as a liquid crystal display (LCD) **1650**. Systems and methods for controlling solid state backlight panels are described, for example, in U.S. Patent Application Ser. No. 11/368,976, filed March 6, 2006 entitled *Adaptive Adjustment of Light Output of Solid State Lighting Panels*, which is assigned to the assignee of the present invention and the disclosure of which is incorporated herein by reference in its entirety. As shown in Figure 16, an LCD **1650** may include a lighting panel **1640** that is positioned relative to an LCD screen **1654** such that light **1656** emitted by the lighting panel **1640** passes through the LCD screen **1654** to provide backlight for the LCD screen **1654**. The LCD screen **1654** includes appropriately arranged shutters and associated filters that are configured to selectively pass/block a selected color of light **1656** from the lighting panel **1640** to generate a display image. The lighting panel **1640** may include a plurality of light emitting devices according to any of the embodiments described herein.

[0096] As an additional example, referring to Figure 17, a lighting panel **1640** including a plurality of light emitting devices according to some embodiments of the invention may be used as a lighting panel for a solid state lighting fixture or luminaire **1660**. Light **1666** emitted by the luminaire **1660** may be used to illuminate an area and/or an object. Solid state luminaires are described, for example, in U.S. Patent Application Ser. No. 11/408,648, filed April 21, 2006, entitled *Solid State Luminaires for General Illumination*, which is assigned to the assignee of the present invention and the disclosure of which is incorporated herein by reference in its entirety.

[0097] Many different embodiments have been disclosed herein, in connection with the above description and the drawings. It will be understood that it would be unduly repetitious and obfuscating to literally describe and illustrate every combination and subcombination of these embodiments. Accordingly, the present specification, including the drawings, shall be construed to constitute a complete written description of all combinations and subcombinations of the embodiments described herein, and of the manner and process of making and using them, and shall support claims to any such combination or subcombination.

[0098] In the drawings and specification, there have been disclosed embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.

We claim:

1. A photonic crystal phosphor comprising a solid phosphor layer that comprises dielectric nanostructures therein.

2. The photonic crystal phosphor of claim 1, wherein the solid phosphor layer consists of a discrete single crystal phosphor.

3. The photonic crystal phosphor of claim 1, wherein the solid phosphor layer consists essentially of a discrete single crystal phosphor.

4. A solid state light emitting device comprising:

a primary solid state light emitting die that is configured to emit light upon energization thereof; and

a light conversion structure comprising a photonic crystal phosphor on a light emitting surface of the primary solid state light emitting die,

wherein the photonic crystal phosphor comprises a solid phosphor layer having dielectric nanostructures therein.

5. The solid state light emitting device of claim 4, wherein the dielectric nanostructures comprise holes within the solid phosphor layer.

6. The solid state light emitting device of claim 4, wherein the solid phosphor layer consists of a discrete single crystal phosphor.

7. The solid state light emitting device of claim 4, wherein the solid phosphor layer consists essentially of a discrete single crystal phosphor.

8. The solid state light emitting device of claim 4, further comprising an adhesive layer that attaches the light conversion structure to the light emitting surface.

9. The solid state light emitting device of claim 8, wherein the adhesive layer comprises silicone polymer.

10. The solid state light emitting device of claim 4, wherein the light conversion structure is sized to fit the light emitting surface of the primary solid state light emitting die.

11. The solid state light emitting device of claim 4, wherein the solid phosphor layer comprises cerium.

12. The solid state light emitting device of claim 11, wherein the solid phosphor layer comprises cerium at a concentration in a range of about 0.1 to about 20 weight percent.

13. The solid state light emitting device of claim 11, wherein the solid phosphor layer comprises $Y_3Al_5O_{12}$ doped with Ce^{3+} (Ce:YAG).

14. The solid state light emitting device of claim 11, wherein solid phosphor layer comprises $Ca_xSr_yMg_{1-x-y}AlSiN_3$ doped with cerium or strontium thio-gallate doped with cerium.

15. The solid state light emitting device of claim 4, wherein the solid phosphor layer comprises europium.

16. The solid state light emitting device of claim 15, wherein the solid phosphor layer comprises europium at a concentration in a range of about 0.5 to about 20 weight percent.

17. The solid state light emitting device of claim 15, wherein the solid phosphor layer comprises $Sr_{2-x}Ba_xSiO_4$ doped with Eu^{2+} (BOSE).

18. The solid state light emitting device of claim 15, wherein the solid phosphor layer comprises a europium doped material, wherein the material is selected from the group consisting of $Ca_xSr_{1-x}AlSiN_3$, strontium thio-gallate, alpha-SiAlON, silicon garnet, Y_2O_2S and La_2O_2S.

19. The solid state light emitting device of claim 4, wherein a surface of the photonic crystal phosphor light conversion structure is texturized, roughened, etched and/or featured.

20. The solid state light emitting device of claim 4, wherein the light conversion structure is directly on the light emitting surface of the primary solid state light emitting die.

21. The solid state light emitting device of claim 4, wherein the light conversion structure acts as a substrate for the primary solid state light emitting die.

22. The solid state light emitting device of claim 4, wherein the solid phosphor layer has a thickness in a range of about 1μm to about 200 μm.

23. The solid state light emitting device of claim 4, wherein the solid phosphor layer is spatially separated from the primary solid state light emitting die.

24. The solid state light emitting device of claim 4, further comprising one or more additional solid state light emitting dice configured to emit light upon energization thereof.

25. The solid state light emitting device of claim 24, wherein a first portion of the dielectric nanostructures are configured to interact with the primary solid state light emitting die and a second portion of the dielectric nanostructures are configured to interact with at least one of the additional solid state light emitting dice.

26. A method of fabricating a solid state light emitting device comprising:

placing a light conversion structure comprising a photonic crystal phosphor on a light emitting surface of a solid state light emitting die,

wherein the photonic crystal phosphor comprises a solid phosphor layer having dielectric nanostructures therein.

27. The method of claim 26, wherein placing the light conversion structure on the light emitting surface comprises adhesively attaching the light conversion structure to the light emitting surface of the solid state light emitting die.

28. The method of claim 26, wherein the dielectric nanostructures comprise holes within the solid phosphor layer.

29. A method of fabricating a solid state light emitting device comprising:

placing a light conversion structure comprising a solid phosphor layer on a light emitting surface of a solid state light emitting die, and

forming dielectric nanostructures in the solid phosphor layer.

30. The method of claim 29, wherein the dielectric nanostructures comprise holes in the solid phosphor layer.

31. The method of claim 29, wherein placing the light conversion structure on the light emitting surface comprises adhesively attaching the solid phosphor layer to the light emitting surface of the solid state light emitting die.

32. The method of claim 29, wherein placing the light conversion structure on the light emitting surface comprises growing a solid phosphor layer on the surface of the solid state light emitting die via a thin film deposition technique.

33. A method of fabricating a solid state light emitting device comprising

growing a solid state light emitting die on a surface of a light conversion structure that comprises a solid phosphor layer having dielectric nanostructures defined therein.

34. The method of claim 33, further comprising polishing the surface of the light conversion structure before the solid state light emitting die is grown thereon.

