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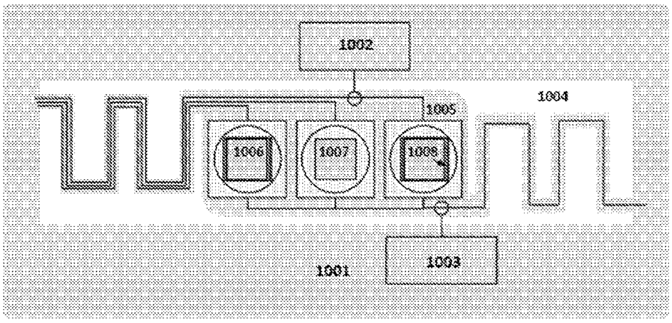

FIG. 10

(57) Abstract: Disclosed herein are methods of operating one or more light-generating structures in combination with one or more light-conditioning structures for enhanced energy efficiency. Also disclosed are light-emitting assemblies comprising two or more of these structures operated using the disclosed method. These light-emitting assemblies exploit the thermal voltage defect and other thermal effects by transferring a fraction of the heat generated within one or more light-conditioning structures to one or more light-generating structures, and may optionally involve thermally isolating both the light-generating structures and light- conditioning structures from the ambient environment.

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LIGHT EMITTING DIODE ASSEMBLIES UTILIZING HEAT SHARING FROM LIGHT-CONDITIONING STRUCTURES FOR ENHANCED ENERGY EFFICIENCY

CROSS-REFERENCE

[0001] This application claims the benefit of U.S. Provisional Application No. 62/301,752, filed March 1, 2016, which application is incorporated herein by reference.

BACKGROUND

[0002] In a conventional light-emitting diode, the drive voltage V applied to the semiconductor p-n junction at moderate brightness is roughly equal to the energy of a typical emitted photon, $\hbar\omega$, divided by the magnitude of the charge of the electron, q. As the temperature T of the junction increases, the drive voltage required to flow the same amount of current through the junction is reduced. We refer hereafter to this effect as the thermal voltage defect.

[0003] As the temperature T of the junction increases, there is also a reduction of the quantum efficiency for photon emission known as thermal droop, *i.e.*, less optical power is emitted by the diode and its surrounding optical and mechanical structures at constant current as temperature increases. The thermal voltage defect is typically insufficient to overcome this quantum efficiency reduction, and thus elevated temperatures typically cannot be used to improve the efficiency of the combined light-emitting assembly.

SUMMARY

[0004] Disclosed herein are light-emitting assemblies comprising a) a light-generating structure which is configured to generate photons upon application of a drive voltage; b) a light-conditioning structure; and c) a thermally-isolating structure, wherein the wall-plug efficiency of the light-generating structure is increased by having its lattice temperature exceed the ambient temperature, and wherein a fraction of the heat generated within the light-conditioning structure is transferred to the light-generating structure.

[0005] In some embodiments, the light emitting assembly further comprises a plurality of light-generating structures, a plurality of light-conditioning structures, a plurality of thermally-isolating structures, or any combination thereof. In some embodiments, the light-generating structure or plurality of light generating structures comprises a semiconductor p-n or p-i-n junction. In some embodiments, at least one thermally-isolating structure comprises a mechanical structure. In some embodiments, the mechanical structure comprises a printed circuit board. In some embodiments, the drive voltage of the light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron's charge. In some embodiments, the drive voltage of the light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron's charge by at least 150 mV. In some embodiments, the wall-plug efficiency of the light-generating structures is greater than 50%. In some embodiments, the wall-plug efficiency of the light-generating structures is greater than 100%. In some embodiments, the wall-plug efficiency of the light-generating structures is greater than 110%. In some embodiments, the light-generating structures are configured to utilize phonon recycling. In some embodiments, the light-generating structures are not configured to utilize phonon recycling. In some embodiments, the light-generating structures produce light with a free space wavelength of greater than about 600 nm. In some embodiments, the light-generating structures produce light with a free space wavelength of greater than about 850 nm. In some embodiments, the light-generating structures produce light with a free space wavelength of greater than about 1000 nm. In some embodiments, the light-generating structures produce light between about 350 nm and about 500 nm in free space wavelength. In some embodiments, the light-generating structures produce light with a free space wavelength of less than about 500 nm. In some embodiments, the light-conditioning structures produce light between about 380 nm and about 780 nm in free space wavelength. In some embodiments, the lattice temperature of the light-generating structures is at least 300K. In some embodiments, the lattice temperature of the light-generating structures is at least 305K. In some embodiments, the lattice temperature of the light-generating structures is at least 320K. In some embodiments, the lattice temperature of the light-generating structures is at least 350K. In some embodiments, the lattice temperature of the light-generating structures is at least 400K. In some embodiments, the lattice temperature of the light-conditioning structures is at least 300K. In some embodiments, the lattice temperature of the light-conditioning structures is at least 310K. In some embodiments, the lattice temperature of the light-conditioning structures is at least 360K. In some embodiments, the plurality of light-generating structures and/or light-conditioning structures are arranged in a planar configuration. In some embodiments, the plurality of light-generating structures and/or light-conditioning structures are arranged in a linear configuration. In some embodiments, a plurality of light-generating structures and/or light-conditioning structures are arranged in a configuration with the shape of a spherical shell or a section of a spherical shell. In some embodiments, the plurality of light-generating structures and/or light-conditioning structures are arranged in a configuration with the shape of a conical surface or conic section. In some embodiments, the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 300K. In some embodiments, the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 310K. In some embodiments, the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 360K. In some embodiments, the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 600K. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 10 mm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 1 mm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 100 μm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 10 μm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 1 μm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is less than about 1 μm. In some embodiments, the fraction of the heat generated within the light-conditioning structures which is transferred to light-generating structures exceeds about 5%. In some embodiments, the fraction of the heat generated within the light-conditioning structures which is transferred to light-generating structures exceeds about 50%. In some embodiments, the fraction of the heat generated within the light-conditioning structures which is transferred to light-generating structures exceeds about 80%.

[0006] Also disclosed herein are methods of operating one or more light-generating structures in combination with one or more light-conditioning structures, the method comprising: a) thermally-isolating a section of the assembly which comprises the one or more light-generating structures; b) applying a drive voltage to the one or more light-generating structures; and c) transferring a fraction of the heat produced within the one or more light-conditioning structures to at least one of the light-generating structures, wherein the transferred heat serves to increase the wall-plug efficiency of the one or more light-generating structures.

[0007] In some embodiments, the light-generating structures comprise semiconductor p-n or p-i-n junctions. In some embodiments, the thermally-isolating step comprises mounting the one or more light-generating structures on a thermally-isolating structure. In some embodiments, the thermally-isolating structure comprises a mechanical structure. In some embodiments, the mechanical structure comprises a printed circuit board. In some embodiments, the drive voltage applied to one or more light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron's charge. In some embodiments, the drive voltage applied to one or more light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron's charge by at least 150 mV. In some embodiments, the wall-plug efficiency of the one or more light-generating structures is greater than 50%. In some embodiments, the wall-plug efficiency of the one or more light-generating structures is greater than 100%. In some embodiments, the wall-plug efficiency of the one or more light-generating structures is greater than 110%. In some embodiments, the one or more light-generating structures are configured to utilize phonon recycling. In some embodiments, the one or more light-generating structures are not configured to utilize phonon recycling. In some embodiments, the one or more light-generating structures produce light with a free space wavelength of greater than about 600 nm. In some embodiments, the one or more light-generating structures produce light with a free space wavelength of greater than about 800 nm. In some embodiments, the one or more light-generating structures produce light with a free space wavelength of greater than about 1000 nm. In some embodiments, the one or more light-generating structures produce light with a free space wavelength of greater than about 2000 nm. In some embodiments, the one or more light-generating structures produce light with a free space wavelength between about 350 nm and about 500 nm. In some embodiments, the one or more light-generating structures produce light with a free space wavelength of less than about 500 nm. In some embodiments, one or more light-conditioning structures produce light with a free space wavelength between about 380 nm and about 780 nm. In some embodiments, one or more light-conditioning structures produce light with a free space wavelength of greater than about 500 nm. In some embodiments, the lattice temperature of the one or more light-generating structures is at least 300K. In some embodiments, the lattice temperature of the one or more light-generating structures is at least 305K. In some embodiments, the lattice temperature of the one or more light-generating structures is at least 320K. In some embodiments, the lattice temperature of the one or more light-generating structures is at least 350K. In some embodiments, the lattice temperature of the one or more light-generating structures is at least 400K. In some embodiments, the lattice temperature of the one or more light-conditioning structures is at least 300K. In some embodiments, the lattice temperature of the one or more light-conditioning structures is at least 310K. In some embodiments, the lattice temperature of the one or more light-conditioning structures is at least 360K. In some embodiments, the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a planar configuration. In some embodiments, the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a linear configuration. In some embodiments, the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a configuration with the shape of a spherical shell or a section of a spherical shell. In some embodiments, the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a configuration with the shape of a conical surface or a conic section. In some embodiments, the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 300K. In some embodiments, the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 310K. In some embodiments, the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 360K. In some embodiments, the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 600K. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 10 mm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 1 mm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 100 μm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 10 μm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is greater than about 1 μm. In some embodiments, the center-to-center spacing between adjacent light-generating structures is less than about 1 μm. In some embodiments, the fraction of the heat produced within the one or more light-conditioning structures which is transferred to at least one of the light-generating structures exceeds about 5%. In some embodiments, the fraction of the heat produced within the one or more light-conditioning structures which is transferred to at least one of the light-generating structures exceeds about 50%. In some embodiments, the fraction of the heat produced within the one or more light-conditioning structures which is transferred to at least one of the light-generating structures exceeds about 80%.

INCORPORATION BY REFERENCE

[0008] All publications, patents, and patent applications mentioned in this specification are herein incorporated by reference in their entirety to the same extent as if each individual publication, patent, or patent application was specifically and individually indicated to be incorporated by reference in its entirety. In the event of a conflict between a term herein and a term in an incorporated reference, the term herein controls.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The novel features of the invention are set forth with particularity in the appended claims. A better understanding of the features and advantages of the present invention will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the invention are utilized, and the accompanying drawings of which:

[0010] FIG. 1 shows a heat flow diagram for a light-emitting assembly that utilizes both heat sharing and phonon recycling.

[0011] FIG. 2 shows a heat flow diagram for a light-emitting assembly that utilizes heat sharing but not phonon recycling.

[0012] FIG. 3 shows a heat flow diagram for a light-emitting assembly that utilizes phonon recycling but not heat sharing.

