

ENERGY CONVERSION DEVICE

BACKGROUND OF THE INVENTION

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Field of the Invention

This invention relates to energy conversion and more particularly to an energy conversion device for converting energy between electromagnetic and electrical energy such as light emitting device, photovoltaic device, solar liquid heating device and water purification.

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Description of the Related Art

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Recent concerns regarding the cost and shortage of fossil fuels have challenge the art in developing various types of renewable energy as well as various forms of energy conservation. One of the most promising areas of renewable energy is through the conversion of electromagnetic radiation emitted by the sun into electric power and/or usable heat. It should be realized that nearly all energy other than nuclear energy and geothermal energy is ultimately derived from the sun.

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The prior art has been known various types of devices for converting electromagnetic radiation emitted by the sun into electric power. These types of devices are commonly referred to as photovoltaic devices for converting electromagnetic radiation emitted by the sun electrical energy directly into electric power. These devices produced no harmful gases during the energy conversion process.

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Although photovoltaic energy conversion devices have found use in limited applications, the cost and efficiency of photovoltaic energy conversion devices have limited the widespread use of photovoltaic energy conversion devices.

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One promising area of energy conservation may be found in the use of solid-state light emitting energy conversion devices which produce electromagnetic radiation or light upon an input of electric power. These solid-state light emitting energy conversion devices produce electromagnetic radiation with little energy wasted heat. Although solid-state light emitting energy conversion devices have found use in limited applications, the cost and efficiency of solid state light emitting energy conversion devices have limited the widespread use thereof.

Both solid-state photovoltaic energy conversion devices and solid-state light emitting energy conversion devices operate on similar solid-state principles. In principle, solid-state

energy conversion devices are reversible and maybe operated as a photovoltaic energy conversion device or a light emitting energy conversion device. Typically, solid-state energy conversion device is specifically constructed to operate either as a photovoltaic energy conversion device or a light emitting energy conversion device.

5 A variety of semiconductors including GaN (Gallium Nitride), GaP (Gallium Phosphide), AlGaAs (Aluminum Gallium Arsenide), InP (Indium Phosphide), Si (Silicon) and SiC are currently being studied for light emitting diode (LED) applications. Recently, efficient luminescence has been discovered in silicon, which is an indirect bandgap semiconductor, due to alteration of its defect states [Wai Lek Ng, et al, Nature, Vol. 410, Issue 8 (2001)]. However
10 in SiC, an indirect bandgap wide-bandgap semiconductor (WBGS) generally emitting in the blue spectra, no efficient radiative isoelectronic trap has been discovered; consequently development of this LED material has languished. Other recent papers show that SiC LEDs have potential for high quantum efficiency [a) S.I. Vlaskina, "Silicon Carbide LED", Semiconductor Physics, Quantum Electronics & Optoelectronics, 2002, Vol. 5, No. 1, pp 71-75,
15 b) S. Kamiyama et al, "Extremely high quantum efficiency of donor-acceptor-pair emission in N- and B-doped 6H-SiC, JAP, 99, 093108 (2006).].

P-type doping, particularly exhibiting low resistivity, has been a drawback for wide-bandgap semiconductor LED material candidates. Ion implantation and thermal diffusion are currently the most widely used techniques for doping semiconductors. The energy scattered by
20 the decelerating ions leads to crystal damage by introducing point defects and the formation of amorphous material. Post ion implantation high temperature annealing isothermally heats the wafer inducing undesirable dopant diffusion in previously prepared under layers.

Doping is one of the challenges for wide bandgap semiconductors, particularly SiC, device fabrication, due to its hardness, chemical inertness and the low diffusion coefficient of
25 most impurities [I. A. Salama, Ph.D. Dissertation, University of Central Florida, Spring (2003)]. Current doping methods used for SiC device fabrication include epilayer doping and ion implantation. Maximum doping concentration is limited by the solubility and dopant depth is limited by the mass diffusion coefficient of the dopant in the wide bandgap semiconductor substrate. Epilayer doping is in situ doping during chemical vapor deposition epitaxial growth
30 and is limited in SiC to nitrogen (N) or phosphorous (P) for n-type, aluminum (Al) or boron (B) for p-type and vanadium (V) for semi-insulating type. Ion implantation is the most common doping technique used for wide bandgap semiconductor devices. This process generates implantation-induced defect centers including amorphitization in the wafer and

requires high annealing temperatures to remove these defects and to electrically activate the dopants. In SiC some defects remain after annealing at temperatures up to 1700 °C [Z. Tian., N. R. Quick. and A. Kar, *Acta Materialia*, Vol. 53, (2005), pp. 2835- 2844]. Annealing at these temperatures can cause severe surface damage due to silicon sublimation and redistribution [Z. Tian, N. R. Quick and A. Kar, *Acta Materialia*, 54, 4273, (2006)]. In summary conventional doping processes limit the dopant species, dopant concentrations and create defects.

Photolithographic patterning is necessary to define the areas across the sample to be selectively doped. This usually requires up to 10-15 individual processing steps. Damage assisted sublimation etching (DASE) of Si and dopant out-diffusion are common problems observed during ion implantation of SiC. Techniques allowing direct doping without the requirement for pre patterning can become economically viable [a) S.J. Pearton, *Processing of Wide Bandgap Semiconductors*, 1st Edition, William Andrew Publishing, 2000; b) Z.C. Feng, J. H. Zhao, “Silicon Carbide: Materials, Processing, Devices”, *Optoelectronic Properties of Semiconductors and Superlattices*, vol. 20, Taylor and Francis Books, Inc., 2004; c) M. E. Levinshtein et al, “Properties of Advanced Semiconductor Materials”, Wiley-Interscience Publications, 2001].

U.S. Patent 5,063,421 to Suzuki et al. discloses a silicon carbide light emitting diode having a p-n junction is disclosed which comprises a semiconductor substrate, a first silicon carbide single-crystal layer of one conductivity formed on the substrate, and a second silicon carbide single-crystal layer of the opposite conductivity formed on the first silicon carbide layer, the first and second silicon carbide layers constituting the p-n junction, wherein at least one of the first and second silicon carbide layers contains a tetravalent transition element as a luminescent center.

U.S. Patent 5,243,204 to Suzuki et al. discloses silicon carbide light emitting diodes having a p-n junction which is constituted by a p-type silicon carbide single-crystal layer and an n-type silicon carbide single-crystal layer formed thereon. In cases where light emission caused by recombination of free excitons is substantially utilized, at least a part of the n-type silicon carbide layer adjacent to the interface of the p-n junction is doped with a donor impurity at a concentration of $5 \times 10^{16} \text{ cm}^{-3}$ or lower. In cases where light emission caused by acceptor-associated recombination is substantially utilized, the p-type silicon carbide layer is doped with an acceptor impurity and at least a part of the n-type silicon carbide layer adjacent to the interface of the p-n junction is doped with a donor impurity at a concentration of $1 \times 10^{18} \text{ cm}^{-3}$ or higher. Also provided are a method for producing such silicon carbide light emitting diodes and a method for producing another silicon carbide light emitting diode.

U.S. Patent 5,416,342 to Edmond et al. discloses a light emitting diode that emits light in the blue portion of the visible spectrum with high external quantum efficiency. The diode comprises a single crystal silicon carbide substrate having a first conductivity type, a first epitaxial layer of silicon carbide on the substrate and having the same conductivity type as the substrate, and a second epitaxial layer of silicon carbide on the first epitaxial layer and having the opposite conductivity type from the first layer. The first and second epitaxial layers forming a p-n junction, and the diode includes Ohmic contacts for applying a potential difference across the p-n junction. The second epitaxial layer has side walls and a top surface that forms the top surface of the diode, and the second epitaxial layer has a thickness sufficient to increase the solid angle at which light emitted by the junction will radiate externally from the side walls, but less than the thickness at which internal absorption in said second layer would substantially reduce the light emitted from said top surface of the diode.

U.S. Patent 6,900,465 to Nakamura et al. discloses a nitride semiconductor light-emitting device having an active layer of a single-quantum well structure or multi-quantum well made of a nitride semiconductor containing indium and gallium. A first p-type clad layer made of a p-type nitride semiconductor containing aluminum and gallium is provided in contact with one surface of the active layer. A second p-type clad layer made of a p-type nitride semiconductor containing aluminum and gallium is provided on the first p-type clad layer. The second p-type clad layer has a larger band gap than that of the first p-type clad layer. An n-type semiconductor layer is provided in contact with the other surface of the active layer.

U.S. Patent 6,998,690 to Nakamura et al discloses a gallium nitride-based III-V Group compound semiconductor device having a gallium nitride-based III-V Group compound semiconductor layer provided over a substrate, and an Ohmic electrode provided in contact with the semiconductor layer. The Ohmic electrode is formed from a metallic material, and has been annealed.

U.S. Patent 7,045,375 to Wu et al. discloses a white-light emitting device comprising a first photon recycling semiconductor-light emitting diode (PRS-LED) and a second PRS-LED. The first PRS-LED has a primary light source to emit blue light and a secondary light source to emit red light responsive to the blue light; and the second PRS-LED has a primary light source to emit green light and a secondary light source for emitting red light responsive to the green light. Each of the primary light sources is made from an InGaN layer disposed between a p-type GaN layer and an n-type GaN layer. The secondary light sources are made from AlGaInP. The primary light source and the secondary light source can be disposed on opposite sides of a

sapphire substrate. Alternatively, the second light source is disposed on the n-type GaN layer of the primary light source. The second light sources may comprise micro-rods of AlGaInP of same or different compositions.

U.S. Patent 7049641 to Pan discloses semiconductor devices that employ deep-level
5 transitions (i.e., deep-level-to-conduction-band, deep-level-to-valence-band, or deep-level-to-deep-level) to achieve useful results. A principal aspect of the invention involves devices in which electrical transport occurs through a band of deep-level states and just the conduction band (or through a deep-level band and just the valence band), but where significant current does not flow through all three bands. This means that the deep-state is not acting as a nonradiative trap,
10 but rather as an energy band through which transport takes place. Advantageously, the deep-level energy-band may facilitate a radiative transition, acting as either the upper or lower state of an optical transition.