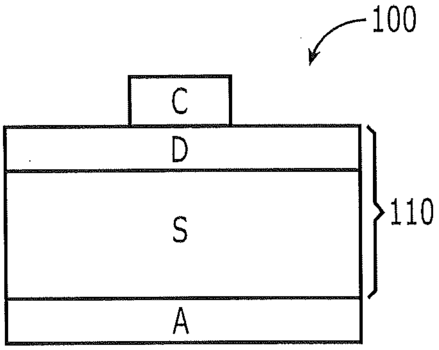

FIG. 1A
(PRIOR ART)

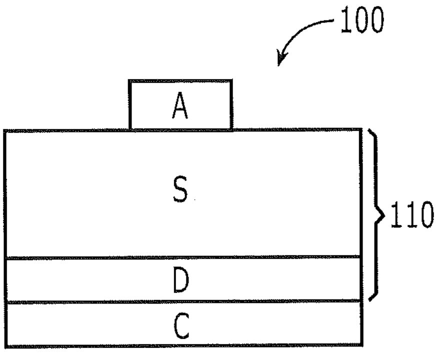

FIG. 1B
(PRIOR ART)

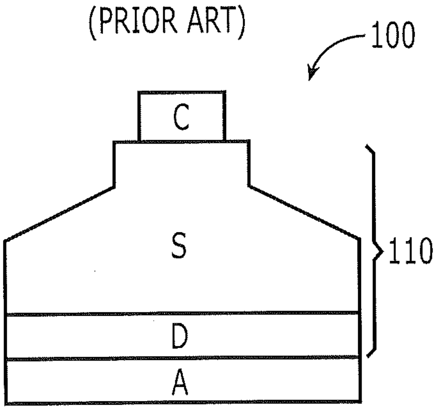

FIG. 1C
(PRIOR ART)

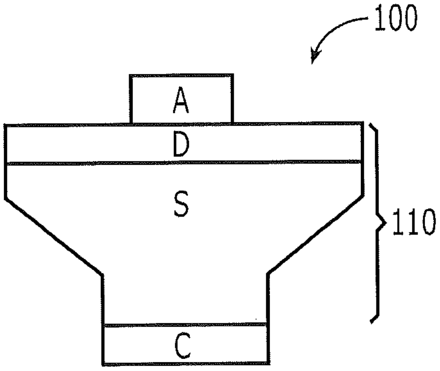

FIG. 1D
(PRIOR ART)

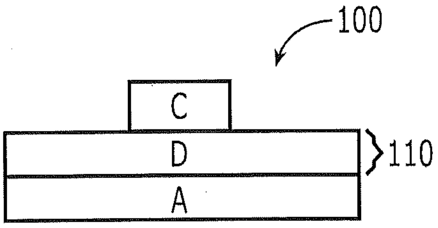

FIG. 1E
(PRIOR ART)

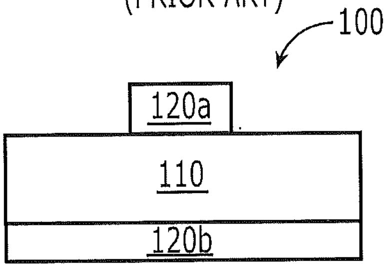

FIG. 1F
(PRIOR ART)