[0013] FIG. 4 shows a heat flow diagram for a light-emitting assembly that utilizes neither heat sharing nor phonon recycling.

[0014] FIG. 5 shows a graph that highlights the key differences between different regimes of thermal transport for different light-emitting assemblies.

[0015] FIGS. 6A-B illustrate a packaged LED which combines light-generating structures (the diode, 203) and light-conditioning structures (the phosphor, 204) for use in an embodiment of light-engine scale heat sharing. FIG. 6A: cross-sectional view. FIG. 6B: top view.

[0016] FIG. 7 provides a non-limiting example of how packaged LEDs such as those described in FIGS. 6A-B can be combined with a mechanical structure which provides thermal isolation of the light-generating and light-conditioning structures to implement light-engine scale heat sharing.

[0017] FIG. 8 provides a non-limiting example of the use of a thermally isolating light-conditioning structure, such as a distributed Bragg reflector, within a packaged LED to implement package level heat sharing between light-generating structures and light-conditioning structures.

[0018] FIG. 9 provides another non-limiting example of the use of a thermally isolating light-conditioning structure, such as a distributed Bragg reflector, within a packaged LED to implement package level heat sharing between light-generating structures and light-conditioning structures.

[0019] FIG. 10 illustrates a specific embodiment of a light bar for illuminating a backplane for a tablet's LCD display.

DETAILED DESCRIPTION

[0020] In this disclosure we outline a method of operating one or more light-generating structures (*e.g.*, a light-emitting semiconductor p-n or p-i-n junction) in combination with one or more light-conditioning structures (*e.g.*, an optical down-conversion phosphor) in order to improve the overall energy efficiency of the light-emitting assembly. Also disclosed are light-emitting assemblies comprising two or more of these structures operated by the disclosed method. These light-emitting assemblies exploit the thermal voltage defect and other thermal effects by diverting a fraction of the heat generated within one or more light-conditioning structures to one or more light-generating structures to improve the overall energy efficiency of the light-emitting assemblies, and may optionally involve thermally isolating both the light-generating structures and light-conditioning structures from the ambient environment.

[0021] The principle of operation of the disclosed devices and assemblies is related to the phonon recycling concepts disclosed in U.S. Patent No. 9,557,215 and U.S. Patent Application Publication No. 2015/0311401, but differs in key ways which allow for the possibility of both principles to be independently used, as will be discussed in more detail below.

Definitions:

[0022] Unless otherwise defined, all technical terms used herein have the same meaning commonly understood by one of ordinary skill in the art in the field to which this disclosure belongs. As used in this specification and the appended claims, the singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise. Any reference to "or" herein is intended to encompass "and/or" unless otherwise stated.

[0023] *Light-generating structures:* As used herein, a "light-generating structure" is a physical body which serves to convert electrical power in the form of current and voltage into optical power capable of propagating in free space. Examples of light-generating structures include, but are not limited to, light-generating semiconductor p-n junctions, p-i-n junctions, or p-n-p-n junctions, *e.g.*, light-emitting diodes (LEDs), for example, Gallium Arsenide (GaAs) infra-red light-emitting diodes, Aluminum Gallium Arsenide (AlGaAs) red light-emitting diodes, Gallium Arsenide Phosphide (GaAsP) red to infra-red and orange light-emitting diodes, Aluminium Gallium Arsenide Phosphide (AlGaAsP) high-brightness red, orange-red, orange, and yellow light-emitting diodes, Gallium Phosphide (GaP) red, yellow and green light-emitting diodes, Aluminium Gallium Phosphide (AlGaP) green light-emitting diodes, Gallium Nitride (GaN) green and emerald green light-emitting diodes, Gallium Indium Nitride (GaInN) near- ultraviolet, bluish-green, and blue light-emitting diodes, Silicon Carbide (SiC) blue light-emitting diodes, Zinc Selenide (ZnSe) blue light-emitting diodes, and Aluminium Gallium Nitride (AlGaN) ultraviolet light-emitting diodes, quantum dot light-emitting diodes, organic light-emitting diodes, LED filaments, laser diodes, *etc.* A light-generating structure is not a light-conditioning structure.

[0024] *Light-conditioning structures:* As used herein, a “light-conditioning structure” is a physical body which serves to modify the wavelength, direction, position, polarization, coherence, or another physically measurable property of incident light. Examples include, but are not limited, to any structure which: (1) down-converts light by absorption and re-emission at a longer wavelength (a phosphor coating or quantum dot-based coating, for example), (2) filters light by way of wavelength-selective absorption, reflection, refraction, or scattering (a band-pass optical filter, for example), (3) refracts light (a lens, for example), (4) scatters light (a diffuser, for example), (5) reflects light (a Winston cone reflector with a metallic surface, or a multilayer dielectric distributed Bragg reflector, for example), or (6) extracts light from a high-index medium (an anti-reflection coating, or an immersion lens structure, for example).

[0025] *Light-emitting assemblies:* As used herein, a “light-emitting assembly” is an assembly comprised of at least one light-generating structure, at least one light-conditioning structure, at least one thermally-isolating structure, and optionally, other mechanical structures, which serves to convert electrical power into optical power (*i.e.*, light). Examples of light-emitting assemblies include, but are not limited to, light-emitting diodes packaged with phosphor or quantum dot-based coatings, laser diodes packaged with one or more light-conditioning elements, light engine technologies comprising arrays of LED-phosphor devices, LED edge-lit light bars or panels, *etc.*

[0026] In some embodiments, the number of light-generating structures in the light-emitting assembly may range from 1 to about 20×10^6. In some embodiments, the number of light-generating structures may be at least 1, at least 10, at least 100, at least 1,000, at least 10,000, at least 100,000, at least 1×10^6, at least 10×10^6, or at least 20×10^6. In some embodiments, the number of light-generating structures in the light-emitting assembly may be at most 20 x 10^6, at most 10 x 10^6, at most 1 x 10^6, at most 100,000, at most 10,000, at most 1,000, at most 100, at most 10, or at most 1. Any of the lower and upper values described in this paragraph may be combined to form a range included within the disclosure, for example, the number of light-generating structures in the light-emitting assembly may range from 10 to 1 x 10^6. Those of skill in the art will recognize that the number of light-generating structures in the light-emitting assembly may have any value within this range, *e.g.*, 128.

[0027] In some embodiments, the number of light-conditioning structures in the light-emitting assembly may range from 1 to about 100 x 10^6. In some embodiments, the number of light-conditioning structures may be at least 1, at least 10, at least 100, at least 1,000, at least 10,000, at least 100,000, at least 1 x 10^6, at least 10 x 10^6, or at least 100 x 10^6. In some embodiments, the number of light-conditioning structures in the light-emitting assembly may be at most 100 x 10^6, at most 10 x 10^6, at most 1 x 10^6, at most 100,000, at most 10,000, at most 1,000, at most 100, at most 10, or at most 1. Any of the lower and upper values described in this paragraph may be combined to form a range included within the disclosure, for example, the number of light-conditioning structures in the light-emitting assembly may range from 100 to 1 x 10^6. Those of skill in the art will recognize that the number of light-conditioning structures in the light-emitting assembly may have any value within this range, *e.g.*, 256.

[0028] In some embodiments of the disclosed light-emitting assemblies, a plurality of light-generating structures and/or light-conditioning structures are arranged in a planar configuration. In some embodiments, a plurality of light-generating structures and/or light-conditioning structures are arranged in a linear configuration, a cylindrical configuration, a toroidal configuration, a configuration with the shape of a spherical shell or a section of a spherical shell, or a configuration with the shape of a conical surface or conical section.

[0029] In some embodiments, the center-to-center spacing between adjacent light-generating structures within a light-emitting assembly may be greater than about 1 μm, 3 μm, 10 μm, 30 μm, 100 μm, 300 μm, 1 mm, 3 mm, or 10 mm. In some embodiments, the center-to-center spacing between adjacent light-generating structures may have any value within this range, *e.g.*, about 0.8 mm. In some embodiments, the center-to-center spacing between adjacent light-generating structures within a light-emitting assembly may be less than about 1 μm.

[0030] *Mechanical structures:* As used herein, a “mechanical structure” is a physical body which is neither a light-generating structure nor a light-conditioning structure. Examples include, but are not limited to, a printed circuit board on which one or more light-generating structures and light-conditioning structures are mounted.

[0031] *Thermally isolating structures:* As used herein, a "thermally isolating structure" may also be a light-generating structure, a light-conditioning structure, or a mechanical structure. In some embodiments, the thermally-isolating structure may be a printed circuit board. In some embodiments, the printed circuit board may be fabricated from one or more fiberglass materials, laminates (*e.g.*, layers of cloth, paper, or other fiber material bonded with a thermoset resin), copper-clad laminates, resin impregnated B-stage cloth (*e.g.*, FR-2 (phenolic cotton paper), FR-3 (cotton paper and epoxy), FR-4 (woven glass and epoxy), FR-5 (woven glass and epoxy), FR-6 (matte glass and polyester), G-10 (woven glass and epoxy), CEM-1 (cotton paper and epoxy), CEM-2 (cotton paper and epoxy), CEM-3 (non-woven glass and epoxy), CEM-4 (woven glass and epoxy), or CEM-5 (woven glass and polyester)), copper foil, kapton, pyralux, *etc.*, or any combination thereof.

[0032] *Wall-plug efficiency:* As used herein, the "wall-plug efficiency," denoted with the symbol η, denotes the ratio of the optical power emitted by a light-generating structure or light-emitting assembly (measured in Watts) to the electrical power required to drive it (also measured in Watts).

[0033] *Quantum efficiency:* As used herein, the "quantum efficiency," denoted with the symbol Q, denotes the fraction of electrons flowing through a light-generating structure (such as a light-emitting semiconductor p-n or p-i-n junction) which are converted into photons which escape the structure.

[0034] *Light:* As used herein, the term "light" refers to electromagnetic radiation capable of propagating in free space.

[0035] *Average energy of generated photons:* As used herein, the phrase "the average energy of the generated photons" refers to the average energy of photons created within one or more light-generating structures.

[0036] *Average energy of emitted photons:* As used herein, the phrase "the average energy of the emitted photons" refers to the average energy of photons emerging from the light-emitting assembly.

Phonon Recycling and Heat Sharing:

[0037] Phonon recycling is a technique for improving the wall-plug efficiency of a single light-generating semiconductor junction as described in U.S. Patent No. 9,557,215 and U.S.

Patent Application Publication US2015/0311401A1. In phonon recycling, non-radiative recombination processes and internal reabsorption of photons produce phonons that are absorbed by the semiconductor lattice forming the light-generating structure (*e.g.*, an LED's active region), thereby elevating the light-generating structure's operating temperature. By contrast, heat sharing is a technique for improving the wall-plug efficiency of a light-emitting assembly by diverting a fraction of the heat from one or more light-conditioning structures to one or more light-generating structures.