Discussion of wide bandgap materials and the processing thereof are discussed in U.S. Patent 5,145,741; U.S. Patent 5,391,841; U.S. Patent 5,793,042; U.S. Patent 5,837,607; U.S.
15 Patent 6,025,609; U.S. Patent 6,054,375; U.S. Patent 6,271,576, U.S. Patent 6,670,693, U.S. Patent 6,930,009, U.S. Patent 6,939,748, U.S. Patent 7,013,695, U.S. Patent 7,237,422, U.S. Patent 7,268,063, U.S. Patent 7,419,887 and 7,618,880 are hereby incorporated by reference into the present application.

Therefore, it is an objective of this invention to provide an energy conversion device and
20 method of making comprising a solid state energy conversion device formed in situ within a wide bandgap material or an insulating material.

Another objective of this invention is to provide an energy conversion device and method of making that is incorporated into a light emitting device to produce electromagnetic radiation upon the application of electrical power.

25 Another objective of this invention is to provide an energy conversion device and method of making that is incorporated into a photovoltaic device to produce electrical power upon the application of electromagnetic radiation.

Another objective of this invention is to provide an energy conversion device and method of making that is incorporated into a photovoltaic device and a solar liquid heater for providing
30 electrical power and heated liquid upon the application of electromagnetic radiation.

Another objective of this invention is to provide an energy conversion device and method of making that is incorporated into a photovoltaic device and a solar liquid heater for providing electrical power and for treating water upon application of electromagnetic radiation.

Another objective of this invention is to provide an energy conversion device and method of making that incorporates a process for doping conventional and unconventional dopants in indirect wide bandgap semiconductors to create efficient radiative states to provide an efficient solid state energy conversion device.

Another objective of this invention is to provide an energy conversion device and method of making that incorporates combinations of dopants which enables the tuning of the energy conversion device to a white light sensitivity of the solid state energy conversion device.

Another objective of this invention is to provide an energy conversion device formed within a one-piece substrate.

Another objective of this invention is to provide a process for making an energy device that is low cost and may be fabricated in large surface areas.

The foregoing has outlined some of the more pertinent objects of the present invention. These objects should be construed as being merely illustrative of some of the more prominent features and applications of the invention. Many other beneficial results can be obtained by applying using the disclosed invention in a different manner or modifying the invention. Accordingly other objects in a full understanding of the invention may be had by referring to the summary of the invention and the detailed description describing the preferred embodiment of the invention.

SUMMARY OF THE INVENTION

The present invention is defined by the appended claims with specific embodiments being shown in the attached drawings. For the purpose of summarizing the invention, the invention relates to a solid state energy conversion device and a method of making for converting energy between electromagnetic and electrical energy. The solid state energy conversion device comprises a wide bandgap semiconductor material having a first doped region. A doping gas is applied to the first doped region of the wide bandgap semiconductor material. A thermal energy beam is directed onto the first doped region of the wide bandgap semiconductor material in the presence of the doping gas for converting a portion of the first doped region into a second doped region in the wide bandgap semiconductor material. A first and a second Ohmic contact are applied to the first and the second doped regions of the wide bandgap semiconductor material.

In a more specific embodiment of the invention, the step of providing a wide bandgap

semiconductor material having a first doped region comprises providing a wide bandgap semiconductor material selected from the group consisting of silicon carbide, gallium nitride, aluminum nitride, diamond, diamond like carbon, boron nitride and gallium phosphide.

5 In another specific embodiment of the invention, the step of applying a doping gas to the first doped region of the wide bandgap semiconductor material comprises applying a doping gas selected from the group consisting of nitrogen, trimethylaluminum, Bis (ethyl benzene)-chromium, diethylselenium and Eurpoium 2,2,6,6, Tetramethyl 3,5, heptanedionate. Preferably, the step of applying a doping gas to the first doped region of the wide bandgap semiconductor material comprises applying a doping gas containing a dopant atom having a valence sufficiently
10 greater that the valence of the wide bandgap semiconductor material to provide a multi-hole donor within the first doped region of the wide bandgap semiconductor material. In the alternative, the step applying of a doping gas to the first doped region of the wide bandgap semiconductor material comprises applying a doping gas containing a dopant atom having a valence sufficiently less that the valence of the wide bandgap semiconductor material to provide a
15 multi-hole acceptor within the first doped region of the wide bandgap semiconductor material. The step of applying the first and second Ohmic contact may comprises applying the first and second Ohmic contact selected from the group consisting of indium, aluminum and laser synthesized carbon rich conductor.

The solid state energy conversion device may operate as a light emitting device or a
20 photovoltaic device. The solid state energy conversion device produces electromagnetic radiation upon the application of electrical power to the first and second Ohmic contacts to operate as a light emitting device. The solid state energy conversion device produces electrical power between the first and second Ohmic contacts upon the application of electromagnetic radiation to operate as a photovoltaic device.

25 In another embodiment of the invention, the invention is incorporated into solid state energy conversion device comprising a wide bandgap semiconductor material having a first doped region. A second doped region is formed in situ within a portion of the first doped region by directing a thermal energy beam onto the first doped region in the presence of a doping gas for converting a portion of the first doped region into a second doped region. A first and a second
30 Ohmic contact are connected to the first and the second doped regions of the wide bandgap semiconductor material. In one example, the solid state energy conversion device operates as a light emitting device to produce electromagnetic radiation upon the application of electrical power to the first and second Ohmic contacts. In another example, the solid state energy

conversion device operates as a photovoltaic device to produce electrical power between the first and second Ohmic contacts upon the application of electromagnetic radiation.

In still another embodiment of the invention, the invention is incorporated into the process of making a solid state light emitting device in a substrate of a wide bandgap semiconductor material. The process comprises the steps of providing a wide bandgap semiconductor material having a first doped region. A doping gas is applied to the first doped region of the wide bandgap semiconductor material. A thermal energy beam is directed onto the first doped region of the wide bandgap semiconductor material in the presence of the doping gas for converting a portion of the first doped region into a second doped region in the wide bandgap semiconductor material.

A first and a second Ohmic contact is applied to the first and the second doped regions of the wide bandgap semiconductor material. In one example, the solid state energy conversion device produces electromagnetic radiation upon the application of electrical power to the first and second Ohmic contacts to operate as a light emitting device having a color temperature that is between bright midday daylight and average daylight. In another example, the solid state energy conversion device produces electromagnetic radiation upon the application of electrical power to the first and second Ohmic contacts to operate as a light emitting device having a color temperature that is between bright midday daylight and average daylight.

In still another embodiment of the invention, the invention is incorporated into a solid state light emitting device comprising a wide bandgap semiconductor material having a first doped region. A second doped region is formed in situ within a portion of the first doped region by directing a thermal energy beam onto the first doped region in the presence of a doping gas for converting a portion of the first doped region into a second doped region. A first and a second Ohmic contact are connected to the first and the second doped regions of the wide bandgap semiconductor material.

In a further embodiment of the invention, the invention is incorporated into a solid state photovoltaic device comprising a wide bandgap semiconductor material having a first doped region. A second doped region is formed in situ within a portion of the first doped region by directing a thermal energy beam onto the first doped region in the presence of a doping gas for converting a portion of the first doped region into a second doped region. A first and a second Ohmic contact are connected to the first and the second doped regions of the wide bandgap semiconductor material.

The invention is also incorporated into a process for making a solid-state energy device from an insulating substrate comprising the steps of providing a substrate of an insulating

material having a first surface and a second surface. A portion of the insulating material of the substrate is converted into a first type wide bandgap semiconductor material. An adjacent portion of the insulating material of the substrate is converted into a second type wide bandgap semiconductor material in contact with the first type wide bandgap semiconductor material. A first conductor is provided in electrical contact with the first type wide bandgap semiconductor material. A second conductor is provided in electrical contact with the second type wide bandgap semiconductor material.

In a more specific embodiment of the invention, the solid-state energy device is a photovoltaic energy device for providing electrical power between the first and second conductors upon impingement of electromagnetic radiation. In the alternative, the solid-state energy device is a light emitting energy device for emitting electromagnetic radiation upon the application of electrical power between the first and second conductors.

In another specific embodiment of the invention, the invention is incorporated into the process for making a solid-state energy device from an insulating substrate comprising providing a substrate of an insulating material having a first surface and a second surface. A region of the insulating material of the substrate is converted into a wide bandgap semiconductor material. A first conductor is formed in the wide bandgap semiconductor material. A first portion of the wide bandgap semiconductor material is converted into a first type wide bandgap semiconductor material in contact with the first conductor. A second portion of the wide bandgap semiconductor material is converted into a second type wide bandgap semiconductor material in contact with the first wide bandgap semiconductor material. A second conductor is formed in contact with the second type wide bandgap semiconductor material.

The invention is also incorporated into a solid-state energy device comprising a substrate of an insulating material having a first surface and a second surface. A first conductor is located inside of the substrate between the first and second surfaces of the substrate. A first type wide bandgap semiconductor material is located inside of the substrate in contact with the first conductor. A second type wide bandgap semiconductor material located inside of the substrate in contact with the first type wide bandgap semiconductor material. A second conductor is located in contact with the second type wide bandgap semiconductor material.

In another embodiment of the invention, the invention is incorporated into a solid-state energy conversion device comprising a one-piece insulating substrate. A photovoltaic device is formed within the one-piece insulating substrate for enabling electromagnetic radiation propagating into the one-piece insulating substrate to impinge upon the photovoltaic device for

generating electrical power.

In a further embodiment of the invention, the invention is incorporated into a solid-state energy conversion device comprising a one-piece insulating substrate. A light-generating device is formed within the one-piece insulating substrate for propagating electromagnetic radiation from the one-piece insulating substrate to impinge upon the application of electrical power.

In still a further embodiment of the invention, the invention is incorporated into a solid-state energy conversion device comprising a one-piece insulating substrate. An energy conversion device is formed within the one-piece insulating substrate for converting energy between electromagnetic radiation and electrical power. A transparent wave guide is affixed to the one-piece insulating substrate for directing electromagnetic radiation relative to the energy conversion device formed within the one-piece insulating substrate.