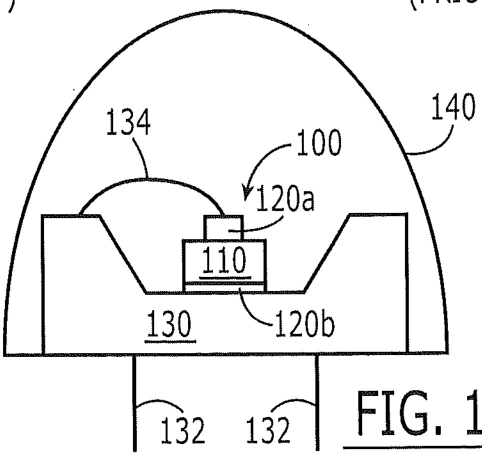

FIG. 1G

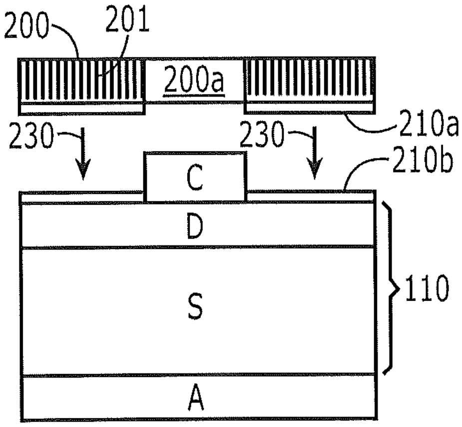

FIG. 2A

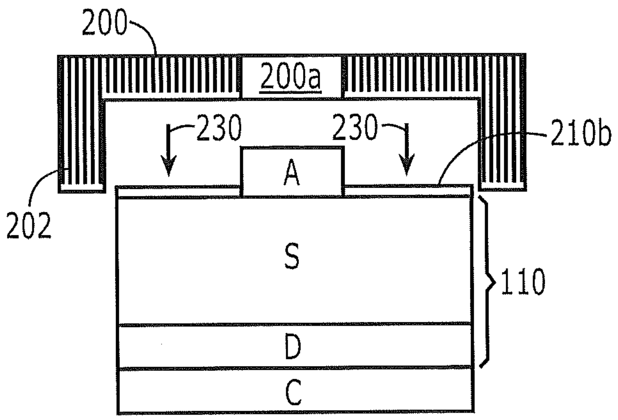

FIG. 2B

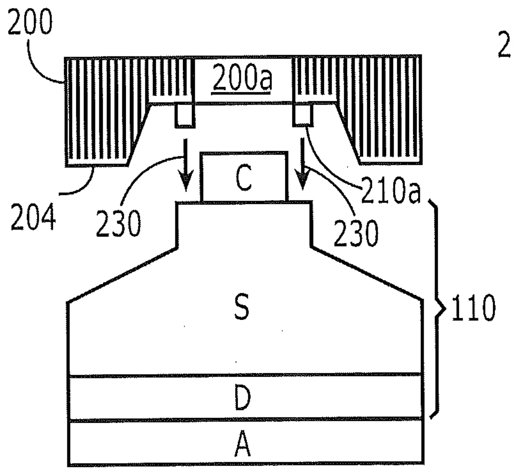

FIG. 2C

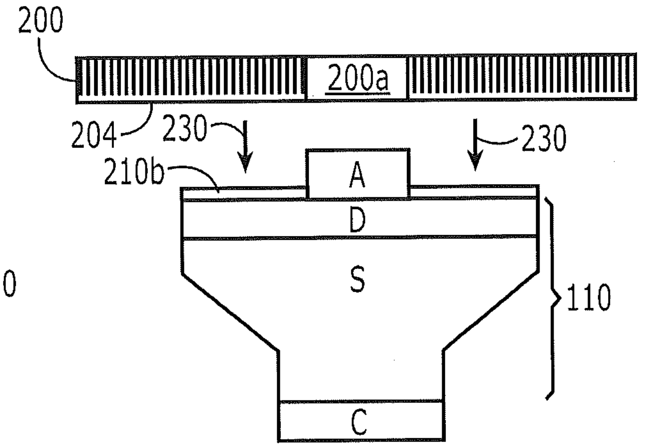

FIG. 2D

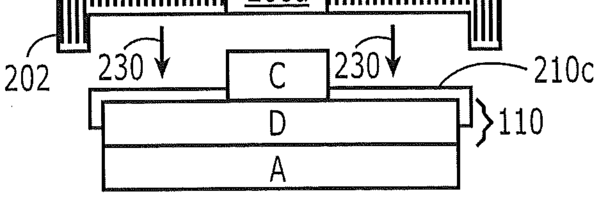

FIG. 2E

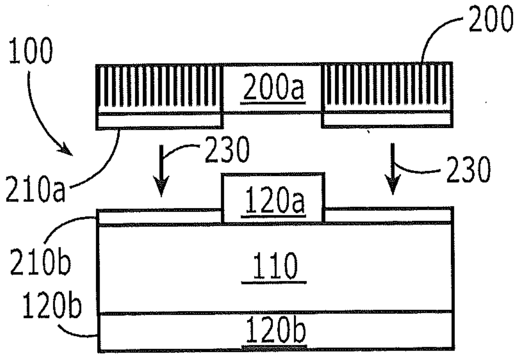

FIG. 2F

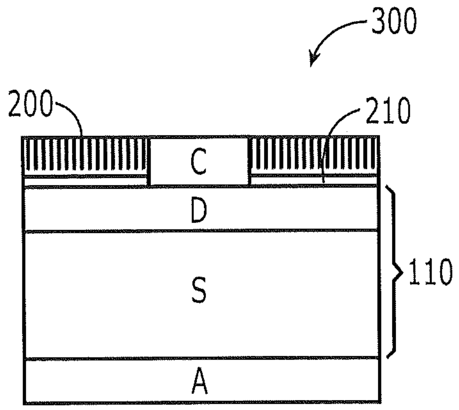

FIG. 3A

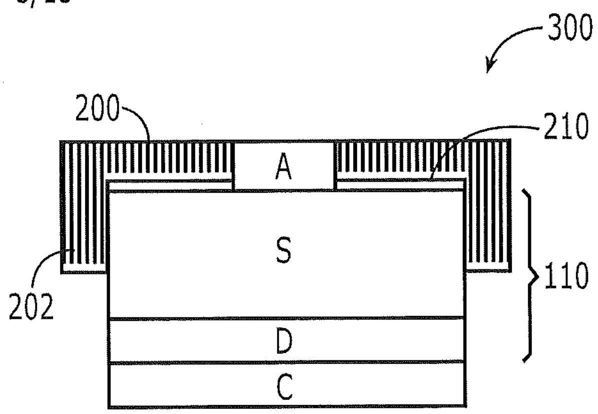

FIG. 3B

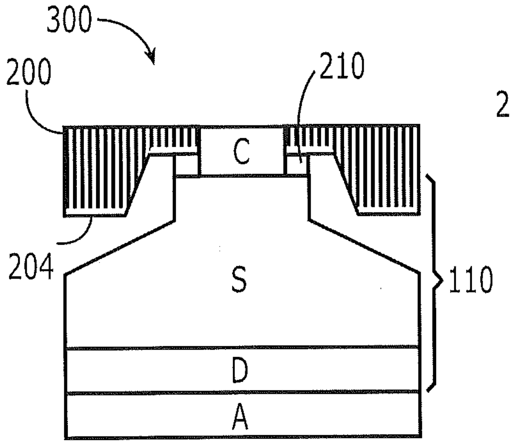

FIG. 3C

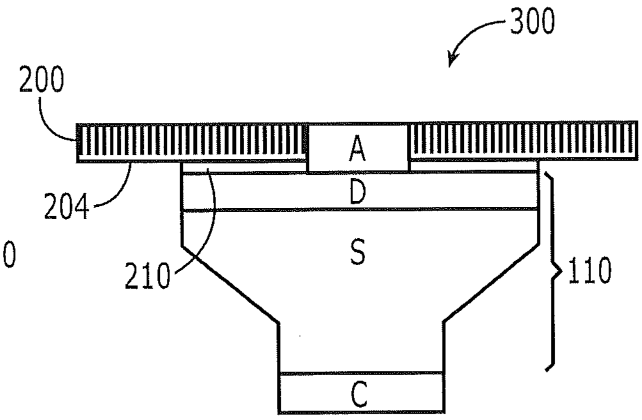

FIG. 3D

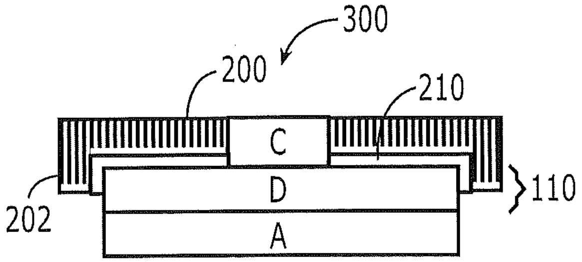

FIG. 3E

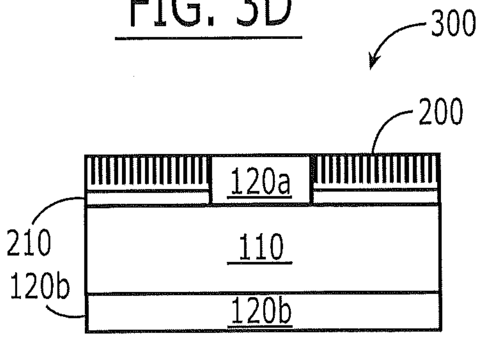

FIG. 3F

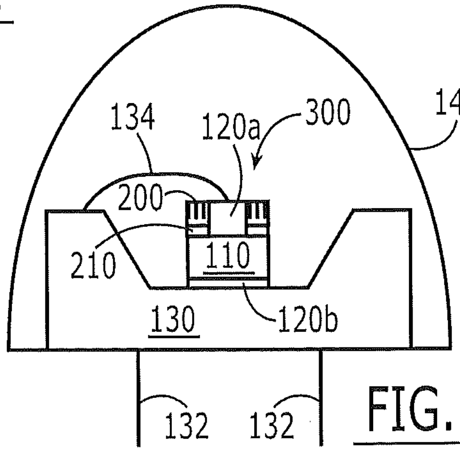

FIG. 3G