[0038] The essential difference is in where the heat being utilized originates. In phonon recycling, as noted above, heat from non-radiative recombination within the active region of a light-generating semiconductor p-n or p-i-n junction is used. By contrast, in the method disclosed here heat from light-conditioning structures surrounding the light-generating structure is used. In certain non-limiting cases, the heat from light-conditioning structures may be generated in close proximity to the active region of the semiconductor junction. Usage of this heat to enhance the wall-plug efficiency of a light-emitting assembly falls under the category of heat sharing. FIGS.1-4 illustrate the distinction between phonon recycling and heat sharing.

[0039] FIG. 1 shows the energy flow diagram for a light-emitting assembly that utilizes both heat sharing and phonon recycling. Electrical power is converted by the light-generating structure into a combination of internal optical power and thermal power (heat). The internal optical power generated by the light-generating structure is further modified by the light-conditioning structure to yield a combination of emitted optical power and additional thermal power (heat). The net result is that the combined light-emitting assembly converts 1000 mW of electrical power into 600 mW of conditioned optical power and 400 mW of waste heat which escapes to the local environment. The wall-plug efficiency of the light-generating structure in this example is 80%, which is below the conventional limit of 100%, while the power conversion efficiency of the light-conditioning structure is 75%. The operating temperature of the light-generating structure is 400 K. The operating temperature of the light-conditioning structure is 402 K. The light-emitting assembly comprises a light-generating structure and a light-conditioning structure that are in intimate thermal contact with a small thermal impedance of just 10 K/W between them. Furthermore the thermal resistance between the light-generating structure and the heat sink slug (denoted by the symbol for electrical ground: three lines crossing the wire) is a value typical of common 5mm epoxy packages at 250 K/W; the thermal impedance between the light-conditioning structure and the heat sink slug is shown as an open circuit because no other thermal paths than the ones previously described are relevant to heat transport.

[0040] FIG. 2 shows the energy flow diagram for a light-emitting assembly that utilizes heat sharing but not phonon recycling. The light-generating structure absorbs thermal power (heat) and combines this with electrical power to generate internal optical power. The internal optical power generated by the light-generating structure is further modified by the light-conditioning structure to yield a combination of emitted optical power and additional thermal power (heat). The net result is that the combined light-emitting assembly converts 1000 mW of electrical power into 900 mW of conditioned optical power and 100 mW of waste heat which escapes to the local environment. The wall-plug efficiency of the light-generating structure is 120%, which is above the conventional limit of 100%, while the power conversion efficiency of the light-conditioning structure is 75%. The operating temperature of the light-generating structure is 400 K. The operating temperature of the light-conditioning structure is 403 K. The light-emitting assembly comprises a light-generating structure and a light-conditioning structure that are in intimate thermal contact with a small thermal impedance of just 10 K/W between them. Furthermore the thermal resistance between the light-generating structure and the heat sink slug (*i.e.*, thermal ground) is a purposefully increased resistance of 1000 K/W; the thermal impedance between the light-conditioning structure and the heat sink slug is shown as an open circuit because no other thermal paths than the ones previously described are relevant to heat transport.

[0041] FIG. 3 shows the energy flow diagram for a light-emitting assembly that utilizes phonon recycling but not heat sharing. Electrical power is converted by the light-generating structure into a combination of internal optical power and thermal power (heat). The internal optical power generated by the light-generating structure is further modified by the light-conditioning structure to yield a combination of emitted optical power and additional thermal power (heat). The net result is that the combined light-emitting assembly converts 1000 mW of electrical power into 900 mW of conditioned optical power and 100 mW of waste heat which escapes to the local environment. The wall-plug efficiency of the light-generating structure is 80%, which is below the conventional limit of 100%, while the power conversion efficiency of the light-conditioning structure is 75%. The operating temperature of the light-generating structure is 400 K. The operating temperature of the light-conditioning structure is 302 K. The light-emitting assembly comprises a light-generating structure and a light-conditioning structure that are not in thermal contact. Furthermore the thermal resistance between the light-generating structure and the heat sink slug (*i.e.* thermal ground) is a purposefully increased resistance of 500 K/W; the thermal impedance between the light-conditioning structure and the heat sink slug is a small value of 10 K/W indicating that the light-conditioning structure is well heat sunk.

[0042] FIG. 4 shows the energy flow diagram for a light-emitting assembly that utilizes neither heat sharing nor phonon recycling. The light-generating structure absorbs thermal power (heat) and combines this with electrical power to generate internal optical power. The internal optical power generated by the light-generating structure is further modified by the light-conditioning structure to yield a combination of emitted optical power and additional thermal power (heat). The net result is that the combined light-emitting assembly converts 1000 mW of electrical power into 900 mW of conditioned optical power and 100 mW of waste heat which escapes to the local environment. The wall-plug efficiency of the light-generating structure is 120%, which is above the conventional limit of 100%, while the power conversion efficiency of the light-conditioning structure is 75%. The operating temperature of the light-generating structure is 298 K. The operating temperature of the light-conditioning structure is 303 K. The light-emitting assembly comprises a light-generating structure and a light-conditioning structure that are not in thermal contact. Furthermore the thermal resistance between the light-generating structure and the heat sink slug (*i.e.* thermal ground) is a small resistance of just 10 K/W; the thermal impedance between the light-conditioning structure and the heat sink slug is a small value of just 10 K/W indicating that the light-conditioning structure is well heat sunk.

[0043] FIG. 5 shows a graph that highlights the key differences between different regimes of thermal transport for different light-emitting assemblies. The horizontal axis indicates the wall-plug efficiency of the light-generating structure (LGS), one non-limiting example of which is a multi-quantum well InGaN blue light-emitting diode. The vertical axis indicates the thermal resistance between the light-generating structure and ambient, one non-limiting example of which is the resistance of the thermal path between the quantum wells where the blue light is generated and a heat sink slug embedded in the ceramic submount. The graph is divided into four regions separated by a qualitatively important efficiency level of 100% and a thermal resistance value of 300 K/W that is slightly greater than the 250 K/W typical of low-power epoxy packages popularized in the 1970's [E. Schubert, Light-Emitting Diodes, Cambridge University Press, 2nd Edition, Chapter 11].

[0044] In FIG. 5, the operating characteristics of typical existing light-emitting assemblies **501** fall in the bottom left quadrant of the graph because the wall-plug efficiency of their light-generating structures (*e.g.*, LEDs) are below the conventional limit of 100% and they are designed to be well heat sunk in order to maximize the optical power that can be produced for a given maximum operating temperature. The operating characteristics of a next-generation light-emitting assembly **502** which is designed according to conventional wisdom will fall in the bottom right quadrant of the graph because the wall-plug efficiency of the light-generating structure (*e.g.*, an LED) has been improved beyond the conventional limit of 100% and the device remains heat sunk in order to absorb a small amount of heat from ambient to drive the device. The operating characteristics of a light-emitting assembly which makes use of phonon recycling **503** falls in the top left quadrant of the graph because the light-generating structure's wall-plug efficiency is below the conventional limit of 100%, but because the thermal voltage defect is strong the package is designed to purposely raise the thermal resistance from the junction to ambient so as to raise the operating temperature of the device to a more efficient operating point. The operating characteristics of a light-emitting assembly which comprises a nearly optimal (*i.e.*, nearly unity quantum efficiency) light-generating structure (LGS) and a nearly optimal light-conditioning structure (LCS) and uses heat sharing **504** falls in the top right quadrant of the graph. The LGS is operating above unity efficiency, so it absorbs net heat and therefore cannot achieve temperatures above ambient on its own. The LCS is thermally shorted to the LGS, in contrast to the conventional wisdom of separating the waste heat from the LCS from the energy losses in the LGS. Here the waste heat from the LCS exceeds the cooling power of the LGS so that the combined LGS-and-LCS structure can operate at an elevated temperature which permits the LGS to exploit the thermal voltage defect. This light-emitting assembly utilizes heat sharing to achieve an overall system efficiency for generating Stokes shifted (*i.e.*, red-shifted) light which exceeds the limit imposed by the efficiency of the LGS combined with the necessary Stokes shift loss.

[0045] In FIG. 5, note that since phonon recycling requires a light-generating structure to produce more waste heat via non-radiative recombination than it absorbs via Peltier heat exchange during charge transport from the contacts to the active region, the vertical 100% line on the horizontal axis defines a region to the left of said line where phonon recycling cannot be used. However, heat sharing can be used in these cases as described in the preceding descriptions of the light-emitting assemblies corresponding to **502** and **504**.

Light-Emitting Assembly Design Examples

[0046] In general, the light-emitting assemblies of the present disclosure comprise: a) at least one light-generating structure; b) at least one light-conditioning structure; and c) at least one thermally-isolating structure, wherein the wall-plug efficiency of at least one light-generating structure is increased by having its lattice temperature exceed the ambient temperature, and wherein a fraction of the heat generated within at least one light-conditioning structure is transferred to at least one light-generating structure. In some embodiments, the light-generating structures comprise a semiconductor p-n or p-i-n junction and are configured to generate photons upon application of a drive voltage.

[0047] FIGS. 6A-B illustrate a packaged LED which combines a light-generating structure (the diode, **602**) and light-conditioning structure (*e.g.*, the phosphor **603**) that exemplifies one embodiment of a heat sharing design that is applicable to individual LEDs or to multi-pixel light-engine devices. The sub-mount **601** comprises metal contacts **600** and supports light-generating semiconductor p-n or p-i-n junction structures **602**. In some embodiments, sub-mount **601** may comprise a heat sink slug. Light-emitting diode **602** is packaged with a light-conditioning phosphor layer **603** and light-conditioning solid immersion lens structure **604**. FIG. 6A shows a cross-sectional view of the device. FIG. 6B shows a top view of the device.

[0048] FIG. 7 provides a non-limiting example of how packaged LEDs such as those described in FIGS. 6A-B can be combined with a mechanical structure, *e.g.*, a printed circuit board, which is designed to provide thermal isolation of the light-generating and light-conditioning structures in order to implement heat sharing for improved energy efficiency. In this example, conductive heat loss is minimized by using one or more through holes to maximize the resistance to heat flow between the light-generating and light-conditioning structures and the surrounding system architecture.