In an alternate embodiment of the invention, the invention is incorporated into an energy device for generating electrical power and for heating a liquid upon the impingement of electromagnetic energy. A glass substrate is positioned adjacent to the conduit receiving the liquid. A photovoltaic device is disposed within the glass substrate for enabling a first wavelength of the electromagnetic radiation to propagate through the glass substrate to impinge upon the conduit to heat the liquid and for enabling a second wavelength of the electromagnetic radiation to be absorbed by the photovoltaic device for generating electrical power.

In still a further embodiment of the invention, the invention is incorporated into an energy device for generating electrical power upon the impingement of electromagnetic energy in combination with a solar water heater for the heat purification of water through solar radiation.

The foregoing has outlined rather broadly the more pertinent and important features of the present invention in order that the detailed description that follows may be better understood so that the present contribution to the art can be more fully appreciated. Additional features of the invention will be described hereinafter which form the subject matter of the invention. It should be appreciated by those skilled in the art that the conception and the specific embodiments disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and objects of the invention, reference should be

made to the following detailed description taken in connection with the accompanying drawings in which:

FIG. 1 is a side view of an air-tight chamber with a thermal energy beam impinging on a wide-bandgap semiconductor substrate for forming a solid state energy conversion device of the present invention;

FIG. 2 is an enlarged isometric view of the substrate of FIG. 1;

FIG 3A is a graph illustrating a direct transition between the valence band and the conduction band of a semiconductor;

FIG 3B is a graph illustrating an indirect transition between the valence band and the conduction band of a semiconductor;

FIG 3C is a graph illustrating a deep level transition between the valence band and the conduction band of a semiconductor;

FIG. 4A is a side sectional view of a first example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state light emitting device;

FIG. 4B is a side sectional view of a second example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state light emitting device;

FIG. 4C is a side sectional view of a third example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state light emitting device;

FIG. 5A is a side sectional view of a fourth example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state photovoltaic device;

FIG. 5B is a side sectional view of a fifth example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state photovoltaic device;

FIG. 5C is a side sectional view of a sixth example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state photovoltaic device;

FIG. 6 is a graph of conventional dopant diffusivity in SiC as a function of reciprocal temperature for conventional processing;

FIG. 7 is a graph of concentration of the dopants Cr, N and Al as a function of depth

within a 6H-SiC silicon carbide wide bandgap substrate;

FIG. 8 is a graph of concentration of the dopants Cr, N and Al as a function of depth within a 4H-SiC silicon carbide wide bandgap substrate;

FIG. 9A is a side sectional view of a first example of a white light solid state emitting device fabricated on 6H:SiC (n-type) substrate by doping with aluminum and chromium;

FIG. 9B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 9A;

FIG. 10A is a side sectional view of a second example of a white light solid state light emitting device fabricated on 4H:SiC (p-type) substrate by doping with nitrogen and chromium;

FIG. 10B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 10A;

FIG. 11A is a side sectional view of a third example of an orange-red solid state light emitting device fabricated on 4H:SiC (p-type) substrate by doping with chromium;

FIG. 11B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 11A;

FIG. 12A is a side sectional view of a fourth example of a green light solid state light emitting device fabricated on 6H:SiC (n-type) substrate by doping with chromium;

FIG. 12B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 12A;

FIG. 13A is a side sectional view of a fifth example of a red light solid state light emitting device of fabricated on 4H:SiC (n-type) substrate by doping with chromium;

FIG. 13B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 13A;

FIG. 14A is a side sectional view of a sixth example of a blue light solid state light emitting device fabricated on 6H:SiC (n-type) substrate by doping with aluminum;

FIG. 14B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 14A;

FIG. 15A is a side sectional view of a seventh example of a blue-green solid state light emitting device fabricated on 6H:SiC (n-type) substrate by doping with boron;

FIG. 15B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 15A;

FIG. 16 is a graph of operational temperature as a function of band gap for various solid state devices;

FIG. 17 is a side sectional view of a solid state photovoltaic device fabricated on 6H:SiC (n-type) substrate by doping with aluminum and chromium;

FIG. 18 is an isometric view of a building structure having glass windows incorporating the energy conversion device of the present invention;

5 FIG. 19 is an enlarged sectional view along line 19-19 in FIG. 18;

FIG. 20 is an enlarged sectional view along line 20-20 in FIG. 18;

FIG. 21 is a magnified view of a portion of FIG. 19;

FIG. 22 is a magnified view of a portion of FIG. 20;

10 FIG. 23 is a magnified view similar to FIGS. 21 and 22 illustrating the incorporation of both of the energy conversion devices of FIGS. 21 and 22;

FIG. 24 is an alternate embodiment of FIG. 21 incorporating a diode connected in series with the energy conversion device;

FIG. 25 is a block diagram of the process of making the energy conversion device of the present invention;

15 FIG. 26 illustrates the sequence of forming the energy conversion device of the present invention;

FIG. 27 is a magnified view of a photovoltaic energy conversion device of FIG. 21;

FIG. 28 is a magnified view of a light emitting energy conversion device of FIG. 22;

FIG. 29 is a magnified view of a light emitting energy conversion device of FIG. 24;

20 FIG. 30 illustrates a portion of an apparatus for converting an insulating substrate into components of the energy conversion device through the use of a thermal energy beam in the presence of a doping gas;

FIG. 31 illustrates an alternate portion of an apparatus for converting an insulating substrate into components of the energy conversion device through the use of a thermal energy beam in the presence of a doping gas;

25 FIG. 32 illustrates a specific example of the energy conversion device of the present invention formed in an insulating glass substrate;

FIG. 33 illustrates a specific example of the energy conversion device of the present invention formed in an aluminum oxide substrate;

30 FIG. 34 illustrates the photovoltaic energy device of the present invention coupled to a wave guide;

FIG. 35 illustrates the light emitting energy device of the present invention coupled to a wave guide;

FIG. 36 illustrates an energy conversion device of the present invention in the form of a combined photovoltaic device and a solar liquid heater;

FIG. 37 is a magnified view of a portion of FIG. 36;

FIG. 38 is an enlarged sectional view along line 38-38 in FIG. 37;

5 FIG. 39 illustrates an energy conversion device of the present invention in the form of a combined photovoltaic device and a solar heater for treating water; and

FIG. 40 illustrates the apparatus of FIG. 39 with the valves position to circulate the water.

Similar reference characters refer to similar parts throughout the several Figures of the drawings.

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DETAILED DISCUSSION

FIG. 1 is a side view of an apparatus 5 for forming a solid state energy conversion device 10 on a wide-bandgap semiconductor substrate 20. The wide-bandgap semiconductor substrate 15 20 is shown located in an air-tight chamber 30. The chamber 30 has an inlet valve combination 31 and outlet valve 32 connected to the sidewall of the chamber 30 for injecting and removing gases into and out of the chamber 30, respectively. The chamber 30 includes an airtight transmission window 34. The chamber 30 is disposed on a support member 36 forming an airtight seal therewith.

20 FIG. 2 is an enlarged isometric view of the solid state energy conversion device 10 formed in situ within the wide-bandgap semiconductor substrate 20 shown in FIG. 1. The wide-bandgap semiconductor substrate 20 defines a first and a second side 21 and 22 and a peripheral edge 23. Although the wide-bandgap semiconductor substrate 20 is shown as a square, the present invention is not limited by the physical configuration of the wide-bandgap semiconductor 25 substrate 20 as shown herein.

Preferably, the wide-bandgap semiconductor 20 has a bandgap greater than 2.0 electron volts. In one example, the wide-bandgap semiconductor 20 is selected from the group IV of the periodic table and having a bandgap greater than 2.0 electron volts. In a more specific example of the invention, the wide-bandgap semiconductor 20 is essentially a single crystal structure.

30 In still a more specific example of the invention, the wide-bandgap semiconductor 20 may be a single crystal compound. The elements of the single crystal compound selected are from the group III, the group IV and the group V of the periodic table and having bandgap greater than 2.0 electron volts. Preferably, one element of the compound has a higher melting point element than

the other element of the compound. Specific examples of the wide-bandgap semiconductor compound are selected from the group consisting of Aluminum Nitride, Silicon Carbide, Boron Nitride, Gallium Nitride, diamond, diamond like carbon (DLC) and Gallium Phosphide.

5 A thermal energy beam 40 is shown emanating from a source 42 and passing through the airtight transmission window 34 to impinge on the first surface 21 of the wide-bandgap semiconductor substrate 20. In one example, the thermal energy beam 40 is a beam of charged particles such as a beam of electrons or a beam of ions. In another example, the thermal energy beam 40 is a beam of electromagnetic radiation such as a laser beam. Examples of a suitable source of the laser beam include a Nd:YAG laser, a frequency double 2ω Nd:YAG laser, 10 frequency tripled 3ω Nd:YAG, frequency quadrupled 4ω Nd:YAG, CO_2 or an Excimer laser.

The thermal energy beam 40 is scanned in two dimensions across the first surface 21 of the wideband gap semiconductor substrate 20 to form the solid state energy conversion device 10. In this example, the first surface 11 of the solid state energy conversion device 10 is coincident with the first surface 21 of the wideband gap semiconductor substrate 20 with the remainder of 15 the solid state energy conversion device 10 including the second surface 12 and the peripheral surface 13 being embedded within the wideband gap semiconductor substrate 20.

The thermal energy beam 40 impinges on the wide-bandgap semiconductor substrate 20 to create the solid state energy conversion device 10 within the wide-bandgap semiconductor substrate 20. In this example, the solid state energy conversion device 10 is located on the first 20 side 21 of the wide-bandgap semiconductor substrate 20. The solid state energy conversion device 10 is shown as a portion of the wide-bandgap semiconductor substrate 20 formed by causing relative movement between the wide-bandgap semiconductor substrate 20 and the thermal energy beam 40.