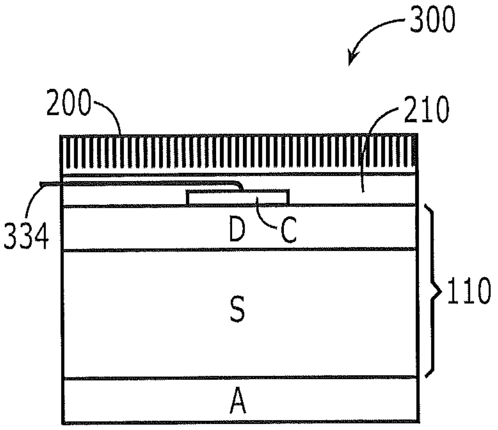

FIG. 3H

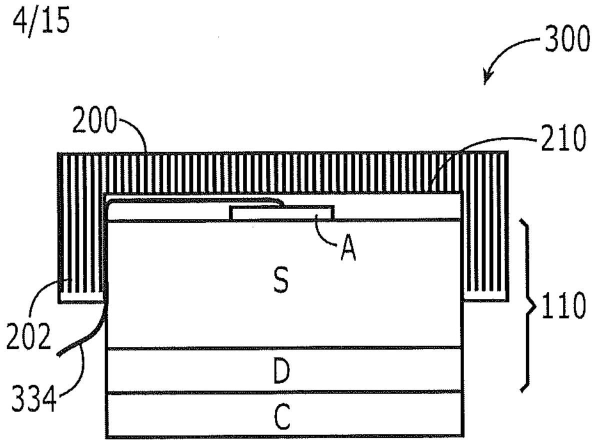

FIG. 3I

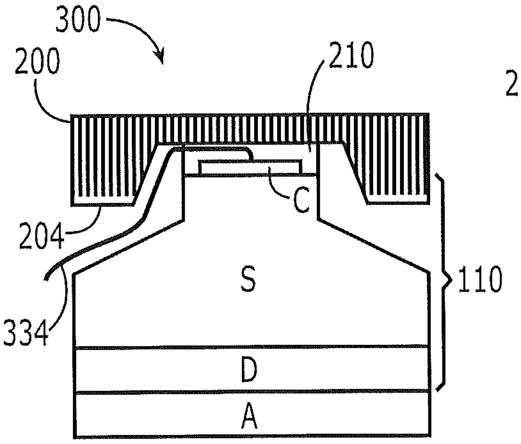

FIG. 3J

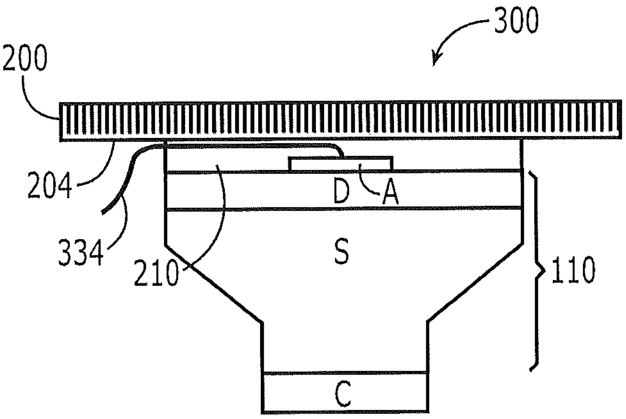

FIG. 3K

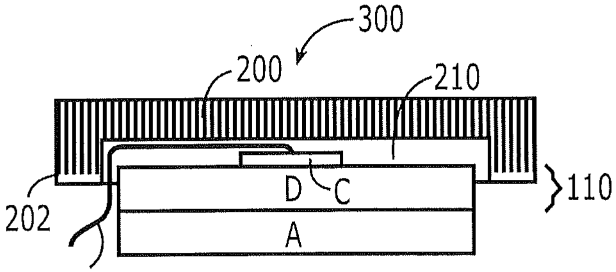

FIG. 3L

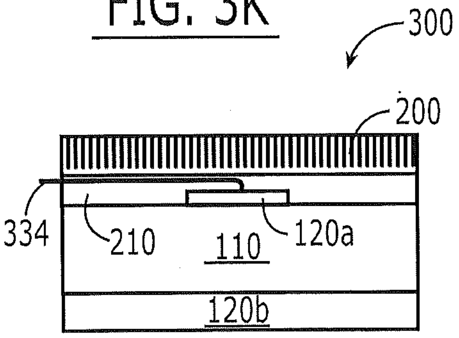

FIG. 3M

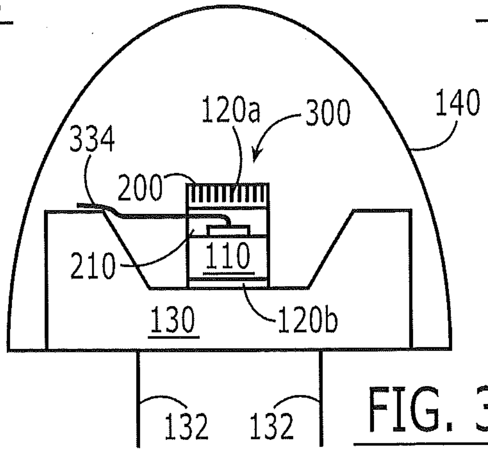

FIG. 3N

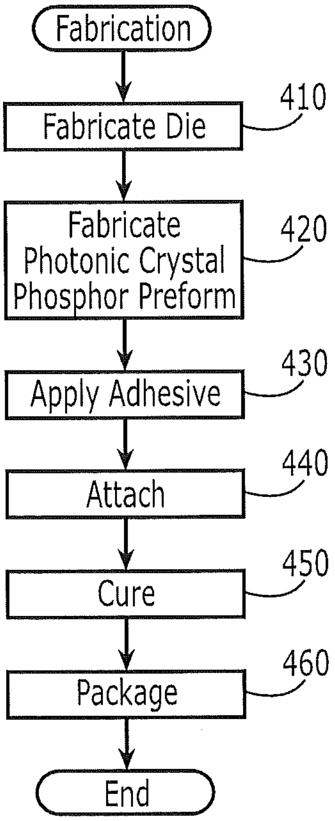
Fabrication
Fabricate Die
410
Fabricate Photonic Crystal Phosphor Preform
420
Apply Adhesive
430
Attach
440
Cure
450
Package
460
End

FIG. 4

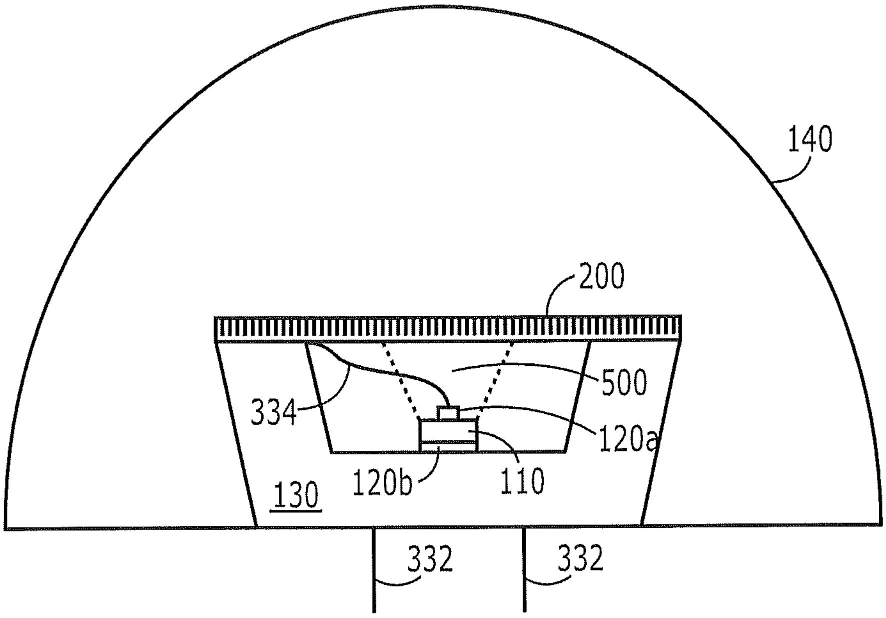
140
200
500
334
120a
130
120b
110
332
332

FIG. 5A

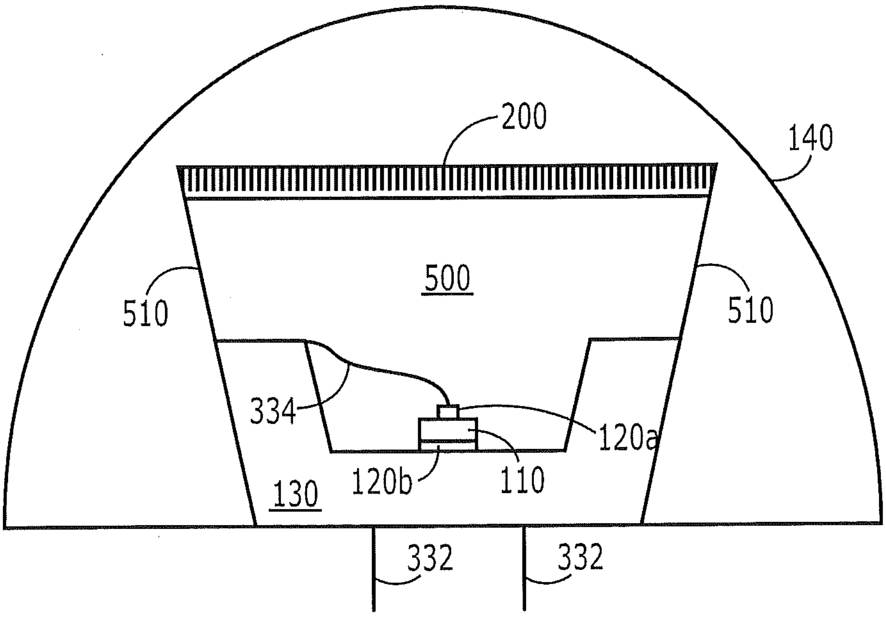
200
140
500
510
510
334
120a
130
120b
110
332
332