[0049] FIG. 8 provides a non-limiting example of the use of a thermally isolating light-conditioning structure, such as a distributed Bragg reflector, within a packaged LED to implement package level heat sharing between light-generating structures and light-conditioning structures. Metal contact **801** supports a thermally-isolating light-conditioning reflector structure **802**, which in turn supports a light-generating semiconductor p-n or p-i-n junction structure **803**. The reflector structure **802** and semiconductor p-n or p-i-n junction **803** are in turn packaged within light-conditioning phosphor layer **804**, and all three layers are encased in a light-conditioning solid immersion lens structure **805**.

[0050] FIG. 9 provides a non-limiting example of the use of a thermally isolating light-conditioning structure, such as a distributed Bragg reflector, within a packaged LED to implement package level heat sharing between light-generating structures and light-conditioning structures. Metal contact **901** supports thermally isolating light-conditioning reflector structure **902**, which in turn supports a light-generating semiconductor p-n or p-i-n junction structure **903**. The semiconductor structure **903** is packed within a phosphor layer **904**, and both the semiconductor p-n or p-i-n junction structure **903** and phosphor layer **904** are packaged within a light-conditioning solid immersion lens structure **905**.

[0051] In some embodiments of the disclosed designs, the utilization of the disclosed heat sharing design concepts may result in improved energy efficiencies such that the wall plug efficiency of one or more light-generating structures of a light-emitting assembly may be at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 100%, at least 110%, at least 120%, at least 130%, at least 140%, or at least 150%. In some embodiments, the wall plug efficiency of one or more light-generating structures of a light-emitting assembly may be any value within this range, *e.g.*, about 82%.

[0052] In some embodiments of the disclosed designs, the wall-plug efficiency of at least one light generating structure within a light-emitting assembly may be an increasing function of its own temperature at 300K, at 302K, at 305K, at 310K, at 320K, at 330K, at 340K, at 350K, at 360K, at 370K, at 380K, at 390K, at 400K, at 410K, at 420K, at 430K, at 440K, at 450K, at 500K, at 550K, at 600K, at 650K, at 700K, at 750K, at 800K, or at 900K. In some embodiments, the wall-plug efficiency of at least one light generating structure within a light-emitting assembly may be an increasing function of its own temperature at any temperature value within this range, *e.g.*, at about 335K.

[0053] In some embodiments of the disclosed designs, the fraction of heat generated within at least one light-conditioning structure which is transferred to light-generating structures within a light-emitting assembly may exceed about 2%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, or 98%. In some embodiments, the fraction of heat generated within at least one light-conditioning structure which is transferred to light-generating structures within a light-emitting assembly may exceed any value within this range, *e.g.*, about 65%.

[0054] In some embodiments of the disclosed designs, the drive voltage of the light-emitting assemblies of the present disclosure may be less than the average energy of the generated photons divided by the magnitude of the charge of an electron. In some embodiments, the drive voltage may be less than the average energy of the generated photons divided by the magnitude of the charge of an electron by at least 10 mV, at least 25 mV, at least 50 mV, at least 75 mV, at least 100 mV, at least 150 mV, at least 200 mV, at least 250 mV, at least 300 mV, at least 350 mV, at least 400 mV, at least 450 mV, at least 500 mV, at least 550 mV, at least 600 mV, at least 650 mV, at least 700 mV, at least 750 mV, at least 800 mV, at least 850 mV, at least 900 mV, at least 950 mV, or at least 1,000 mV. In some embodiments, the drive voltage may be less than the average energy of the generated photons divided by the magnitude of the charge of an electron by any value within this range, *e.g.*, by at least 120 mV.

[0055] In some embodiments of the disclosed designs, at least one light-generating structure within a light-emitting assembly is configured to utilize phonon recycling. In some embodiment, at least one light-generating structure within a light-emitting assembly is not configured to utilize phonon recycling.

[0056] In some embodiments of the disclosed designs, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of greater than about 350 nm, 400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 650 nm, 700 nm, 750 nm, 800 nm, 850 nm, 900 nm, 950 nm, 1000 nm, 1500 nm, 2000 nm, 2500 nm, 3000 nm, 3500 nm, 4000 nm, 4500 nm, or 5000 nm. In some embodiments, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of greater than any value within this range, *e.g.*, greater than about 822 nm.

[0057] In some embodiments, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of less than about 5000nm, 4500 nm, 4000 nm, 3500 nm, 3000 nm, 2500 nm, 2000 nm, 1500 nm, 1000 nm, 900 nm, 850 nm, 800 nm, 750 nm, 700 nm, 650 nm, 600 nm, 550 nm, 500 nm, 450 nm, 400 nm, or 350 nm. In some embodiments, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of less than any value within this range, *e.g.*, less than about 765 nm.

[0058] In some embodiments of the disclosed designs, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of between about 350 nm and about 500 nm, between about 500 nm and about 640 nm, between about 640 nm and 940 nm, between about 940 nm and 1600 nm, or between about 1600 nm and 5000 nm. Any of the lower and upper values described in this paragraph may be combined to form a range included within the disclosure, for example, in some embodiments, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of between about 350 nm and about 940 nm.

[0059] In some embodiments of the disclosed designs, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of between about 380 nm and 780 nm, or between about 780 nm and about 1100 nm. Any of the lower and upper values described in this paragraph may be combined to form a range included within the disclosure, for example, in some embodiments, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of between about 380 nm and about 1100 nm.

[0060] In some embodiments of the disclosed designs, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of greater than about 380 nm, 400 nm, 500 nm, 600 nm, 700 nm, 800 nm, 900 nm, 1000 nm, or 1100 nm. In some embodiments, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of greater than any value within this range, *e.g.*, about 560 nm.

[0061] In some embodiments of the disclosed designs, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of less than about 1100 nm, 1000 nm, 900 nm, 800 nm, 700 nm, 600 nm, 500 nm, 400 nm, or 380 nm. In some embodiments, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of less than any value within this range, *e.g.*, less than about 765 nm.

[0062] In some embodiments of the disclosed designs, the lattice temperature of at least one light-generating structure within a light-emitting assembly may be at least 300K, 302K, 305K, 310K, 320K, 330K, 340K, 350K, 360K, 370K, 380K, 390K, 400K, 410K, 420K, 430K, 440K, 450K, 500K, 550K, 600K, 650K, 700K, 750K, 800K, 850K, or 900K. In some embodiments, the lattice temperature of at least one light-generating structure within a light-emitting assembly may be at least any value within this range, *e.g.*, at least about 335K.

[0063] In some embodiments of the disclosed designs, the lattice temperature of at least one light-conditioning structure within a light-emitting assembly may be at least 300K, 302K, 305K, 310K, 320K, 330K, 340K, 350K, 360K, 370K, 380K, 390K, 400K, 410K, 420K, 430K, 440K, 450K, 500K, 550K, 600K, 650K, 700K, 750K, 800K, 850K, or 900K. In some embodiments, the lattice temperature of at least one light-conditioning structure within a light-emitting assembly may be at least any value within this range, *e.g.*, at least 322K.

Operating Methods for Light-Emitting Assemblies

[0064] Also disclosed herein are methods for operating one or more light-generating structures in combination with one or more light-generating structures. In general, the methods for operating the disclosed light-emitting assemblies comprise: a) thermally-isolating a section of the assembly which comprises the one or more light-generating structures; b) applying a drive voltage to the one or more light-generating structures; and c) transferring a fraction of the heat produced within the one or more light-conditioning structures to at least one of the light-generating structures. In some embodiments, the one or more light-generating structures each comprise a semiconductor p-n or p-i-n junction. In some embodiments, the thermally-isolating step comprises mounting the one or more light-generating structures on a thermally-isolating structure, *e.g.*, a mechanical structure. In some embodiments, the mechanical structure may comprise a printed circuit board as discussed previously.

[0065] In some embodiments of the disclosed methods, the drive voltage applied to one or more light-generating structures within a light-emitting assembly of the present disclosure is less than the average energy of the generated photons divided by the magnitude of the charge of an electron. In some embodiments, the drive voltage may be less than the average energy of the generated photons divided by the magnitude of the charge of an electron by at least 50 mV, 100 mV, 150 mV, 200 mV, 300 mV, 400 mV, 500 mV, 600 mV, 700 mV, 800 mV, 900 mV, or 1000 mV. In some embodiments, the drive voltage may be less than the average energy of the generated photons divided by the magnitude of the charge of an electron by any value within this range, *e.g.*, by at least 110 mV.

[0066] In some embodiments of the disclosed methods, the wall-plug efficiency of one or more light-generating structures within a light-emitting assembly may be greater than 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, or 150%. In some embodiments, the wall plug efficiency of one or more light-generating structures of a light-emitting assembly may be any value within this range, *e.g.*, about 105%.

[0067] In some embodiments of the disclosed methods, the wall-plug efficiency of one or more light generating structures within a light-emitting assembly may be an increasing function of its own temperature at 300K, at 302K, at 305K, at 310K, at 320K, at 330K, at 340K, at 350K, at 360K, at 370K, at 380K, at 390K, at 400K, at 410K, at 420K, at 430K, at 440K, at 450K, at 500K, at 550K, at 600K, at 650K, at 700K, at 750K, at 800K, or at 900K. In some embodiments, the wall-plug efficiency of at least one light generating structure within a light-emitting assembly may be an increasing function of its own temperature at any temperature value within this range, *e.g.*, at about 345K.

[0068] In some embodiments of the disclosed methods, the fraction of heat generated within one or more light-conditioning structures which is transferred to light-generating structures within a light-emitting assembly may exceed about 2%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, or 98%. In some embodiments, the fraction of heat generated within at least one light-conditioning structure which is transferred to light-generating structures within a light-emitting assembly may exceed any value within this range, *e.g.*, about 75%.

[0069] In some embodiments of the disclosed methods, one or more light-generating structures within a light-emitting assembly are configured to utilize phonon recycling. In some embodiments, one or more light-generating structures within a light-emitting assembly are not configured to utilize phonon recycling.

[0070] In some embodiments of the disclosed methods, one or more light-generating structures within a light-emitting assembly may produce light with a free space wavelength of greater than about 350 nm, 400 nm, 500 nm, 600 nm, 700 nm, 800 nm, 900 nm, 1000 nm, 2000 nm, 3000 nm, 4000 nm, or 5000 nm. In some embodiments, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of greater than any value within this range, *e.g.*, greater than about 950 nm.

[0071] In some embodiments of the disclosed methods, one or more light-generating structures within a light-emitting assembly produce light with a free space wavelength between about 350 nm and about 500 nm, about 500 nm and about 640 nm, about 640 nm and about 940 nm, about 940 nm and about 1600 nm, or about 1600 nm and about 5000 nm. Any of the lower and upper values described in this paragraph may be combined to form a range included within the disclosure, for example, in some embodiments, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of between about 350 nm and about 940 nm.