25 The wide-bandgap semiconductor substrate 20 may be formed as a monolith or a thin film substrate having suitable properties for forming the solid state energy conversion device 10 in the wide-bandgap semiconductor substrate 20. Laser doping can be conducted on opposing surfaces of a substrate, wafer, thin film, thin film deposited on a flexible substrate or in different regions on the same surface.

Table 1 sets the initial properties of a wide-bandgap semiconductor substrate 20 suitable 30 for creating the solid state energy conversion device 10 of the present invention.

TABLE 1

Properties of Parent Substrates for SiC Energy Conversion Device Fabrication

Parent Substrate	Typical Resistivity (ohm-cm)	Principle Dopant	Typical principle dopant concentration (/cc)	Notes:
6H-SiC n-type	0.05	Nitrogen	10^{16}	a) acceptor impurities may be present b) defects can behave as acceptors
6H-SiC p-type	0.1-0.2	Aluminum	$10^{17} - 10^{20}$	a) Nitrogen (donor) impurities may be present. b) defects can behave as donors
6H-SiC semi-insulating	$10^6 - 10^{11}$	Vanadium	$<10^{14}$	a) Vanadium can behave as a donor or acceptor. b) Vanadium can complex with defects creating local strains, which create local dipoles which behave as electron carriers. c) Nitrogen can be on the order of $10^{16}/\text{cc}$
4H-SiC n-type	0.044	Nitrogen	10^{16}	a) acceptor impurities may be present b) defects can behave as acceptors
4H-SiC p-type	0.1-0.2	Aluminum	$10^{17} - 10^{20}$	a) Nitrogen (donor) impurities may be present. b) point defects can behave as donors
4H-SiC semi-insulating	$10^9 - 10^{11}$	Vanadium	$<10^{14}$	a) Vanadium can behave as a donor or acceptor; b) Vanadium can complex with defects creating local strains, which create local dipoles which behave as electron carriers. c) Nitrogen can be on the order of $10^{16}/\text{cc}$

Wide bandgap semiconductors (WBGs) have been laser doped with both n-type and p-type dopants. Specific dopant types and substrates include nitrogen and cobalt in diamond-like carbon; magnesium in GaN; and aluminum, nitrogen, chromium, boron, gallium, europium, erbium, selenium, oxygen and thulium in silicon carbide from metal-organic and powder precursors.

Laser doping achieves higher dopant concentration than by conventional ion implantation doping. Nitrogen dopant concentration is increased one to three orders of magnitude while aluminum doping is increased from one to four orders of magnitude compared to ion implantation without creating lattice defects. Laser doping depths can be 200-300 nm up to 4
5 microns or greater. Laser doping enables the doping of atoms, from preferably a metal-organic precursor, that have a valence greater than the positive valence atom in the parent substrate. These unconventional dopants contribute multiple holes per atom creating more efficient radiative states in indirect wide bandgap semiconductors.

For n-type doping, the sample was placed in nitrogen atmosphere at pressure of 30 psi and
10 laser-doped regions were formed on the sample surface by moving the chamber with a stepper motor-controlled translation stage. The height of the chamber was controlled manually through an intermediate stage to obtain different laser spot sizes on the SiC substrate. In case of gallium phosphide (GaP), nitrogen acts as an iso-electronic defect rather than a n-type dopant. For p-type doping, TMA (trimethylaluminum, $(\text{CH}_3)_3\text{Al}$), Bis (ethyl benzene)-chromium and boron were
15 used. TMA was heated in a bubbler source immersed in a water bath maintained at 70°C until it evaporated and then a carrier gas, methane, was passed through the bubbler to transport the TMA vapor to the laser doping chamber. Similarly for chromium doping, Bis (ethyl benzene)-chromium was heated in a bubbler source immersed in a water bath maintained at 100°C until it evaporated and then a carrier gas, argon, was passed through the bubbler to transport the ethyl
20 benzene chromium vapor to the laser doping chamber. These dopant gas species decompose at the laser-heated substrate surface producing Al and Cr atoms, which subsequently diffuse into the substrate.

A more detailed discussion follows on the importance doping with atoms that have a sufficient valence to create multi-hole acceptors. Chromium (6+), which has a valence of two
25 greater than the silicon (4+) component of silicon carbide, is used as a dopant example to create efficient radiative states. Normally dopant atoms are from the adjacent groups in the periodic table that are on either side of the atom of an atomic constituent of the parent wide bandgap semiconductor. For example Si is in group IV and elements such as Al (p-type dopant) and P (n-type dopant) are in groups III and V respectively. The transition metal Cr has been doped into
30 SiC, which does not follow this conventional approach. Additionally Cr acts as an acceptor creating two holes per Cr atom (a multi-hole acceptor); higher Cr concentrations greatly increase the acceptor population as confirmed by deep level transient spectroscopy (DLTS). DLTS spectra of a 4H-SiC (n-type-N) wafer substrate laser doped with chromium shows minority carrier trap

peaks due to acceptor (holes) states in a chromium-doped 4H-SiC (n-type) wafer, which confirms that chromium is a p-type dopant. The DLTS technique is a powerful tool for determining the defect properties such as defect energy level, capture cross-section, and trap density. A modified DLTS that combines junction spectroscopy with illumination in a double pulse approach can be used to identify the minority carrier traps acting as recombination centers.

The technique is based on the transient capacitance change associated with the thermal emission of charge carriers from a trap level to thermal equilibrium after an initial non-equilibrium condition in the space-charge region of a Schottky barrier or a p-n junction diode. The polarity of the DLTS peak depends on the capacitance change after trapping the minority or majority carriers. In general, a minority carrier trap produces a positive DLTS peak, while a majority carrier trap yields a negative DLTS peak. [D. V. Lang, Fast capacitance transient apparatus: Application to ZnO and O centers in GaP p-n junctions, J. Appl. Phys. 45 (1974) 3014-3022.

The active state of Cr was confirmed by Hall effect measurements using a Cr-doped n-type (nitrogen-doped) 4H-SiC sample. This sample was prepared using the same laser doping parameters as used for laser doping Cr into the p-type 4H-SiC wafer. The Hall measurement identified the Cr-doped region as p-type with a carrier concentration of $1.942 \times 10^{19} \text{ cm}^{-3}$ which is almost twice the average dopant concentration ($\sim 10^{19} \text{ cm}^{-3}$). The average dopant concentration is based on the Secondary Ion Mass Spectroscopy (SIMS) data for n-type 4H-SiC with a concentration of $2 \times 10^{19} \text{ cm}^{-3}$ at the wafer surface and 10^{17} cm^{-3} at a depth of 500 nm. This data confirms Cr as a double acceptor and also indicate that the laser doping technique activated all the dopant atoms without the need of any additional annealing step.

Conversely, SiC can be doped with fewer Cr atoms than Al atoms to achieve the same hole concentration. Fewer Cr atoms in the SiC lattice is expected to produce less strain and defects in the material than in the case of higher concentrations of Al.

Similarly, multi-electron donors can be laser doped into SiC. Europium having a +2 valence, derived from a Europium Tetramethyl, 3,5 heptanedionate precursor vapor decomposes upon laser heating and is diffused into SiC substrate using the process described for Cr laser doping. Selenium derived from a diethylselenium precursor also behaves as a multi-electron donor.

The preferred dopants create a band of deep level states that do not behave as nonradiative traps but as an energy band through which charge carrier transport occurs. These deep level states behave as an upper or lower state of the optical transition and essentially can convert indirect

bandgap materials to direct bandgap materials.

FIG. 3A is a graph illustrating a direct transition between the valence band and the conduction band of a semiconductor. In the direct transition, essentially all energy between the valence band and the conduction band is converted into photons.

5 FIG. 3B is a graph illustrating an indirect transition between the valence band and the conduction band of a semiconductor. In the indirect transition, essentially a part of the energy between the valence band and the conduction band is converted into photons and a part of the energy between the valence band and the conduction band converted into phonons.

10 FIG. 3C is a graph illustrating a deep level transition between the valence band and the conduction band of a semiconductor. In the deep level transition, essentially all energy between the valence band and the conduction band is converted into photons. The deep levels can produce optically active, e.g., direct bandgap semiconductor behavior. FIGS. 3A-3C schematically shows this effect.

15 More specifically, laser doping can convert indirect bandgap semiconductors to direct bandgap semiconductors by intentionally inducing strain to alter electron momentum states. An indirect bandgap semiconductor has a conduction band bottom that does not occur at momentum (k)=0 while the top of the valence band does occur at $k=0$. Therefore energy released during electron recombination with a hole is converted primarily into a phonon (additional momentum), a quasi-particle which is a quantized sound wave; e.g. Si, GaP, SiC. A direct bandgap
20 semiconductor has a conduction band bottom and valence band top occurring at the momentum $k=0$. Therefore energy released during band-to-band electron recombination with a hole is converted primarily into photon radiation (radiant recombination) exhibiting a wavelength determined by the energy gap; e.g. GaAs, InP, GaN; no extra momentum is required. Direct bandgap semiconductors are sometimes referred to as "optically active" and indirect as "optically
25 inactive". Laser doping where the dopant has a valence greater than the highest valence atom of the comprising the parent wide bandgap semiconductor can transform the SiC indirect wide bandgap semiconductor into a direct bandgap semiconductor; dopants with a valence 2 or greater than the highest valence atom comprising the parent wide bandgap semiconductor are preferred. This doping induces strain which alters the momentum state of the electrons and facilitates the
30 transfer of electron-hole recombination between the conduction and valence bands with no additional momentum. U.S. Patent 7049641 issued to Pan discloses that phonons are not required for deep level transitions to the conduction band, to the valence band or deep level to deep level energy levels.

Conversely a solid state photovoltaic device with p and n regions can produce electric current when light or electromagnetic radiation is irradiated on the solid state photovoltaic device.

The laser doping technology of the present invention can be used to create energy conversion devices in many semiconductor structures such as diodes, transistors and other
5 electron components in monolithic or thin film geometries.