FIG. 5B

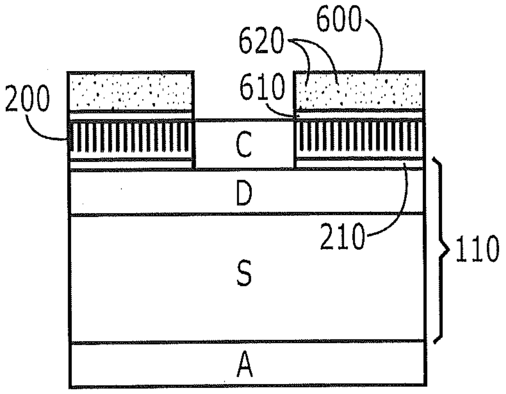

FIG. 6A

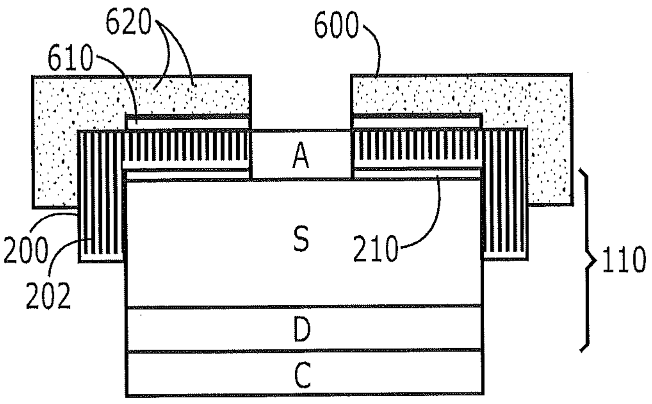

FIG. 6B

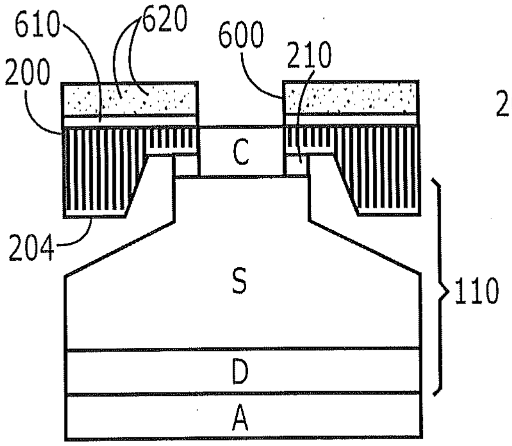

FIG. 6C

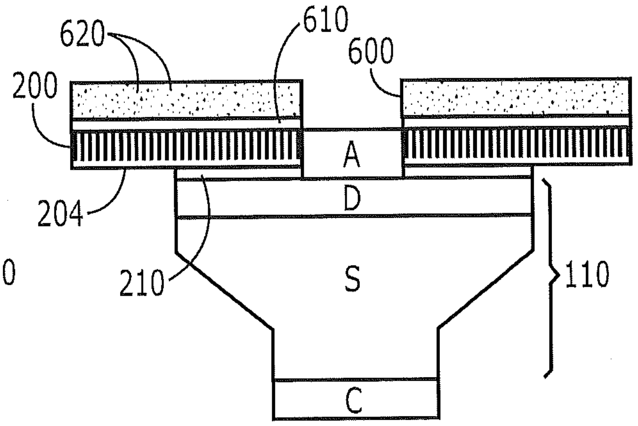

FIG. 6D

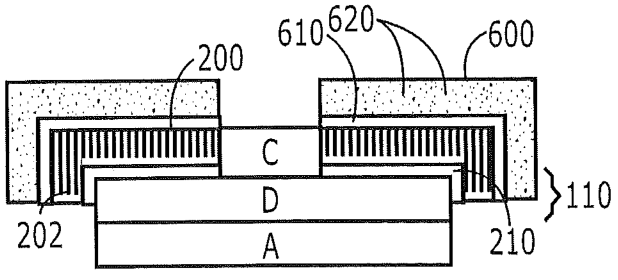

FIG. 6E

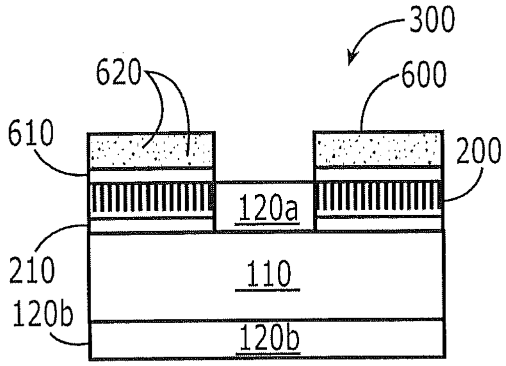

FIG. 6F

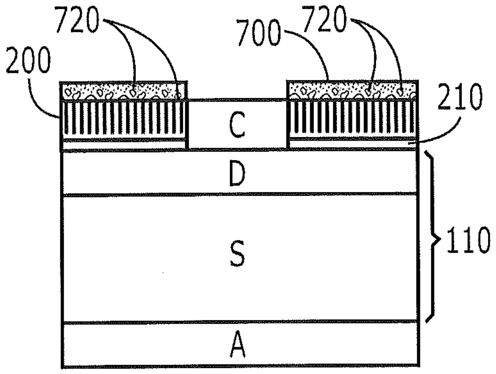

FIG. 7A

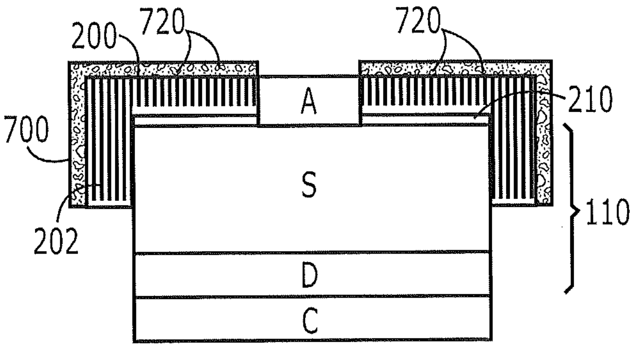

FIG. 7B

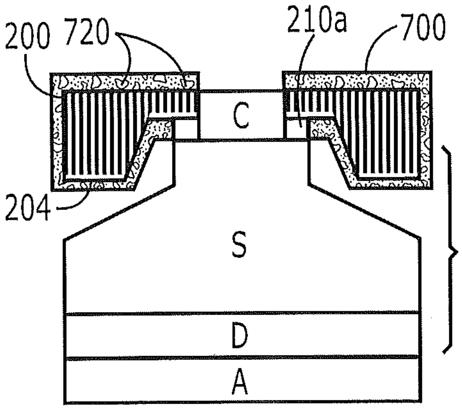

FIG. 7C

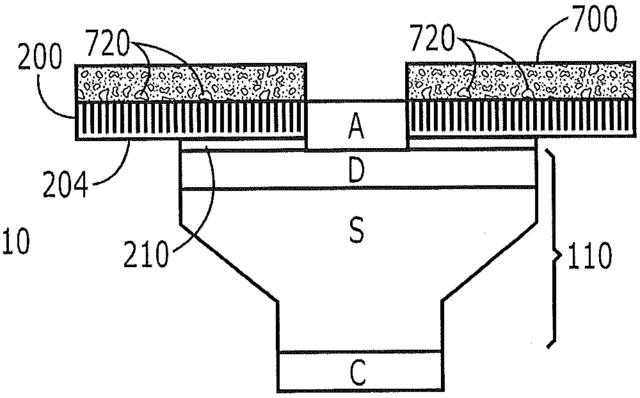

FIG. 7D

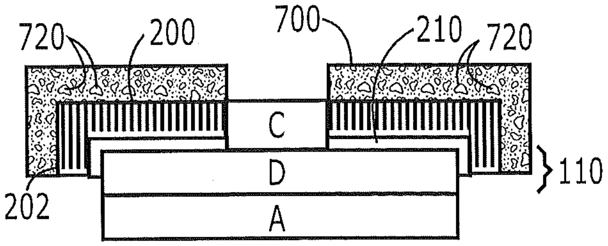

FIG. 7E