[0072] In some embodiments of the disclosed methods, one or more light-generating structures within a light-emitting assembly may produce light with a free space wavelength of less than about 5000 nm, 4000 nm, 3000 nm, 2000 nm, 1000 nm, 900 nm, 800 nm, 700 nm, 600 nm, 500 nm, 400 nm, or 350 nm. In some embodiments, at least one light-generating structure within a light-emitting assembly may produce light with a free space wavelength of less than any value within this range, *e.g.*, less than about 775 nm.

[0073] In some embodiments of the disclosed methods, one or more light-conditioning structures of the light-emitting assembly may produce light with a free space wavelength between about 380 nm and about 780 nm, or between about 780 nm and about 1100 nm. Any of the lower and upper values described in this paragraph may be combined to form a range included within the disclosure, for example, in some embodiments, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of between about 380 nm and about 1100 nm.

[0074] In some embodiments of the disclosed methods, one or more light-conditioning structures of the light-emitting assembly may produce light with a free space wavelength of greater than about 380 nm, 400 nm, 500 nm, 600 nm, 700 nm, 800 nm, 900 nm, 1000 nm, 1100 nm. In some embodiments, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of greater than any value within this range, *e.g.*, about 720 nm.

[0075] In some embodiments of the disclosed methods, one or more light-conditioning structures of the light-emitting assembly produce light with a free space wavelength of less than about 1100 nm, 1000 nm, 900 nm, 800 nm, 700 nm, 600 nm, 500 nm, 400 nm, or 380 nm. In some embodiments, at least one light-conditioning structure within a light-emitting assembly may produce light with a free space wavelength of less than any value within this range, *e.g.*, less than about 850 nm.

[0076] In some embodiments of the disclosed methods, the lattice temperature of one or more light-generating structures within a light-emitting assembly is at least 300K, 302K, 305K, 310K, 320K, 330K, 340K, 350K, 360K, 370K, 380K, 390K, 400K, 410K, 420K, 430K, 440K, 450K, 500K, 550K, 600K, 650K, 700K, 750K, 800K, 850K, or 900K. In some embodiments, the lattice temperature of at least one light-generating structure within a light-emitting assembly may be at least any value within this range, *e.g.*, at least about 315K.

[0077] In some embodiments of the disclosed methods, the lattice temperature of one or more light-conditioning structures within a light-emitting assembly is at least 300K, 302K, 305K, 310K, 320K, 330K, 340K, 350K, 360K, 370K, 380K, 390K, 400K, 410K, 420K, 430K, 440K, 450K, 500K, 550K, 600K, 650K, 700K, 750K, 800K, 850K, or 900K. In some embodiments, the lattice temperature of at least one light-conditioning structure within a light-emitting assembly may be at least any value within this range, *e.g.*, at least 332K.

Applications for Light-Emitting Assemblies that Utilize Phonon Recycling and/or Heat-Sharing

[0078] The methods and devices of the present disclosure may find commercial application in any market where efficient light generation is important. Potential applications and markets include, but are not limited to: display backlighting, *e.g.*, development of multi-colored “white light” sources for use with optical filters and LCD/TFT arrays to form back-lit displays; signage and next-generation displays featuring arrays of micro-LEDs for direct display illumination; interior and exterior automotive lighting; interior and exterior aerospace lighting; solid-state lighting applications; and visible-light communication applications. An example of one embodiment for a light emitting assembly using an InGaN emitter with a Ce:YAG phosphor layer will be discussed in more detail below.

Example 1 - Analysis of Thermal Voltage Defects:

[0079] A calculation is provided that illustrates the relationship between the current density, J, of current flowing through a light-generating semiconductor junction structure and the magnitude of the thermal voltage defect. The following symbols are used in the calculation:

[0080] J is the current density [Amps per cm^2]

[0081] q is the magnitude of the electron's charge [Coulombs]

[0082] R is the radiative recombination rate per unit cross-sectional area [per cm^2 per second]

[0083] W is the width of the active region in the direction of current flow [cm]

[0084] B_0 is the radiative recombination coefficient [cm^3 per second]

[0085] n_i is the intrinsic carrier concentration [per cm^3]

[0086] kT is the thermal energy (*i.e.* absolute temperature times Boltzmann's constant) [Joules]

[0087] V is the drive voltage [Volts]

[0088] The current density in the light-generating semiconductor junction structure may be written in terms of the bimolecular recombination formula as follows. When the drive voltage V is more than a few hundred mV in magnitude, the "-1" term may optionally be approximated out.

$$J/q = R = W \cdot B_0 \cdot {n_i}^2 \cdot \left(e^{qV/kT} - 1\right) \approx B_0 \cdot {n_i}^2 \cdot e^{qV/kT}$$

[0089] $N_{c,0}$ is the effective density of states at the conduction band edge at 300 Kelvin [cm^{-3}]

[0090] $N_{v,0}$ is the effective density of states at the valence band edge at 300 Kelvin [cm^{-3}]

[0091] E_{gap} is the band gap energy [Joules]

[0092] T is the absolute temperature [Kelvin]

[0093] T_0 is the absolute temperature of the ambient, here taken as 300 Kelvin [Kelvin]

[0094] The intrinsic carrier concentration is quite sensitive to temperature as expressed by the conventional formulation below.

$${n_i}^2 = N_{c,0} \cdot N_{v,0} \cdot \left(\frac{T}{T_0}\right)^3 \cdot e^{-E_{gap}/kT}$$

[0095] When this expression for the intrinsic carrier concentration is inserted into the first equation, we arrive at an equation for the current density in terms of both the drive voltage V and the temperature T.

$$J/q = R = W \cdot B_0 \cdot N_{c,0} \cdot N_{v,0} \cdot e^{-E_{gap}/kT} \cdot \left(e^{qV/kT} - 1\right) \cdot \left(\frac{T}{T_0}\right)^3$$

[0096] Using the approximation above, we may simplify the equation as follows.

$$J/q = R = W \cdot B_0 \cdot N_{c,0} \cdot N_{v,0} \cdot \left(\frac{T}{T_0}\right)^3 \cdot e^{-(E_{gap}-qV)/kT}$$

[0097] We may now define a scale J_0 for the current density J.

$$J_0 \equiv W \cdot B_0 \quad \cdot N_{c,0} \cdot N_{v,0} \cdot q$$

[0098] We may now express the current density's dependence on temperature and drive voltage in a compact way.

$$J = J_0 \cdot \left(\frac{T}{T_0}\right)^3 \cdot e^{-(E_{gap}-qV)/kT}$$

[0099] This expression can then be inverted to solve for the drive voltage, yielding two terms that contribute to the thermal voltage defect.

$$E_{gap} - k_B T \cdot ln\left(\frac{J_0}{J}\right) - 3k_B T \cdot ln\left(\frac{T}{T_0}\right) = qV$$

[0100] From the second term in the above equation, we can see that as the current density J is reduced, the magnitude of the thermal voltage defect is enhanced. The light-engine scale and package scale embodiments of the heat sharing design concepts found in this disclosure take advantage of this enhancement to overcome thermal droop in the quantum efficiency.

Example 2 – Prophetic Example of Light-Emitting Assembly Design for Solid State Lighting Applications

[0101] As discussed above, the heat sharing design concept disclosed herein has potential applications in a variety of markets, *e.g.*, display backlighting (using, for example, InGaN emitters packaged with green quantum dot-based light conditioning layers or InGaN emitters packaged with red and green quantum dot-based light conditioning layers) or solid state lighting (using, for example, InGaN emitters packaged with Ce:YAG phosphor layers).

[0102] Within the solid-state lighting market, the application of the heat sharing device design and operation concepts could lead to designs in which a large area of epitaxially-grown Indium Gallium Nitride (InGaN) would efficiently generate blue light, which would optically pump a Cerium-doped YAG phosphor layer or a phosphor layer composed of a mixture of quantum dots with photoluminescence spanning the visible spectrum. To understand the benefit of the heat sharing design concept, it is useful to consider the case of an assembly made with ideal components having unity quantum efficiency. We define an ideal blue InGaN emitter for which each electron passing through the diode produces one photon which can escape the emitter into the far field. We define an ideal phosphor layer as one for which every absorbed blue photon results in the emission of one yellow photon that escapes the phosphor into the far field. If a minimum photon flux is required, this corresponds to a minimum carrier density required in the InGaN quantum wells. The drive voltage required to generate this carrier density is dependent on the temperature of the InGaN lattice in such a way that higher lattice temperature corresponds to a lower required drive voltage. Let us consider the case where the desired photon flux corresponds to a drive voltage of 2.60 V at 300 K or 2.50 V at 360 K. Assume the ambient temperature is 300 K. Assume that the InGaN emits 2.75 eV blue photons.

[0103] If heat sharing is not utilized, because the InGaN device is operating above the conventional limit of 100% wall-plug efficiency, the highest operating temperature is achieved by heat sinking the InGaN to a heat sink slug which allows it to operate close to 300 K. The InGaN device could operate at 297 K and utilize the 3 K difference between its lattice and the heat sink slug to absorb the heat required to reach steady state despite the net cooling power of the InGaN diode. The wall-plug efficiency of the InGaN light-generating structure is given by the ratio of the average photon energy to the electrical energy required for carrier injection: 2.75 / 2.60 ≈ 106%. If 80% of the 2.75 eV blue photons need to be down-converted to make white light and the average energy to which they are converted is 2.25 eV, then the overall efficiency of the conversion from electricity to white light is reduced from 106% to ≈ 90%. The efficiency of the white light source which doesn’t use heat sharing is 90.4%.

[0104] If heat sharing is utilized, the Stokes heat from the phosphor layer can be used to elevate the temperature of the InGaN light-generating structure despite its cooling power. In this case, a superior efficiency is achieved by thermally isolating the InGaN and phosphor at 360 K from the heat sink slug at 300 K. At this temperature, only 2.50 V are required to achieve the carrier density in the InGaN quantum wells necessary to generate the desired photon flux. As a result, the InGaN device generates 2.75 eV photons with a wall-plug efficiency of 2.75 / 2.50 = 110%. If again 80% of the 2.75 eV blue photons need to be down-converted to make white light and the average energy to which they are converted is again 2.25 eV, then the overall efficiency of the conversion from electricity to white light is reduced from 110% to 94%. The efficiency of the white light source which does use heat sharing is 94%.