FIG. 4A is a side sectional view of a first example of a solid state energy conversion device 10A formed in accordance with the present invention to provide a solid state light emitting device. In this example, the substrate 20A has a first and a second side 21A and 22A and a peripheral edge 23A. A laser doped region 51A is formed on the first side 21A of the substrate
10 20A. A first and a second Ohmic contact 61A and 62A are electrically connected to the first and second side 21A and 22A of the substrate 20A. The solid state light emitting device 10A produces electromagnetic radiation when an electric current is injected between the first and second Ohmic contacts 61N and 62N as indicated by the battery 71A.

Preferably, the first and second electrodes 61A and 62A are formed by the thermal
15 conversion of the wide-bandgap semiconductor substrate 20A. The conversion of the portions of the wide-bandgap semiconductor substrate 20A to provide the first and second electrodes 61A and 62A is set forth in my U.S. Patent 5,145,741; U.S. Patent 5,391,841; U.S. Patent 5,793,042; U.S. Patent 5,837,607; U.S. Patent 6,025,609; U.S. Patent 6,054,375; U.S. Patent 6,271,576 and U.S. Patent 6,670,693.

FIG. 4B is a side sectional view of a second example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state light emitting device 10B. In this example, the substrate 20B has a first and a second side 21B and 22B and a peripheral edge 23B. Laser doped regions 51B and 52B are formed on the first side 21B of the substrate 20A. A first and a second Ohmic contact 61B and 62B are electrically connected to the
20 substrate 20A. A first and a second Ohmic contact 61B and 62B are electrically connected to the laser doped regions 51B and 52B. The solid state light emitting device 10B produces electromagnetic radiation when an electric current is injected between the first and second Ohmic contacts 61B and 62B as indicated by the battery 71B.

FIG. 4C is a side sectional view of a third example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state light emitting
30 device 10C. In this example, the substrate 20C has a first and a second side 21C and 22C and a peripheral edge 23C. Laser doped regions 51C and 52C are formed in layers on the first side 21C of the substrate 20A. A first and a second Ohmic contact 61A and 62A are electrically connected to the first and second side 21C and 22C of the substrate 20C. The solid state light emitting

device 10C produces electromagnetic radiation when an electric current is injected between the first and second Ohmic contacts 61C and 62C as indicated by the battery 71C.

FIG. 5A is a side sectional view of a fourth example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state photovoltaic device 10D. In this example, the substrate 20D has a first and a second side 21D and 22D and a peripheral edge 23D. A laser doped region 51D is formed on the first side 21D of the substrate 20D. A first and a second Ohmic contact 61D and 62D are electrically connected to the first and second side 21D and 22D of the substrate 20D. The solid state photovoltaic device 10D produces an electric current between the first and second Ohmic contacts 61D and 62D upon receiving electromagnetic radiation as indicated by the ammeter 72D.

FIG. 5B is a side sectional view of a fifth example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state photovoltaic device 10E. In this example, the substrate 20E has a first and a second side 21E and 22E and a peripheral edge 23E. Laser doped regions 51E and 52E are formed in the first and second sides 21E and 22E of the substrate 20E. A first and a second Ohmic contact 61E and 62E are electrically connected to the first and second side 21E and 22E of the substrate 20E. The solid state photovoltaic device 10E produces an electric current between the first and second Ohmic contacts 61E and 62E upon receiving electromagnetic radiation as indicated by the ammeter 72E.

FIG. 5C is a side sectional view of a sixth example of a solid state energy conversion device formed in accordance with the present invention to provide a solid state photovoltaic device 10F. In this example, the substrate 20F has a first and a second side 21F and 22F and a peripheral edge 23F. Laser doped regions 51F and 52F are formed in layers on the first side 21F of the substrate 20F. A first and a second Ohmic contact 61F and 62F are electrically connected to the first and second side 21F and 22F of the substrate 20F. The solid state photovoltaic device 10F produces an electric current between the first and second Ohmic contacts 61F and 62F upon receiving electromagnetic radiation as indicated by the ammeter 72F.

FIG. 6 is a graph of diffusivity of various conventional dopants into SiC using conventional doping processes (e.g., thermal, ion implantation). Conventional doping processes also limit the choice of dopants. For example, nitrogen diffusivity in silicon carbide SiC is 5×10^{-12} cm²/second at a temperature greater than 2500° C and aluminum diffusivity in silicon carbide SiC is 3×10^{-14} to 6×10^{-12} cm²/second at a temperature greater than 1200° C using conventional doping techniques. The process of laser doping of the present invention increases nitrogen diffusivity in silicon carbide SiC between 2×10^{-5} and 9×10^{-6} cm²/sec and increases

aluminum diffusivity in silicon carbide SiC between 1×10^{-5} and 1×10^{-6} cm²/sec. The process of laser doping of the present invention enables the use of new species of dopants including chromium (Cr), europium (Eu) and selenium (Se) with wide bandgap substrates.

Laser doping, a non-equilibrium process, enables achievement of very high dopant concentrations at the surface, which can exceed the solubility limit. Z. Tian, N. R. Quick and A. Kar, *Acta Materialia*, 54, 4273, (2006) have shown that laser doping enhances the diffusion coefficient of aluminum and nitrogen in SiC by about six orders of magnitude when compared to conventional doping techniques. It readily facilitates the formation of dopant concentration gradients along the depth of the wafer, i.e., the concentration decreases gradually along the depth. A linearly graded junction can be obtained that further facilitates the effective electron-hole recombination within the depletion region for light emitting applications, E. Fred Schubert, "Light Emitting Diodes", Cambridge University Press, (2003).

A PHI Adept 1010 Dynamic Secondary Ion Mass Spectroscopy system (SIMS) was used to determine the dopant concentration and its variation along the depth for the p and n regions of the device. An aluminum-doped SiC standard (1×10^{19} cm⁻³), Cr-implanted SiC standard (1×10^{20} cm⁻³), N-doped SiC standard (5×10^{18} cm⁻³), as received 4H-SiC (p-type) and an as-received 6H-SiC (n-type) (5×10^{18} cm⁻³) were also analyzed for reference and background concentrations

FIG. 7 is a graph of concentration of the dopants Cr, N and Al as a function of depth within a 6H-SiC silicon carbide wide bandgap substrate 20. In case of a 6H-SiC silicon carbide wide bandgap substrate 20, a very high concentration of about 2×10^{20} cm⁻³ was measured for Al at the surface decreasing gradually to 1×10^{18} cm⁻³ to a depth of 700 nm, while a concentration of 1×10^{19} cm⁻³ was measured for Cr at the surface decreasing gradually to the background concentration of 1×10^{17} cm⁻³ at a depth of 420 nm. The penetration depth of Al is much larger than that of Cr due to the size effect of these elements. Aluminum is much smaller than Cr and slightly smaller than Si and it can penetrate SiC easily and occupy the available Si vacancies. For Cr occupancy of Si vacancies the penetration is accompanied by lattice strain. Additionally, the solid solubility limits in SiC for Al (2×10^{21} cm⁻³) is much higher than Cr (3×10^{17} cm⁻³) G. L. Harris, "Properties of silicon carbide", IEE Inspec publication, emis data review series 13, (1995).

The concentration of Cr at the surface is about two orders of magnitude higher than the solid solubility limit, while for aluminum it is very close to the solubility limit.

FIG. 8 is a graph of concentration of the dopants Cr, N and Al as a function of depth within a 4H-SiC silicon carbide wide bandgap substrate 20. In case of a 4H-SiC silicon carbide

wide bandgap substrate 20, a very high concentration of approximately $1 \times 10^{21} \text{ cm}^{-3}$ was obtained for N at the surface decreasing gradually to $3 \times 10^{17} \text{ cm}^{-3}$ to a depth of 8.5 μm , while a concentration of $1.5 \times 10^{19} \text{ cm}^{-3}$ was obtained for Cr at the surface decreasing gradually to the background concentration of $1 \times 10^{15} \text{ cm}^{-3}$ at a depth of 80 nm. The penetration depth of N is much larger than that of Cr, which results from the atomic radius difference. The smaller nitrogen atom can penetrate SiC easily and occupy the available C or Si vacancies. Also, the solid solubility limits in SiC for N ($6 \times 10^{20} \text{ cm}^{-3}$) is much higher than Cr ($3 \times 10^{17} \text{ cm}^{-3}$). These dopant concentration levels and their penetration depths can be altered easily by modifying the doping parameters. Laser doping thus provides this advantage and is compatible with both conventional (e.g., Al, N) and unconventional (e.g., Cr) dopants.

Light Emitting Device

FIG. 9A is a side sectional view of a first example of a light emitting device 10G fabricated on 6H:SiC (n-type) substrate 20G by doping with aluminum and chromium. The substrate 20G defines a first and a second side 21G and 22G and a peripheral edge 23G. A first and a second Ohmic contact 61G and 62G are electrically connected to the first and second side 21G and 22G of the substrate 20G.

Table 2 sets forth the parameters for the fabrication of the light emitting device 10G of FIG. 9A. It should be appreciated by those skilled in the art that Table 2 is a specific example and that numerous other parameters may be used to fabricate light emitting devices having different characteristics.

TABLE 2

Sample	Color Contribution in LEDs	Dopant	Power (W)	Pulse repetition rate (KHz)	Focal Length (mm)	Spot size (μm)	# of passes	Scanning speed (mm/sec)	Dopant medium
6H:SiC n-type	White, Green	Cr	11.6	4	150	65	1	0.8	Bis (ethyl benzene)-chromium, argon 30 psi
	White, Blue	Al	11.5-12	5	150	65	2	0.5	Trimethyl aluminum, Methane 30psi

FIG. 9B is a graph of light intensity as a function of wavelength for the light emitting device 10G of FIG. 9A. The graph of FIG. 9B illustrates the distribution of light intensity, in arbitrary units, as a function of frequency for the light emitting device 10G of FIG. 9A. The sum of the distribution of light intensity from the light emitting device 10G results in a white light. The white light emission is created by laser doping with aluminum and chromium. A broad EL spectrum starting from 400 nm (band gap of 6H-SiC) to 900 nm covering the entire visible spectrum is observed. The red luminescence results from a nitrogen excitation and other defect states luminescence. The green and blue luminescence result from donor-acceptor pair recombination between N-Cr and N-Al, respectively. This red-green-blue (RGB) combination produces an observed broadband white light.