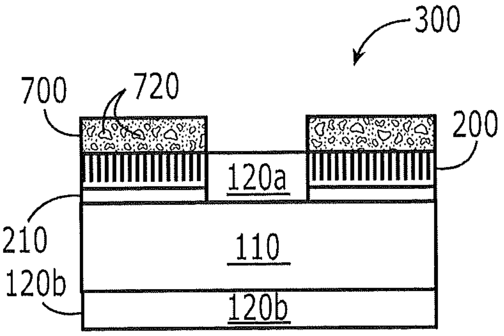

FIG. 7F

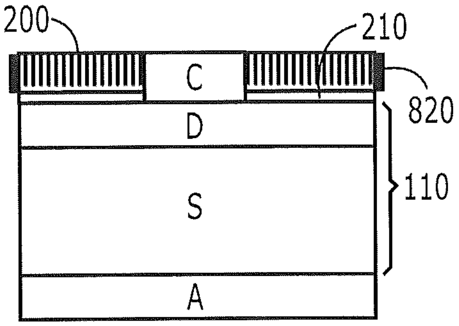

FIG. 8A

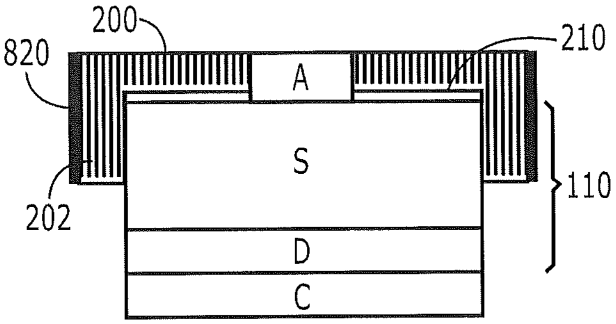

FIG. 8B

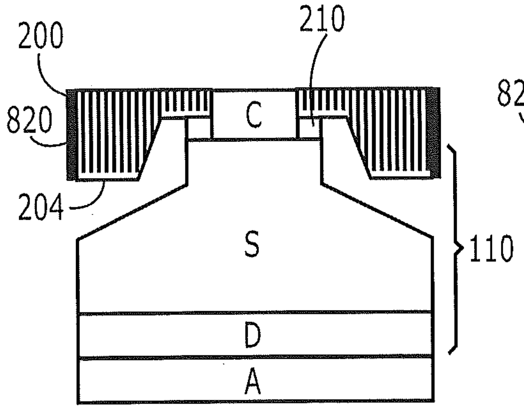

FIG. 8C

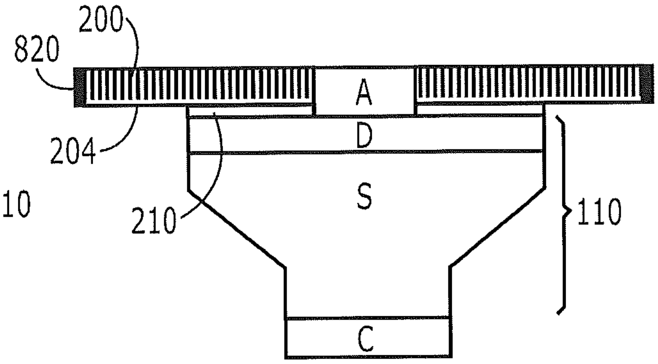

FIG. 8D

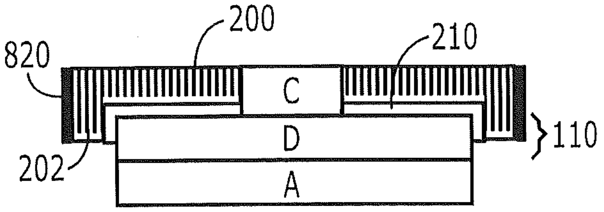

FIG. 8E

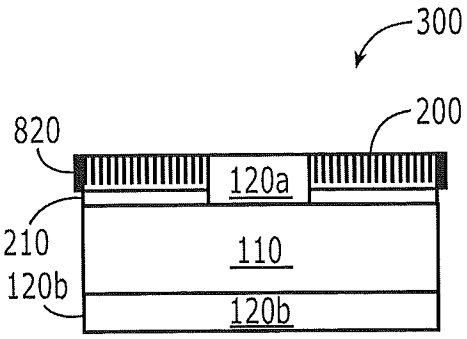

FIG. 8F

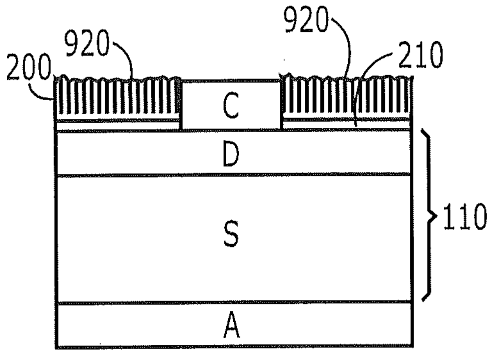

FIG. 9A

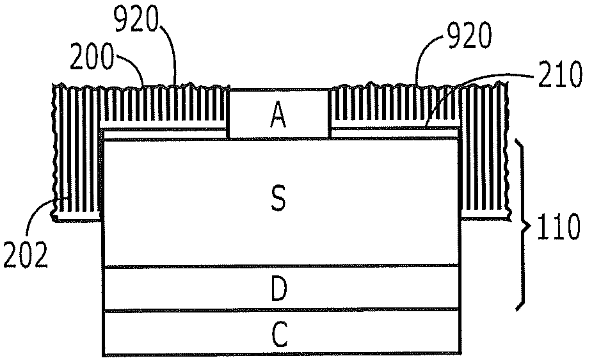

FIG. 9B

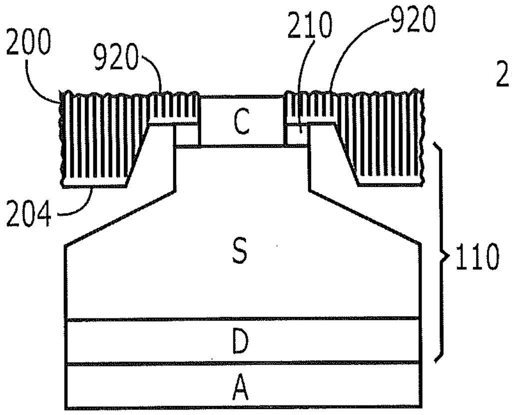

FIG. 9C

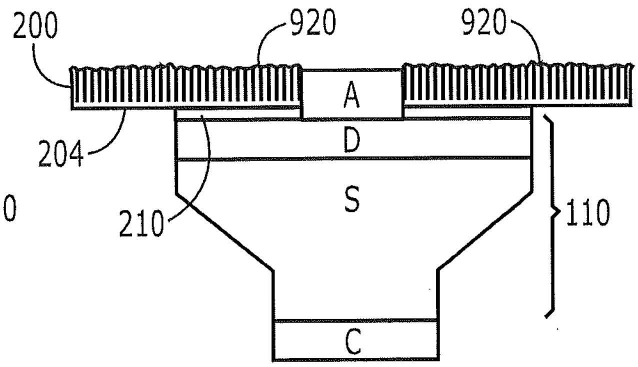

FIG. 9D

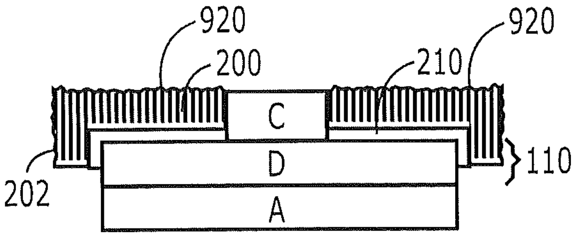