[0105] Essentially our design has harvested waste heat from the Stokes loss of the phosphor layer and shared that heat with the blue InGaN emitter, thereby permitting a lower drive voltage for the same current. Since the technique relies on the thermal voltage defect as described in this document, it is generally more applicable at lower brightness levels (lm/cm2). In display backlighting of a mobile handheld device such as a smartphone or tablet, the required brightness levels are relatively low compared with typical products in solid-state lighting. Moreover, the power conversion efficiency of the backlight can have significant impact on the battery life of the system. In cases where a display for human use is formed by an array of individually addressed light-emitters rather than a backlight plus liquid crystal layer architecture, the brightness conditions can be even lower because the total emission area is larger. Coupled with the benefit of not having to generate the photons which get absorbed by the polarizers in the liquid crystal layer or the filters, the direct display architecture could be chosen because of a system-level need for efficiency of the display. The direct display architecture is commonly used in outdoor signage. Since light-emitting diodes can be switched orders of magnitude more quickly than the response of the human eye, such architectures could also be applicable to future visible light communication technologies.

Example 3 – Prophetic Example of Backplane Light Bar

[0106] A specific embodiment of a light bar for illuminating a backplane for a tablet's LCD display is shown in FIG. 10. The fiberglass printed circuit board (PCB) rectangle **1001** provides a mechanical support for electrical traces at voltage high **1002** and voltage low **1003**, and contains a through hole **1004** machined for the purpose of thermally isolating the devices mounted on the center PCB platform **1005**. Soldered to the center PCB platform are three light-emitting assemblies. The leftmost and rightmost light-emitting assemblies are identical, and each contain both a source which emits both blue and green light through a light-emitting diode **1006** made of Indium Gallium Nitride (InGaN) emitting around a free-space wavelength of $\lambda = 450$ nm, and a phosphor layer **1008** made of quantum dots whose photoluminescence spectrum is peaked around $\lambda = 540$ nm. The light bar in this figure also includes a red light-emitting diode **1007** made of Aluminum Gallium Arsenide. In this case, the thermal isolation provided by the through hole allows the Stokes loss heat from the quantum dots down-converting blue light into green to be shared with the three light-emitting diodes. By using this heat to raise the temperature of the entire center platform, the diodes are able to produce sufficient optical power for the display while operating at a lower voltage than would be possible if the center platform were heat sunk to the body of the tablet. As a result, the electrical power, current times voltage, required to produce the light for the display is less and the overall system is more efficient.

[0107] While preferred embodiments of the present invention have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions will now occur to those skilled in the art without departing from the invention. It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention. It is intended that the following claims define the scope of the invention and that methods and structures within the scope of these claims and their equivalents be covered thereby.

CLAIMS

WHAT IS CLAIMED IS:

1. A light-emitting assembly comprising

a) a light-generating structure which is configured to generate photons upon application of a drive voltage;

b) a light-conditioning structure; and

c) a thermally-isolating structure,

wherein the wall-plug efficiency of the light-generating structure is increased by having its lattice temperature exceed the ambient temperature, and wherein a fraction of the heat generated within the light-conditioning structure is transferred to the light-generating structure.

2. The light-emitting assembly of claim 1, further comprising a plurality of light-generating structures, a plurality of light-conditioning structures, a plurality of thermally-isolating structures, or any combination thereof.

3. The light-emitting assembly of claim 1 or claim 2, wherein the light-generating structure or plurality of light generating structures comprises a semiconductor p-n or p-i-n junction.

4. The light-emitting assembly of any one of claims 1 to 3, wherein at least one thermally-isolating structure comprises a mechanical structure.

5. The light-emitting assembly of claim 4, wherein the mechanical structure comprises a printed circuit board.

6. The light-emitting assembly of any one of claims 1 to 5, wherein the drive voltage of the light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron’s charge.

7. The light-emitting assembly of claim 6, wherein the drive voltage of the light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron’s charge by at least 150 mV.

8. The light-emitting assembly of any one of claims 1 to 7, wherein the wall-plug efficiency of the light-generating structures is greater than 50%.

9. The light-emitting assembly of any one of claims 1 to 7, wherein the wall-plug efficiency of the light-generating structures is greater than 100%.

10. The light-emitting assembly of any one of claims 1 to 7, wherein the wall-plug efficiency of the light-generating structures is greater than 110%.

11. The light-emitting assembly of any one of claims 1 to 10, wherein the light-generating structures are configured to utilize phonon recycling.

12. The light-emitting assembly of any one of claims 1 to 10, wherein the light-generating structures are not configured to utilize phonon recycling.

13. The light-emitting assembly of any one of claims 1 to 12, wherein the light-generating structures produce light with a free space wavelength of greater than about 600 nm.

14. The light-emitting assembly of any one of claims 1 to 12, wherein the light-generating structures produce light with a free space wavelength of greater than about 850 nm.

15. The light-emitting assembly of any one of claims 1 to 12, wherein the light-generating structures produce light with a free space wavelength of greater than about 1000 nm.

16. The light-emitting assembly of any one of claims 1 to 12, wherein the light-generating structures produce light between about 350 nm and about 500 nm in free space wavelength.

17. The light-emitting assembly of any one of claims 1 to 12, wherein the light-generating structures produce light with a free space wavelength of less than about 500 nm.

18. The light-emitting assembly of any one of claims 1 to 17, wherein the light-conditioning structures produce light between about 380 nm and about 780 nm in free space wavelength.

19. The light-emitting assembly of any one of claims 1 to 18, wherein the lattice temperature of the light-generating structures is at least 300K.

20. The light-emitting assembly of any one of claims 1 to 18, wherein the lattice temperature of the light-generating structures is at least 305K.

21. The light-emitting assembly of any one of claims 1 to 18, wherein the lattice temperature of the light-generating structures is at least 320K.

22. The light-emitting assembly of any one of claims 1 to 18, wherein the lattice temperature of the light-generating structures is at least 350K.

23. The light-emitting assembly of any one of claims 1 to 18, wherein the lattice temperature of the light-generating structures is at least 400K.

24. The light-emitting assembly of any one of claims 1 to 23, wherein the lattice temperature of the light-conditioning structures is at least 300K.

25. The light-emitting assembly of any one of claims 1 to 23, wherein the lattice temperature of the light-conditioning structures is at least 310K.

26. The light-emitting assembly of any one of claims 1 to 23, wherein the lattice temperature of the light-conditioning structures is at least 360K.

27. The light-emitting assembly of any one of claims 2 to 26, wherein the plurality of light-generating structures and/or light-conditioning structures are arranged in a planar configuration.

28. The light-emitting assembly of any one of claims 2 to 26, wherein the plurality of light-generating structures and/or light-conditioning structures are arranged in a linear configuration.

29. The light-emitting assembly of any one of claims 2 to 26, wherein a plurality of light-generating structures and/or light-conditioning structures are arranged in a configuration with the shape of a spherical shell or a section of a spherical shell.

30. The light-emitting assembly of any one of claims 2 to 26, wherein the plurality of light-generating structures and/or light-conditioning structures are arranged in a configuration with the shape of a conical surface or conic section.

31. The light-emitting assembly of any one of claims 1 to 30, wherein the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 300K.

32. The light-emitting assembly of any one of claims 1 to 30, wherein the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 310K.

33. The light-emitting assembly of any one of claims 1 to 30, wherein the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 360K.

34. The light-emitting assembly of any one of claims 1 to 30, wherein the wall-plug efficiency of the light-generating structures is an increasing function of their lattice temperature at 600K.

35. The light-emitting assembly of any one of claims 2 to 34, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 10 mm.

36. The light-emitting assembly of any one of claims 2 to 34, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 1 mm.

37. The light-emitting assembly of any one of claims 2 to 34, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 100 μm.

38. The light-emitting assembly of any one of claims 2 to 34, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 10 μm.

39. The light-emitting assembly of any one of claims 2 to 34, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 1 μm.

40. The light-emitting assembly of any one of claims 2 to 34, wherein the center-to-center spacing between adjacent light-generating structures is less than about 1 μm.

41. The light-emitting assembly of any one of claims 1 to 40, wherein the fraction of the heat generated within the light-conditioning structures which is transferred to light-generating structures exceeds about 5%.

42. The light-emitting assembly of any one of claims 1 to 40, wherein the fraction of the heat generated within the light-conditioning structures which is transferred to light-generating structures exceeds about 50%.

43. The light-emitting assembly of any one of claims 1 to 40, wherein the fraction of the heat generated within the light-conditioning structures which is transferred to light-generating structures exceeds about 80%.

44. A method of operating one or more light-generating structures in combination with one or more light-conditioning structures, the method comprising:

a) thermally-isolating a section of the assembly which comprises the one or more light-generating structures;

b) applying a drive voltage to the one or more light-generating structures; and

c) transferring a fraction of the heat produced within the one or more light-conditioning structures to at least one of the light-generating structures,

wherein the transferred heat serves to increase the wall-plug efficiency of the one or more light-generating structures.

45. The method of claim 44, wherein the light-generating structures comprise semiconductor p-n or p-i-n junctions.

46. The method of claim 44 or claim 45, wherein the thermally-isolating step comprises mounting the one or more light-generating structures on a thermally-isolating structure.

47. The method of claim 46, wherein the thermally-isolating structure comprises a mechanical structure.

48. The method of claim 47, wherein the mechanical structure comprises a printed circuit board.

49. The method of any one of claims 44 to 48, wherein the drive voltage applied to one or more light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron’s charge.

50. The method of any one of claims 44 to 48, wherein the drive voltage applied to one or more light-generating structures is less than the average energy of the generated photons divided by the magnitude of the electron’s charge by at least 150 mV.

51. The method of any one of claims 44 to 50, wherein the wall-plug efficiency of the one or more light-generating structures is greater than 50%.

52. The method of any one of claims 44 to 50, wherein the wall-plug efficiency of the one or more light-generating structures is greater than 100%.

53. The method of any one of claims 44 to 50, wherein the wall-plug efficiency of the one or more light-generating structures is greater than 110%.

54. The method of any one of claims 44 to 53, wherein the one or more light-generating structures are configured to utilize phonon recycling.

55. The method of any one of claims 44 to 53, wherein the one or more light-generating structures are not configured to utilize phonon recycling.

56. The method of any one of claims 44 to 55, wherein the one or more light-generating structures produce light with a free space wavelength of greater than about 600 nm.

57. The method of any one of claims 44 to 55, wherein the one or more light-generating structures produce light with a free space wavelength of greater than about 800 nm.

58. The method of any one of claims 44 to 55, wherein the one or more light-generating structures produce light with a free space wavelength of greater than about 1000 nm.

59. The method of any one of claims 44 to 55, wherein the one or more light-generating structures produce light with a free space wavelength of greater than about 2000 nm.

60. The method of any one of claims 44 to 59, wherein the one or more light-generating structures produce light with a free space wavelength between about 350 nm and about 500 nm.

61. The method of any one of claims 44 to 55, wherein the one or more light-generating structures produce light with a free space wavelength of less than about 500 nm.