Current LED technology has shortcomings with matching color rendering index and color temperature of sunlight. The color rendering index (CRI) (sometimes called Color Rendition Index), is a measure of the ability of a light source to reproduce the colors of various objects being lit by the source. It is a method devised by the International Commission on Illumination (CIE). The human eye has receptors for short (S), middle (M), and long (L) wavelengths, also known as blue, green, and red receptors. That means that one, in principle, needs three parameters to describe a color sensation. A specific method for associating three numbers (or tristimulus values) with each color is called a color space, of which the CIE XYZ color space is one of many such spaces. However, the CIE XYZ color space is special, because it is based on direct measurements of the human eye, and serves as the basis from which many other color spaces are defined.

In the CIE XYZ color space, the tristimulus values are not the S, M, and L stimuli of the human eye, but rather a set of tristimulus values called X, Y, and Z, which are also roughly red, green and blue, respectively. Two light sources may be made up of different mixtures of various colors, and yet have the same color (metamerism). If two light sources have the same apparent color, then they will have the same tristimulus values, no matter what different mixtures of light were used to produce them.

"Visible light" is commonly described by color temperature. A traditional incandescent light source's color temperature is determined by comparing its hue with a theoretical, heated black-body radiator. An incandescent light is very close to being a black-body radiator. However, many other light sources, such as fluorescent lamps, do not emit radiation in the form of a black-body curve, and are assigned what is known as a correlated color temperature (CCT), which is the color temperature of a black body which most closely matches the lamp's perceived color.

Because such an approximation is not required for incandescent light, the CCT for an incandescent light is simply its unadjusted Kelvin value, derived from the comparison to a heated black-body radiator. Bright midday sun is 5200 K and average daylight, and electronic flash, is 5500K.

The color rendering index of the white light emitting diode as per the 1931 CIE chromaticity at 2 degree on 6H-SiC (n-type-N) wafer substrate laser doped with aluminum and chromium has the following tristimulus values; $X = 0.3362$, $Y = 0.3424$ and $Z = 0.3214$ which confirms white color space. These values render a color temperature of 5338 K which is very close to the incandescent lamp (or black body) and lies between bright midday sun (5200 K) and average daylight (5500 K)

FIG. 10A is a side sectional view of a first example of a light emitting device 10H fabricated on 4H:SiC (p-type) substrate 20H by doping with a with nitrogen and chromium. The substrate 20H defines a first and a second side 21H and 22H and a peripheral edge 23H. A first and a second Ohmic contact 61H and 62H are electrically connected to the first and second side 21H and 22H of the substrate 20H.

Table 3 sets forth the parameters for the fabrication of the light emitting device 10H of FIG. 10A. It should be appreciated by those skilled in the art that Table 3 is a specific example and that numerous other parameters may be used to fabricate light emitting devices having different characteristics.

TABLE 3

Sample	Color Contribution in LEDs	Dopant	Power (W)	Pulse repetition rate (KHz)	Focal Length (mm)	Spot size (μm)	# of passes	Scanning speed (mm/sec)	Dopant medium
4H:SiC	White	N	12	5	150	80	3	0.8	Ultra high pure nitrogen 30psi
p-type	White, Orange-Red	Cr	12.5-13	5	150	65	1	0.5	Bis (ethyl benzene)-chromium, argon 30 psi

FIG. 10B is a graph of light intensity as a function of wavelength for the light emitting device 10H of FIG. 10A. The graph of FIG. 10B illustrates the distribution of light intensity as a

function of frequency for the light emitting device 10H of FIG. 10A. The sum of the distribution of light intensity of the light emitting device 10H results in a white light. White light emission is created by laser doping with both nitrogen and chromium. A broad spectrum extending from 380 nm (band gap of 4H-SiC) to 850 nm is observed. Green and blue wavelengths are observed due to the occurrence of radiative recombination transitions between donor-acceptors pairs of N-Cr and N-Al respectively, while prominent violet wavelength was observed due to nitrogen-valence band level transitions. The red luminescence was mainly due to nitrogen exciton and other defect levels. This red-green-blue (RGB) combination produces an observed broadband white light. The color rendering index for this white light emitting diode as per the 1931 CIE chromaticity at 2 degree has the following tristimulus values; X = 0.3322, Y = 0.3320 and Z = 0.3358. The color temperature is 5510 K which is very close to average daylight (5500 K)

FIG. 11A is a side sectional view of a first example of a light emitting device 10I fabricated on 4H:SiC (p-type) substrate 20I by doping with chromium. The substrate 20I defines a first and a second side 21I and 22I and a peripheral edge 23I. A first and a second Ohmic contact 61I and 62I are electrically connected to the first and second side 21I and 22I of the substrate 20I.

Table 4 sets forth the parameters for the fabrication of the light emitting device 10I of FIG. 11A. It should be appreciated by those skilled in the art that Table 4 is a specific example and that numerous other parameters may be used to fabricate light emitting devices having different characteristics.

TABLE 4

Sample	Color Contribution in LEDs	Dopant	Power (W)	Pulse repetition rate (KHz)	Focal Length (mm)	Spot size (μm)	# of passes	Scanning speed (mm/sec)	Dopant medium
4H:SiC p-type	White, Orange-Red	Cr	12.5-13	5	150	65	1	0.5	Bis (ethyl benzene)-chromium, argon 30 psi

FIG. 11B is a graph of light intensity as a function of wavelength for the light emitting device 10I of FIG. 11A. The graph of FIG. 11B illustrates the distribution of light intensity as a function of frequency for the light emitting device 10I of FIG. 11A. The sum of the distribution of light intensity of the light emitting device 10I results in an orange-red light.

FIG. 12A is a side sectional view of a first example of a light emitting device 10J fabricated on 6H:SiC (n-type) substrate 20J by doping with chromium. The substrate 20J defines a first and a second side 21J and 22J and a peripheral edge 23J. A first and a second Ohmic contact 61J and 62J are electrically connected to the first and second side 21J and 22J of the substrate 20J.

Table 5 sets forth the parameters for the fabrication of the light emitting device 10J of FIG. 12A. It should be appreciated by those skilled in the art that Table 5 is a specific example and that numerous other parameters may be used to fabricate light emitting devices having different characteristics.

TABLE 5

Sample	Color Contribution in LEDs	Dopant	Power (W)	Pulse repetition rate (KHz)	Focal Length (mm)	Spot size (μm)	# of passes	Scanning speed (mm/sec)	Dopant medium
6H:SiC n-type	White, Green	Cr	11.6	4	150	65	1	0.8	Bis (ethyl benzene)-chromium, argon 30 psi

FIG. 12B is a graph of light intensity as a function of wavelength for the light emitting device 10J of FIG. 12A. The graph of FIG. 12B illustrates the distribution of light intensity as a function of frequency for the light emitting device 10J of FIG. 12A. The sum of the distribution of light intensity of the light emitting device 10J results in a green light.

FIG. 13A is a side sectional view of a first example of a light emitting device 10K fabricated on 4H:SiC (n-type) substrate 20K by doping with chromium. The substrate 20K defines a first and a second side 21K and 22K and a peripheral edge 23K. A first and a second Ohmic contact 61K and 62K are electrically connected to the first and second side 21K and 22K of the substrate 20K.

Table 6 sets forth the parameters for the fabrication of the light emitting device 10K of FIG. 13A. It should be appreciated by those skilled in the art that Table 6 is a specific example and that numerous other parameters may be used to fabricate light emitting devices having different characteristics.

TABLE 6

Sample	Color Contribution in LEDs	Dopant	Power (W)	Pulse repetition rate (KHz)	Focal Length (mm)	Spot size (μm)	# of passes	Scanning speed (mm/sec)	Dopant medium
4H:SiC n-type	White, Red, Green, Violet	Cr	12	5	150	65	2	0.5	Bis (ethyl benzene)-chromium, argon 30 psi

FIG. 13B is a graph of light intensity as a function of wavelength for the light emitting device 10K of FIG. 13A. The graph of FIG. 13B illustrates the distribution of light intensity as a function of frequency for the light emitting device 10K of FIG. 13A. The sum of the distribution of light intensity of the light emitting device 10K results in a red light.

FIG. 14A is a side sectional view of a first example of a light emitting device 10L fabricated on 6H:SiC (n-type) substrate 20L by doping with aluminum. The substrate 20L defines a first and a second side 21L and 22L and a peripheral edge 23L. A first and a second Ohmic contact 61L and 62L are electrically connected to the first and second side 21L and 22L of the substrate 20L.

Table 7 sets forth the parameters for the fabrication of the light emitting device 10L of FIG. 14A. It should be appreciated by those skilled in the art that Table 7 is a specific example and that numerous other parameters may be used to fabricate light emitting devices having different characteristics.

TABLE 7

Sample	Color Contribution in LEDs	Dopant	Power (W)	Pulse repetition rate (KHz)	Focal Length (mm)	Spot size (μm)	# of passes	Scanning speed (mm/sec)	Dopant medium
6H:SiC n-type	White, Blue	Al	11.5-12	5	150	65	2	0.5	Trimethyl aluminum, Methane 30psi

FIG. 14B is a graph of light intensity as a function of wavelength for the light emitting device 10L of FIG. 14A. The graph of FIG. 14B illustrates the distribution of light intensity as a function of frequency for the light emitting device 10L of FIG. 14A. The sum of the distribution of light intensity of the light emitting device 10L results in a white light.

FIG. 15A is a side sectional view of a first example of a light emitting device 10M

fabricated on 6H:SiC (n-type) substrate 20M by doping with boron. The substrate 20M defines a first and a second side 21M and 22M and a peripheral edge 2M. A first and a second Ohmic contact 61M and 62M are electrically connected to the first and second side 21M and 22M of the substrate 20M.

5 Table 8 sets forth the parameters for the fabrication of the light emitting device 10M of FIG. 15A. It should be appreciated by those skilled in the art that Table 8 is specific example and that numerous other parameters may be used to fabricate light emitting devices having different characteristics.