FIG. 9E

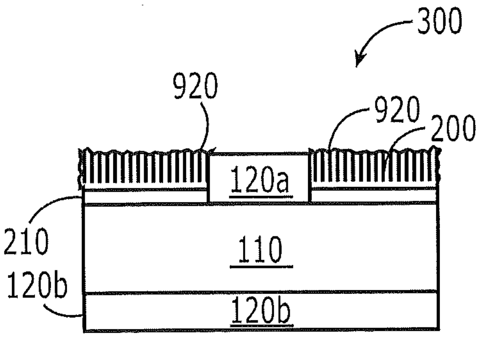

FIG. 9F

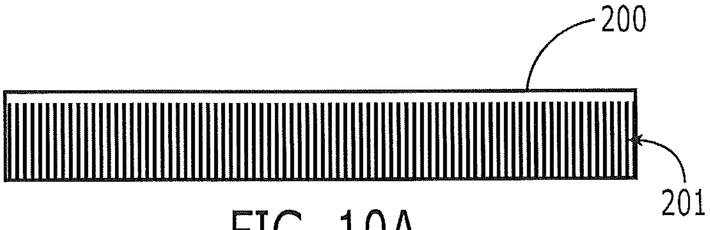

FIG. 10A

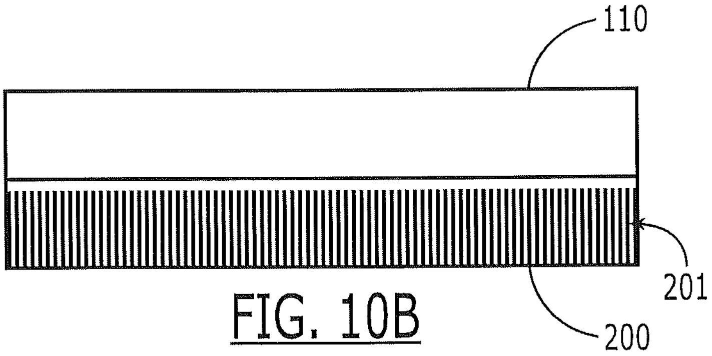

FIG. 10B

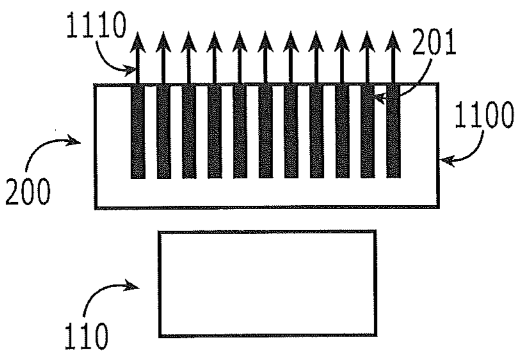

FIG. 11A

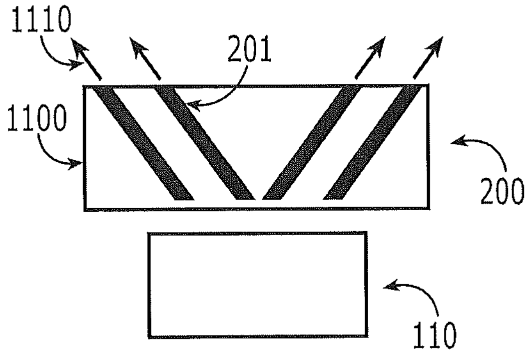

FIG. 11B

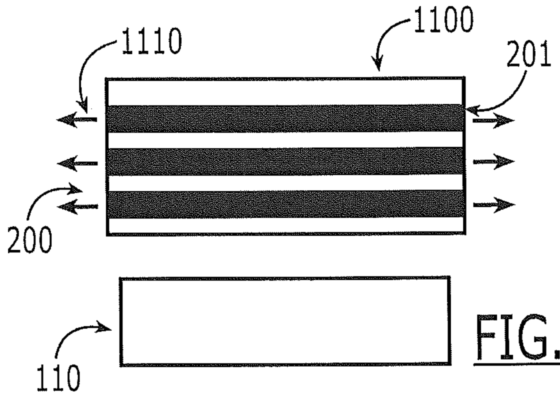

FIG. 11C

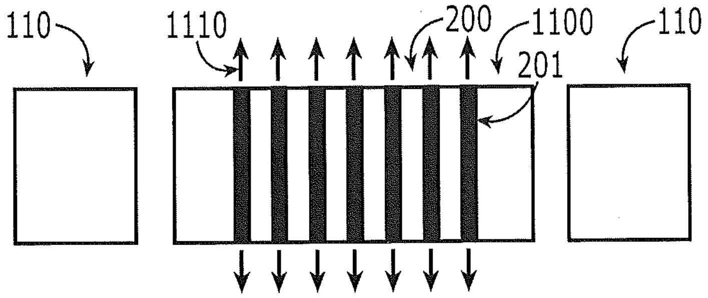

FIG. 11D

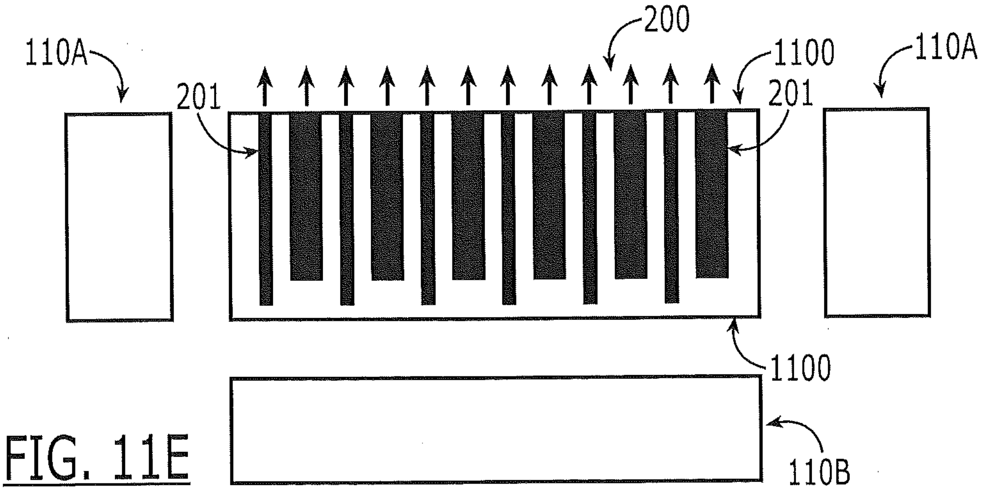

FIG. 11E

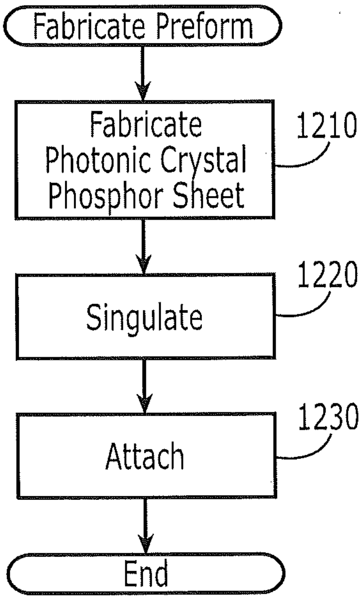
Fabricate Preform
Fabricate Photonic Crystal Phosphor Sheet
1210
Singulate
1220
Attach
1230
End