62. The method of any one of claims 44 to 61, wherein one or more light-conditioning structures produce light with a free space wavelength between about 380 nm and about 780 nm.

63. The method of any one of claims 44 to 61, wherein one or more light-conditioning structures produce light with a free space wavelength of greater than about 500 nm.

64. The method of any one of claims 44 to 63, wherein the lattice temperature of the one or more light-generating structures is at least 300K.

65. The method of any one of claims 44 to 63, wherein the lattice temperature of the one or more light-generating structures is at least 305K.

66. The method of any one of claims 44 to 63, wherein the lattice temperature of the one or more light-generating structures is at least 320K.

67. The method of any one of claims 44 to 63, wherein the lattice temperature of the one or more light-generating structures is at least 350K.

68. The method of any one of claims 44 to 63, wherein the lattice temperature of the one or more light-generating structures is at least 400K.

69. The method of any one of claims 44 to 68, wherein the lattice temperature of the one or more light-conditioning structures is at least 300K.

70. The method of any one of claims 44 to 68, wherein the lattice temperature of the one or more light-conditioning structures is at least 310K.

71. The method of any one of claims 44 to 68, wherein the lattice temperature of the one or more light-conditioning structures is at least 360K.

72. The method of any one of claims 44 to 71, wherein the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a planar configuration.

73. The method of any one of claims 44 to 71, wherein the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a linear configuration.

74. The method of any one of claims 44 to 71, wherein the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a configuration with the shape of a spherical shell or a section of a spherical shell.

75. The method of any one of claims 44 to 71, wherein the one or more light-generating structures and/or one or more light-conditioning structures are arranged in a configuration with the shape of a conical surface or a conic section.

76. The method of any one of claims 44 to 75, wherein the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 300K.

77. The method of any one of claims 44 to 75, wherein the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 310K.

78. The method of any one of claims 44 to 75, wherein the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 360K.

79. The method of any one of claims 44 to 75, wherein the wall-plug efficiency of the one or more light-generating structures is an increasing function of its own lattice temperature at 600K.

80. The method of any one of claims 44 to 79, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 10 mm.

81. The method of any one of claims 44 to 79, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 1 mm.

82. The method of any one of claims 44 to 79, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 100 μm.

83. The method of any one of claims 44 to 79, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 10 μm.

84. The method of any one of claims 44 to 79, wherein the center-to-center spacing between adjacent light-generating structures is greater than about 1 μm.

85. The method of any one of claims 44 to 79, wherein the center-to-center spacing between adjacent light-generating structures is less than about 1 μm.

86. The method of any one of claims 44 to 85, wherein the fraction of the heat produced within the one or more light-conditioning structures which is transferred to at least one of the light-generating structures exceeds about 5%.

87. The method of any one of claims 44 to 85, wherein the fraction of the heat produced within the one or more light-conditioning structures which is transferred to at least one of the light-generating structures exceeds about 50%.

88. The method of any one of claims 44 to 85, wherein the fraction of the heat produced within the one or more light-conditioning structures which is transferred to at least one of the light-generating structures exceeds about 80%.

89. A light-emitting assembly according to any of the embodiments described herein.

90. A method of operating one or more light-generating structures in combination with one or more light-conditioning structures according to any of the embodiments described herein.

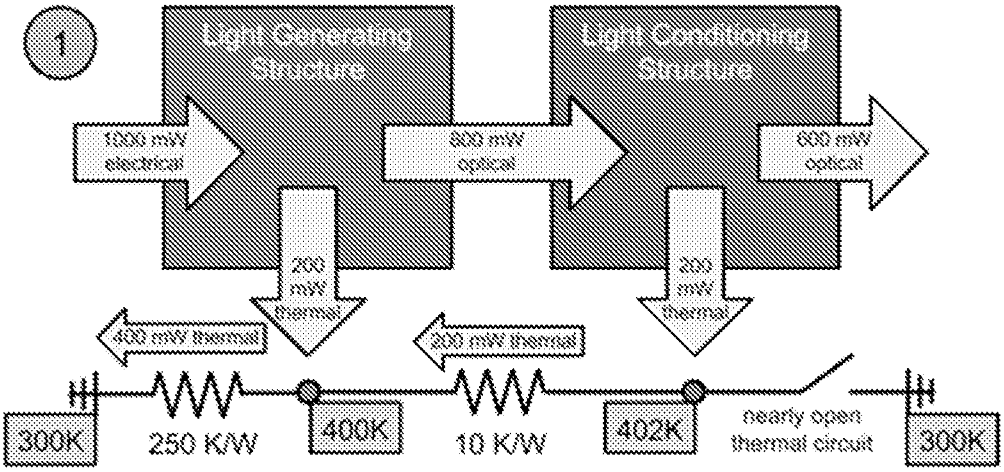
1
Light Generating Structure
Light Conditioning Structure
1000 mW electrical
800 mW optical
600 mW optical
200 mW thermal
200 mW thermal
400 mW thermal
200 mW thermal
300K
250 K/W
400K
10 K/W
402K
nearly open thermal circuit
300K

FIG. 1

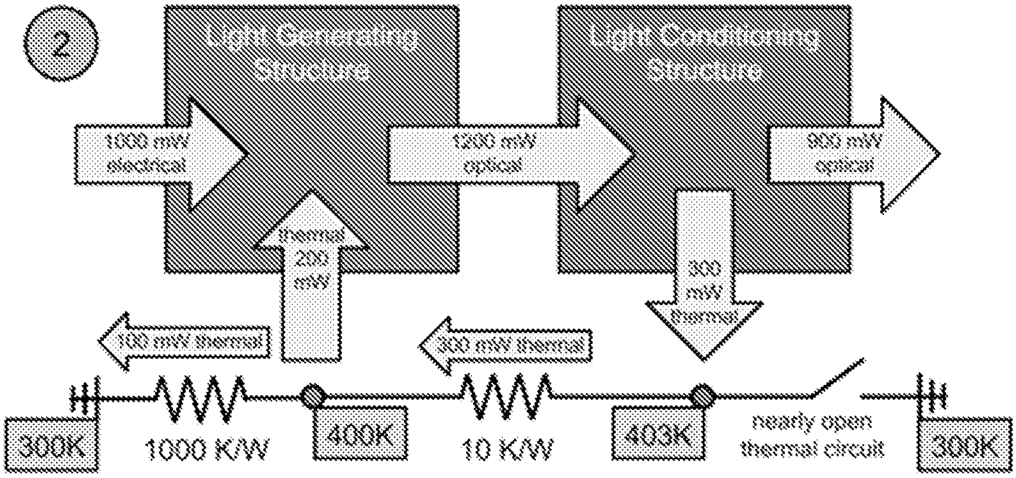
2
Light Generating Structure
Light Conditioning Structure
1000 mW electrical
1200 mW optical
900 mW optical
thermal 200 mW
300 mW thermal
100 mW thermal
300 mW thermal
300K
1000 K/W
400K
10 K/W
403K
nearly open thermal circuit
300K

FIG. 2

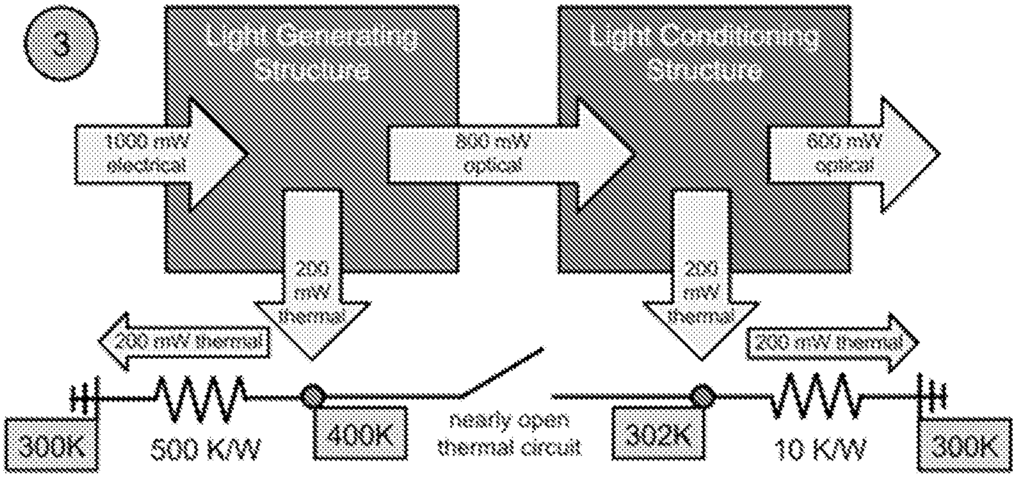
3
Light Generating Structure
Light Conditioning Structure
1000 mW electrical
800 mW optical
600 mW optical
200 mW thermal
200 mW thermal
200 mW thermal
200 mW thermal
300K
500 K/W
400K
nearly open thermal circuit
302K
10 K/W
300K

FIG. 3

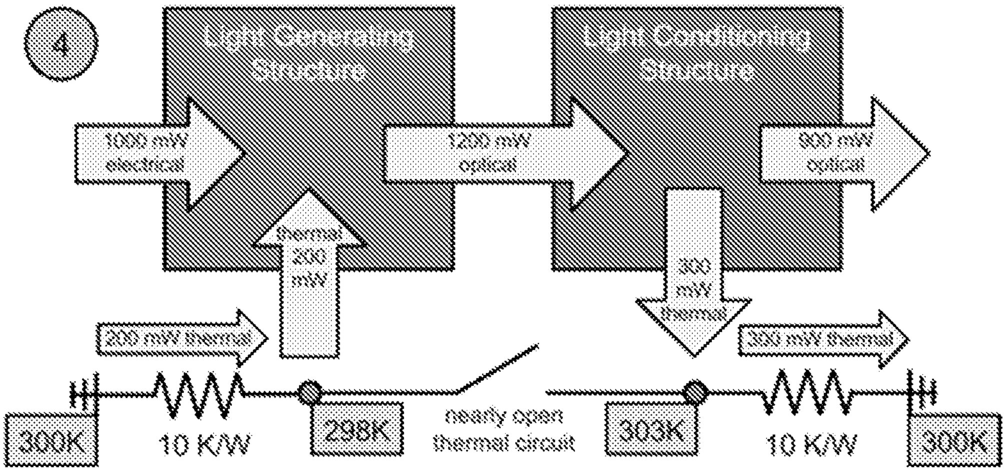
4
Light Generating Structure
Light Conditioning Structure
1000 mW electrical
1200 mW optical
900 mW optical
thermal 200 mW
300 mW thermal
200 mW thermal
300 mW thermal
300K
10 K/W
298K
nearly open thermal circuit
303K
10 K/W
300K