TABLE 8

10

Sample	Color Contribution in LEDs	Dopant	Power (W)	Pulse repetition rate (KHz)	Focal Length (mm)	Spot size (μm)	# of passes	Scanning speed (mm/sec)	Dopant medium
6H:SiC	Blue- Green	B	10.5	CW	150	100	1	0.8	Boron Powder, argon 30 psi
n-type	Blue-Green	B	12	5	150	80	2	0.8	Drive in, Argon 30 psi

FIG. 15B is a graph of light intensity as a function of wavelength for the light emitting device 10M of FIG. 15A. The graph of FIG. 15B illustrates the distribution of light intensity as a function of frequency for the light emitting device 10M of FIG. 15A. The sum of the distribution of light intensity of the light emitting device 10M results in a blue-green light.

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Photovoltaic Device

FIG. 16 is a graph of is a graph of operational temperature as a function of band gap for various solid sate devices. Silicon carbide devices can operate at temperatures exceeding 650 °C [D. K. Sengupta, N. R. Quick and A. Kar, Journal of Laser Applications, pp. 21-26 (2001).] which makes the material attractive as a thermoelectric device [P. M. Martin, "Thin film technology: thermoelectric Energy Conversion 2: Thin film materials", Vacuum Technology & Coating, pg. 8-13, (2007) and Y. Aoki et. al., "Study of Silicon Carbide Thermoelectric Materials made by SPS for MHD Power System", 34th AIAA Plasma dynamics and Lasers Conference, 23-26 June, Orlando, FL, (2003)]. Wide bandgap semiconductor p-n junction devices have potential for operating temperatures greater than 3000 °C.

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An optical device with p and n regions can produce electric current when light or electromagnetic radiation is irradiated on the device. These devices are called photovoltaic cells. The photovoltaic device is fabricated using the same processing and p-n junction structure as our white SiC light emitting diode (LED). The laser doping technology can be used to create any semiconductor structure including transistor structures to create photovoltaic devices.

The p and n regions of the photovoltaic device were fabricated by laser doping a n-type 6H-SiC (as-received nitrogen concentration of $5 \times 10^{18} \text{ cm}^{-3}$) and p-type 4H-SiC (Al doped) (as received aluminum concentration $1 \times 10^{19} \text{ cm}^{-3}$) wafer substrates with respective dopants. Cr and Al were used as p-type dopants while N was used as n-type dopant. A Q-switched Nd:YAG pulse laser (1064 nm wavelength) was used to carry out the doping experiments. The experimental parameters for laser doping of Cr and N were: power 11-13 W, frequency 5-10 kHz for a spot size of 85-150 μm at a scan speed of 0.5-0.8 mm/s.

For n-type doping the sample was placed in a nitrogen atmosphere at pressure of 30 psi and laser-doped regions were formed on the sample surface by moving the chamber with a stepper motor-controlled translation stage. The height of the chamber was controlled manually through an intermediate stage to obtain different laser spot sizes on the SiC substrate. For p-type doping, TMA (trimethylaluminum, $(\text{CH}_3)_3\text{Al}$) and Bis (ethyl benzene)-chromium were used. TMA was heated in a bubbler source immersed in a water bath maintained at 70°C until it evaporated and then a carrier gas, argon, was passed through the bubbler to transport the TMA vapor to the laser doping chamber. Similarly, for chromium doping Bis (ethyl benzene)-chromium was heated in a bubbler source immersed in a water bath maintained at 100°C until it evaporated and then a carrier gas, argon, was passed through the bubbler to transport the ethyl benzene chromium vapor to the laser doping chamber. These dopant gas species decompose at the laser-heated substrate surface producing Al and Cr atoms, which subsequently diffuse into the substrate.

Since crystalline SiC is chemically inert and has good thermo-mechanical properties at high temperatures, photovoltaic cells made of p-n regions in SiC can be located at the walls of combustion chambers to directly convert radiative energy into electrical energy; particularly in power plants. Burning fuels and the resultant flames produce electromagnetic radiation in the ultraviolet (UV), visible and infrared regions of the spectrum. The combustion chamber is modified to contain stacks of SiC photovoltaic cells so that each stack can absorb the radiation of a selected wavelength range to directly produce electricity.

Aluminum and Nickel were deposited on p and n regions respectively on the samples prior to photocurrent measurements to serve as contacts. Contacts can also be laser synthesized producing stable carbon rich conductors that can tolerate high temperatures beyond the capability of conventional materials such as Al and Ni.

5 FIG. 17 is a side sectional view of a solid state photovoltaic device 10N fabricated on 6H:SiC (n-type) substrate by doping with aluminum and chromium. The substrate 20N defines a first and a second side 21N and 22N and a peripheral edge 23N. A first and a second Ohmic contact 61N and 62N are electrically connected to the first and second side 21N and 22N of the substrate 20N. The solid state photovoltaic device 10N produces an electric current between the
10 first and second Ohmic contacts 61N and 62N upon receiving electromagnetic radiation as indicated by the ammeter 72 N.

Photocurrent measurements were conducted using a Keithley pico-ammeter/voltage source Model 6487 was used for carrying out the current measurements, while an Agilent digital multimeter Model 34401A was used for measuring the voltages and the resistances. The
15 light source was a 50W tungsten filament lamp.

With no visible light sources a background voltage and current existed in the SiC samples at room temperature (23°C). Irradiation from a 50W tungsten filament light source produced a greater than 220% voltage boost and a greater than 4350% current output boost in the laser doped 4H-SiC device. A greater than 540% voltage boost and a greater than 1250%
20 current output boost was observed in the laser doped 6H-SiC device.

The mechanism for the observed photocurrent SiC is as follows. When a broadband source of light impinges on the doped SiC structure, the photons with different energies are absorbed, which creates electron hole pairs in the valence band. The photons with energies higher than the band gap of the substrate causes the electron to excite from the valence band (or
25 from impurity levels created by dopants Cr, Al, N) to the conduction band (or same impurity levels). The electron flows through the contact wires generate current and the corresponding voltage.

The photovoltaic device can be laser doped with select dopants or combination of dopants to absorb energy from the complete electromagnetic spectrum. The photovoltaic
30 device can be laser doped with select dopants or combination of dopants to select or filter the range of electromagnetic spectrum energy absorbed using the same laser doping methods described for the LED wavelength emission selectivity.

FIG. 18 illustrates the solid-state energy device 105 of the present invention located in a

building structure 108. The building structure 108 includes a plurality of windows 110 including windows 111 and 112. The window 111 is mounted between window support 113 and 114 whereas window 112 is mounted between window supports 115 and 116. In this example, the solid-state energy device 105 is incorporated into a solid-state energy device 105A located in window 111 as well as a solid-state energy device 105B located in window 112. Although the building structure 108 has been shown as a multi-story building structure, it should be understood that the solid-state energy device 105 maybe any type of building structure.

FIG. 19 is an enlarged sectional view along line 19-19 in FIG. 18 illustrating the window 111. The window 111 comprises an insulating substrate 120A formed from insulating material 124A. A wide bandgap material 130A is formed within the insulating material 124A of the insulating substrate 120A. As will be described in greater detail hereinafter, the solid-state energy device 105A of the present invention is formed within the wide bandgap material 130A of the insulating substrate 120A. In this example, solid-state energy device 105A is a photovoltaic energy device for converting electromagnetic radiation as indicated by the sinusoidal arrows into electrical power as indicated by the ammeter 118.

FIG. 20 is an enlarged sectional view along line 20-20 in FIG. 18 illustrating the window 112. The window 112 comprises an insulating substrate 120B formed from insulating material 124B. A wide bandgap material 130B is formed within the insulating material 124B of the insulating substrate 120B. As will be described in greater detail hereinafter, the solid-state energy device 105B of the present invention is formed within the wide bandgap material 130B of the insulating substrate 120B. In this example, solid state energy device 105B is a light emitting device for converting electrical power as indicate by the battery 119 into electromagnetic radiation as indicated by the sinusoidal arrows.

FIG. 21 is a magnified view of a portion of FIG. 19 illustrating in greater detail the solid-state photovoltaic energy device 105A. The insulating material 124A of the window 111 extends between a first surface 121A and a second surface 122A. The wide bandgap material 130A is formed within the insulating material 124A and extends between a first surface 131A and a second surface 132A. Preferably, the first surface 131A of the wide bandgap material 130A is coincident with the first surface 121A of the insulating material 114A of the window 111A.

The solid-state photovoltaic energy device 105A is contained entirely within the wide bandgap material 130A of the insulating substrate 120A. The solid-state photovoltaic energy device 105A comprises a first conductor 141A formed in the wide bandgap material 130A. A first type wide bandgap semiconductor material 150A is formed within the wide bandgap material

130A and in contact with the first conductor 141A. The first type wide bandgap semiconductor material 150A forms an Ohmic contact with the first conductor 141A.

A second type wide bandgap semiconductor material 160A is formed within the wide bandgap material 130A and in contact with the first type wide bandgap semiconductor material 150A. The first type wide bandgap semiconductor material 150A forms a solid-state junction 163A with the second type wide bandgap semiconductor material 160A. A second conductor 142A is formed in electrical contact with the second type wide bandgap semiconductor material 150A. The second type wide bandgap semiconductor material 160A forms an Ohmic contact with the second conductor 142A. The solid-state photovoltaic energy device 105A provides electrical power between the first and second conductors 141A and 142A as indicated by the ammeter 118 upon impingement of electromagnetic radiation as indicated by the sinusoidal arrows.

FIG. 22 is a magnified view of a portion of FIG. 20 illustrating in greater detail the solid-state photovoltaic energy device 105B. The solid-state photovoltaic energy device 105B comprises a first conductor 141B formed in the wide bandgap material 130B. A first type wide bandgap semiconductor material 150B is formed within the wide bandgap material 130B and in contact with the first conductor 141B. The first type wide bandgap semiconductor material 150B forms an Ohmic contact with the first conductor 141B.