FIG. 12

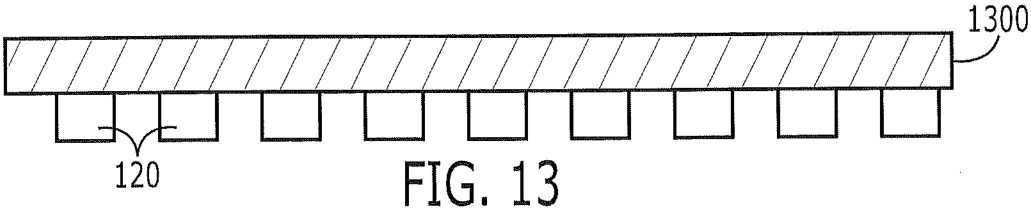
1300
120

FIG. 13

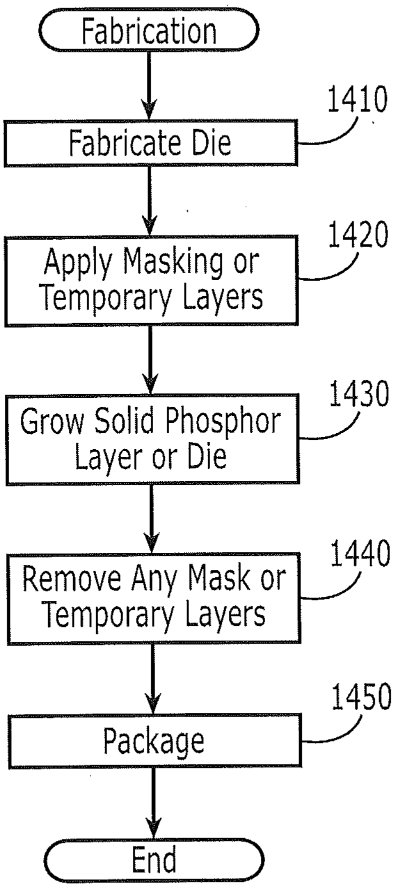
Fabrication
Fabricate Die
1410
Apply Masking or Temporary Layers
1420
Grow Solid Phosphor Layer or Die
1430
Remove Any Mask or Temporary Layers
1440
Package
1450
End

FIG. 14

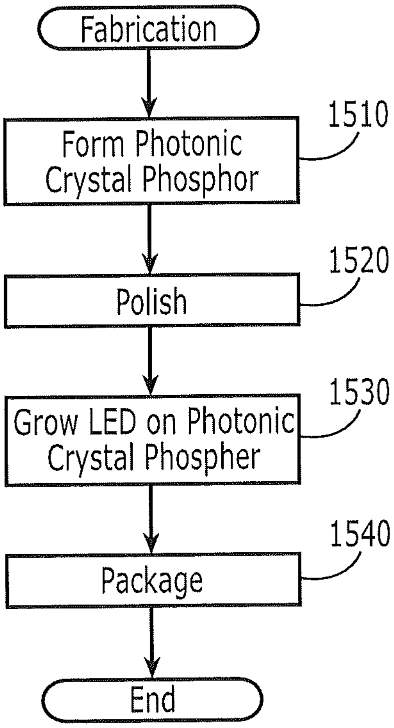
Fabrication
Form Photonic Crystal Phosphor
1510
Polish
1520
Grow LED on Photonic Crystal Phospher
1530
Package
1540
End

FIG. 15

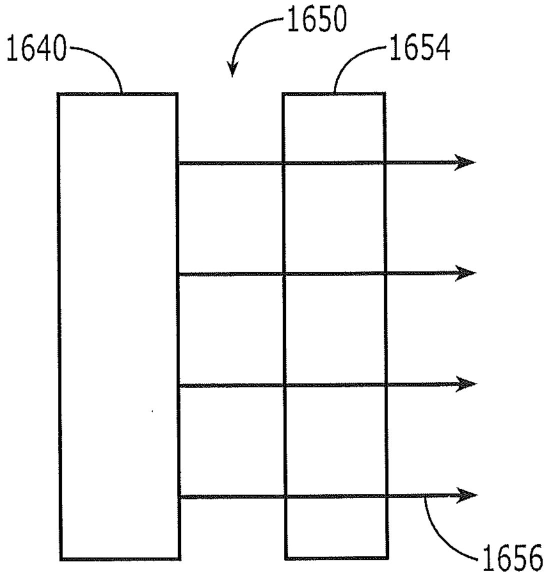

FIG. 16

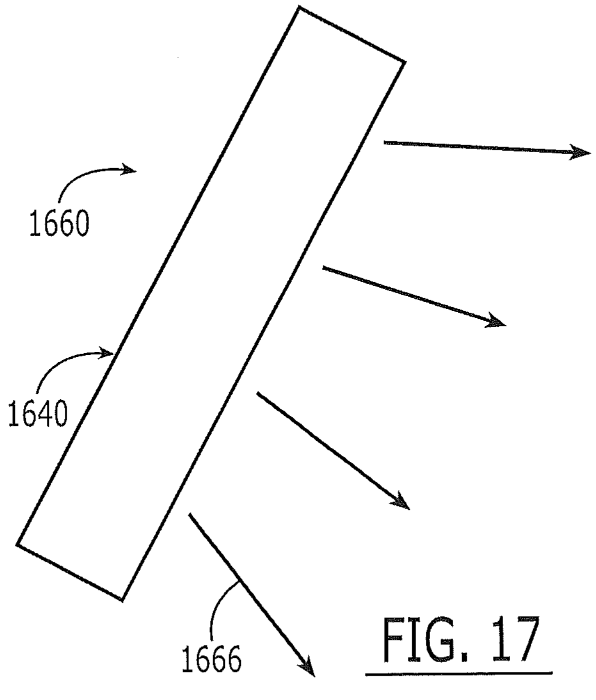

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/026785

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01L 31/00 (2011.01)
USPC - 362/084

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)
IPC(8) - G02B 6/10, 6/12; H01L 21/00, 21/76, 21/84, 29/00, 31/00, 33/00 (2011.01)
USPC - 257/14, 82, 433; 362/084; 385/122, 130, 131; 438/22-35, 64, 65, 66, 67, 69

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ----- Y	US 6,999,669 B2 (SUMMERS et al) 14 February 2006 (14.02.2006) entire document	1-3 --------------- 6-7, 26-34
X ---- Y	US 2009/0127567 A1 (WANG) 21 May 2009 (21.05.2009) entire document	4-5, 8-10, 19-20, 23 -------------------------- 6-7, 11-25
Y	US 7,517,728 B2 (LEUNG et al) 14 April 2009 (14.04.2009) entire document	11-12
Y	PAN et al. Tailored photoluminescence of YAG:Ce phosphor through various methods. May 2004. Science Direct. Journal of Physics and chemistry of solids. Vol. 65. Issue 5, page 845. [retrieved on 2011-04-20]. Retrieved from the Internet: <URL: http://http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TXR-49Y3W6R-2&_user=10&_coverDate=05%2F31%2F2004&_rdoc=1&_fmt=high&_orig=gateway&_origin=gateway&_sort=d&_docanchor=&view=c&_searchStrId=1725777152&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=0b679422ac04ad3c1b96d14df89dd2b7&searchtype=a>. abstract only	11, 13
Y	US 2008/0283864 A1 (LETOQUIN et al) 20 November 2008 (20.11.2008) entire document	14-18, 21-22, 24-34

☒ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"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 20 April 2011	Date of mailing of the international search report 03 MAY 2011
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2005/025831 A1 (NEGLEY et al) 24 March 2005 (24.03.2005) entire document	1-34
A	US 2009/0236621 A1 (CHAKRABORTY) 24 September 2009 (24.09.2009) entire document	1-34
A	US 2009/0050905 A1 (ABU-AGEEL) 26 February 2009 (26.02.2009) entire document	1-34
A	US 2009/0200561 A1 (BURRELL et al) 13 August 2009 (13.08.2009) entire document	1-34
A	MIKAMI et al. New Phosphors for white LEDs: Material Design Concepts. 2009 IOP Conference Series: Materials Science and Engineering I. [retrieved on 2011-04-20]. Retrieved from the Internet: <URL: http://iopscience.iop.org/1757-899X/1/1/012002/pdf/1757-899X_1_1_012002.pdf>. pages 1-9	1-34