FIG. 4

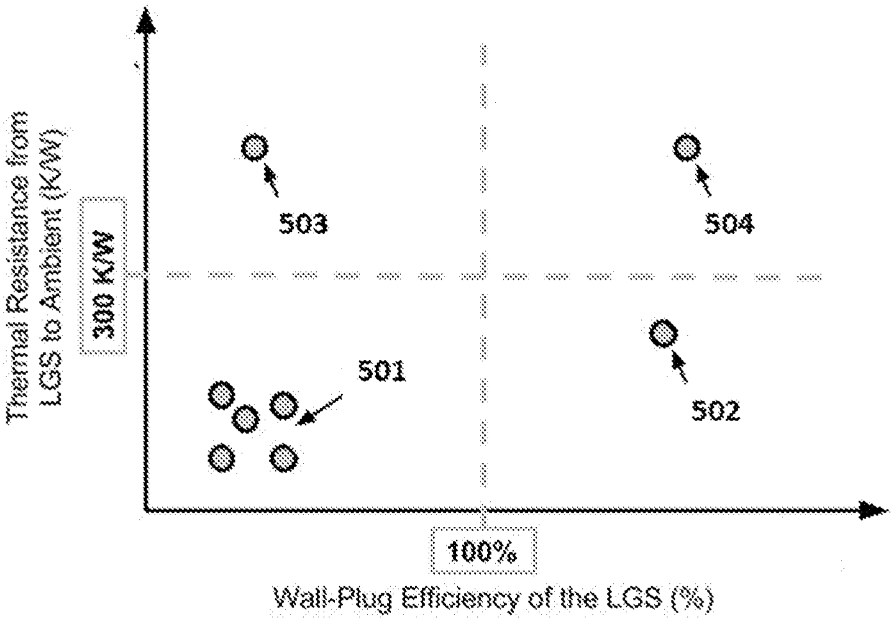
Thermal Resistance from LGS to Ambient (K/W)
300 K/W
503
504
501
502
100%
Wall-Plug Efficiency of the LGS (%)

FIG. 5

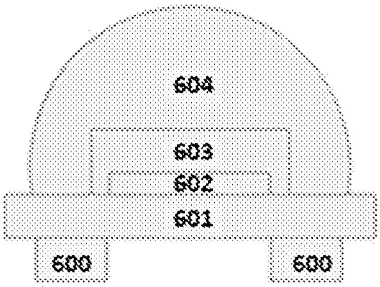

FIG. 6A

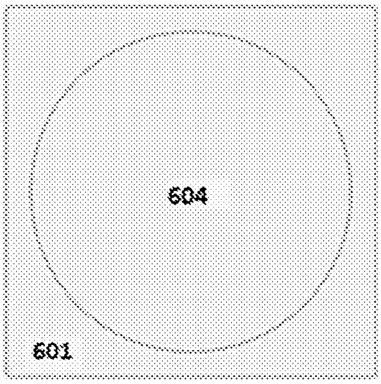

FIG. 6B

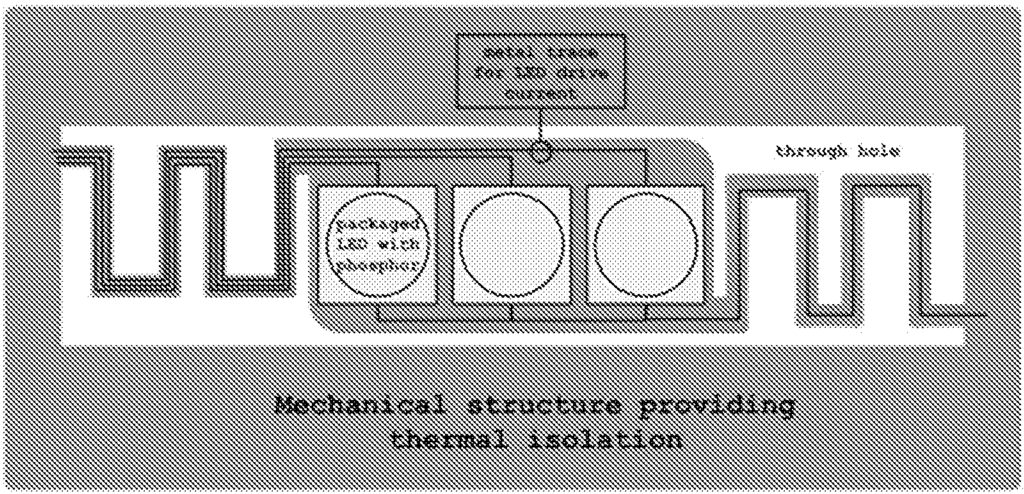
metal trace for LED drive current
through hole
packaged LED with phosphor
Mechanical structure providing thermal isolation

FIG. 7

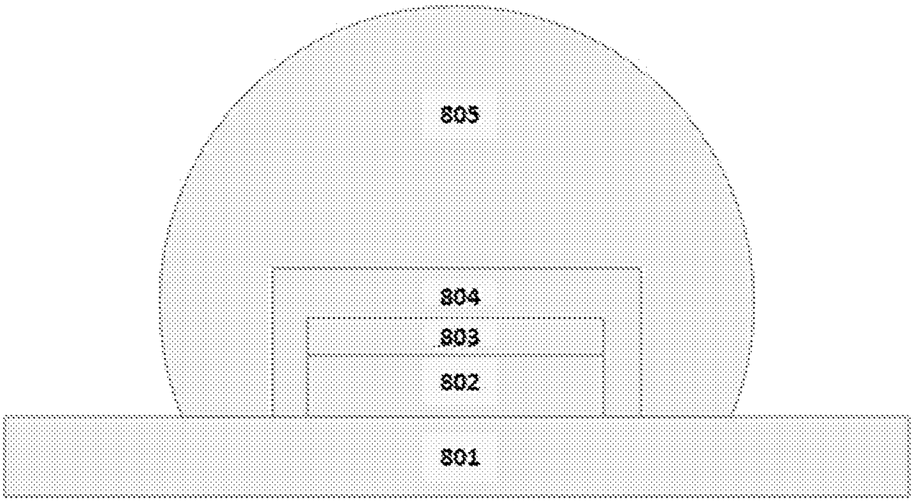

FIG. 8

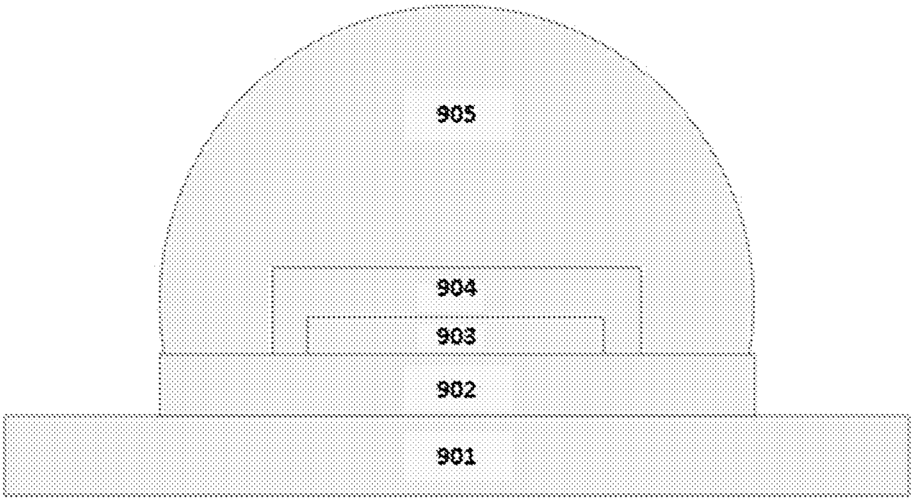

FIG. 9

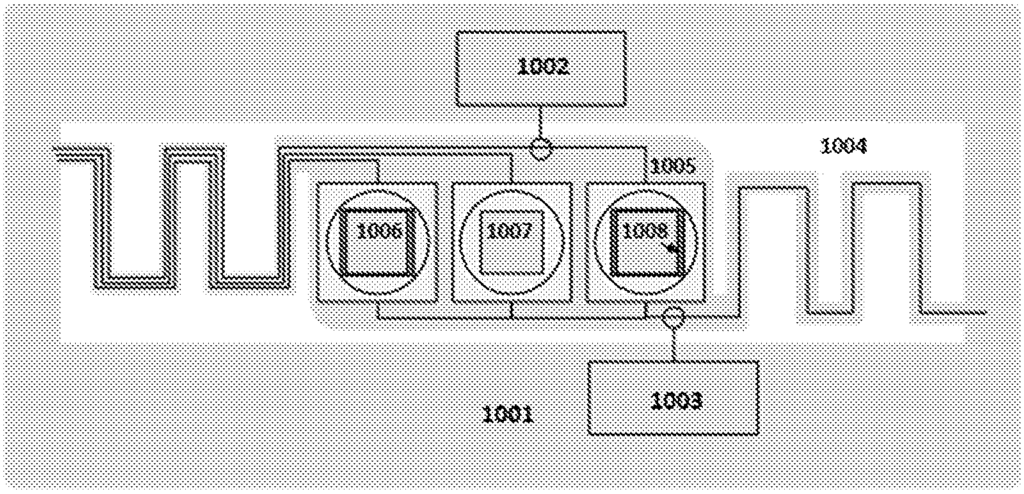

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US17/20139

A. CLASSIFICATION OF SUBJECT MATTER
IPC - F21Y 2115/00, H01L 33/00, F21V 3/02 (2017.01)
CPC - F21Y2115/00, G01J3/108, H01L33/0004, F21K9/20, G01J3/0216, F21V3/02, G01J3/42, H01L33/64, H05B33/08, H01L33/06, H01L33/002, G01J3/4412, H01L33/48, H01L33/30, G01N21/3577, H01L33/645, H01L33/02, H01L25/0753, H01L33/501, H01L33/44, H01L33/507, H01L33/56

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)
See Search History document

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

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

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 2014/0159582 A1(SANTHANAM, P et al.) 12 June 2014; paragraphs [0040]-[0042], [0082], [0103], [0104]	1-3, 44-47 --- 48
Y	US 2013/0200400 A1 (JANG, J) 8 August 2013; paragraph [0057]	48
A	US 2006/0091788 A1 (YAN, X) 4 May 2006; entire document	1-3, 44-48

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* 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 18 April 2017 (18.04.2017)	Date of mailing of the international search report 25 MAY 2017
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US17/20139

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 89-90
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

Claims 89-90 are improper unsearchable omnibus type claims since they refer to any of the embodiments described herein.

3. ☒ Claims Nos.: 4-43, 49-88
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.