A second type wide bandgap semiconductor material 160B is formed within the wide bandgap material 130B and in contact with the first type wide bandgap semiconductor material 150B. The first type wide bandgap semiconductor material 150B forms a solid-state junction 163B with the second type wide bandgap semiconductor material 160B. A second conductor 142B is formed in electrical contact with the second type wide bandgap semiconductor material 160B. The second type wide bandgap semiconductor material 160B forms an Ohmic contact with the second conductor 142B. The solid-state photovoltaic energy device 105B emits electromagnetic radiation as indicated by the sinusoidal arrows when electrical power is applied between the first and second conductors 141B and 142B as indicated by the battery 119.

FIG. 23 is a magnified view similar to FIGS. 21 and 22 illustrating an insulating substrate 120C incorporating the solid-state photovoltaic energy device 105A of FIG. 21 as well as the solid-state photovoltaic energy device 105B of FIG. 22. It should be appreciated by those skilled in the art that the solid-state photovoltaic energy device 105A and the solid-state light emitting energy device 105B maybe located in various configurations within the insulating substrate 120C.

FIG. 24 is a view similar to FIG. 21 illustrating a solid-state photovoltaic energy device

105C incorporating a diode 164A. The insulating material 124A of the window 111 extends between a first surface 121A and a second surface 122A with the wide bandgap material 130A extending between a first surface 131A and a second surface 132A. The solid-state photovoltaic energy device 105A comprises a first type wide bandgap semiconductor material 150A in contact
5 with the first conductor 141A. The second type wide bandgap semiconductor material 160A forms a solid-state junction 163A with the first type wide bandgap semiconductor material 150A. A second conductor 142A is in electrical contact with the second type wide bandgap semiconductor material 150A.

The diode 164A comprises a third type wide bandgap semiconductor material 165A in
10 contact with the second conductor 142A. A fourth type wide bandgap semiconductor material 166A forms a solid-state junction 167A with the third type wide bandgap semiconductor material 165A. A third conductor 143A is in electrical contact with the fourth type wide bandgap semiconductor material 166A.

The diode 164A is connected in series with the solid-state photovoltaic energy device
15 105A to prevent reverse current flow through the solid-state photovoltaic energy device 105A. The diode 164A prevents discharge of a load such a battery (not shown) through the solid-state photovoltaic energy device 105A upon a reduced voltage output of the solid-state photovoltaic energy device 105A.

FIG. 25 is a block diagram of the process 170 of making the energy conversion device
20 105 of the present invention. The process 170 of making the energy conversion device 105 is applicable to the process 170 of making the solid-state photovoltaic energy device 105A and the process 170 of making the solid-state light emitting energy device 105B.

FIG. 26 illustrates the sequence of forming the energy conversion device 105 in
accordance with the process 170 illustrated in the block diagram of FIG. 25. The process 170
25 comprises the process step 171 of providing a substrate 120 of an insulating material 124 having the first surface 121 and the second surface 122.

The process 170 includes the process step 172 of applying a wide bandgap forming
doping gas 172G to the substrate 120. The process step 172 further includes concentrating a
thermal energy beam 172EB inside of the substrate 120 for converting a region of the insulating
30 material 124 between the first and second surfaces 121 and 122 into the wide bandgap semiconductor material 130. Preferably, the thermal energy 172EB is concentrated by focusing the energy beam between the first and second surfaces 121 and 122 of the substrate 120. In this example, the thermal energy is shown as a laser beam focused by a lens 172L between the first

and second surfaces 121 and 122 of the substrate 120. In the event the substrate 120 is originally provided as a wide bandgap semiconductor material, then the process step 172 is unnecessary as should be apparent to those skilled in the art.

5 The process 170 includes the process step 173 of concentrating a first conductor forming thermal energy 173EB inside of the substrate 120 to form a first conductor 141 between the first and second surfaces 131 and 132 of the wide bandgap semiconductor material 130.

10 The process 170 includes the process step 174 of applying a first type semiconductor doping gas 174G to the substrate 120. The process step 174 further includes concentrating a first type semiconductor forming thermal energy 174EB inside of the substrate 120 to form a first type wide bandgap semiconductor material 150 between the first and second surfaces 131 and 132 of the wide bandgap semiconductor material 130 and in electrical contact with the first conductor 141.

15 The process 170 includes the process step 175 of applying a second type semiconductor doping gas 175G to the substrate 120. The process step 175 further includes concentrating a second type semiconductor forming thermal energy 175EB inside of the substrate 120 to form a second type wide bandgap semiconductor material 160 between the first and second surfaces 121 and 122 of the wide bandgap semiconductor material 130 and in electrical contact with the first wide type bandgap semiconductor material 150.

20 The process 170 includes the process step 176 of concentrating a second conductor forming thermal energy 176EB on the first surface 121 of the substrate 120 to form a second conductor 142 in electrical contact with the second type wide bandgap semiconductor material 160.

25 FIG. 27 is a magnified view of a completed photovoltaic energy conversion device 105A of the present invention formed in accordance with the process of FIGS. 25-26. The wide bandgap semiconductor material 130A within the substrate 120A is converted to form the photovoltaic energy conversion device 105A. The photovoltaic energy conversion device 105A is contained completed between the first and second surfaces 121A and 122A of the substrate 120A.

30 FIG. 28 is a magnified view of a completed light emitting energy conversion device 105B of the present invention formed in accordance with the process of FIGS. 25-26. The wide bandgap semiconductor material 130B within the substrate 120B is converted to form the light emitting energy conversion device 105B. The light emitting energy conversion device 105B is contained completed between the first and second surfaces 121B and 122B of the substrate 120B.

FIG. 29 is a view similar to FIG. 27 illustrating a completed photovoltaic energy conversion device 105A incorporating the diode 164A formed in accordance with the process of FIGS. 25-26. The wide bandgap semiconductor material 130A within the substrate 120A is converted to form the photovoltaic energy conversion device 105A and the diode 164A. The photovoltaic energy conversion device 105A the diode 164A are contained completed between the first and second surfaces 121A and 122A of the substrate 120A.

FIG. 30 illustrates a portion of a first example of an apparatus 180 for fabricating the energy conversion device 105 of the present invention. The apparatus 180 illustrates only a first and a second chamber 181A and 181B for accomplishing the process steps 172 and 173 shown in FIGS. 25 and 26. However, it should be understood that the apparatus 180 includes similar chambers for accomplishing the remaining process steps 174-176 shown in FIGS. 25 and 26.

The first chamber 181A comprises a chamber input 182A and a chamber output 183A with a window 184A communicating with a chamber interior 185A. Plural input gas ports 186A are provided for enabling introduction of the wide bandgap doping gas 172G into the chamber interior 185A. An input gas curtain 187A and an output gas curtain 188A retard the outflow of the wide bandgap doping gas 172G from the chamber interior 185A.

In this embodiment, a first and a second thermal energy beam 172EB1 and 172EB2 are directed through the window 184A onto the substrate 120. In a first mode of operation, the first and second thermal energy beams 172EB1 and 172EB2 are directed onto the substrate 120 to intersect between the first and second surfaces 121 and 122 of the substrate 120. The intersecting first and second thermal energy beams 172EB1 and 172EB2 provide heat between the first and second surfaces 121 and 122 of the substrate 120 as the substrate 120 moves through the first chamber 181A. Heat provided by the first and second thermal energy beams 172EB1 and 172EB2 in the presence of the wide bandgap doping gas 172G within the chamber interior 185A converts the insulating material 124 of the substrate into the wide bandgap semiconductor material 130.

In a second mode of operation, the first and second thermal energy beams 172EB1 and 172EB2 are directed onto the substrate 120 to intersect between the first and second surfaces 121 and 122 of the substrate 120. The first thermal energy beam 172EB1 provides heat within the substrate 120 as the substrate 120 moves through the first chamber 181A. Heat provided by the first thermal energy beam 172EB1 in the presence of the wide bandgap doping gas 172G within the chamber interior 185A converts the insulating material 124 of the substrate into the wide bandgap semiconductor material 130. The second thermal energy beam 172EB2 is used for

energizing the dopants to active states. An optional interrogation laser may be added for materials property interrogation and process control as will be explained hereinafter with reference to the second chamber 181B.

The second chamber 181B is similar in design and operation as the first chamber 181A.
5 The second chamber 181B comprises a chamber input 182B and a chamber output 183B with a window 184B communicating with a chamber interior 185B. Plural input gas ports 186B are provided for enabling introduction of a gas into the chamber interior 185B. An input gas curtain 187B and an output gas curtain 188B retard the outflow of any gas from the chamber interior 185B.

10 In this example, the thermal energy beam 173EB is a laser beam focused between the first and second surfaces 121 and 122 of the substrate 120 by the lens 173L. Heat provided by the thermal energy beam 173EB within the chamber interior 185B converts the wide bandgap semiconductor material 130 into the first conductor 141 as the substrate moves through the second chamber 181B. Typically a doping gas is not used for converting the wide bandgap
15 semiconductor material 130 into the first conductor 141.

An optional interrogation laser 173IB has been added for materials property interrogation and process control of the thermal energy beam 173EB based on the properties of the first conductor 141 during the formation thereof.

Preferably, the interrogation laser 173IB is a Helium-Neon (He-Ne) laser having a
20 wavelength of 632.5 nm. The interrogation laser 173IB is able to measure processed material composition before, during and after doping and conductor synthesis process. The interrogation laser 173IB is able to measure the refractive index of the interrogated material. Changes in the refractive index of the interrogated material are feed back through a control 189C to control the operation of the thermal energy beam 173EB. The use of the interrogation laser 173IB enables
25 larges substrate areas to be processed with very uniform properties after the conversion process. It should be understood that the interrogation laser 173IB may be added to any of the stages shown in FIGS. 30 and 31.

FIG. 31 illustrates a portion of a second example of an apparatus 190 for fabricating the energy conversion device 105 of the present invention. The apparatus 190 illustrates only a first
30 and a second chamber 191A and 191B for accomplishing the process steps 172 and 173 shown in FIGS. 25 and 26. However, it should be understood that the apparatus 190 includes similar chambers for accomplishing the remaining process steps 174-176 shown in FIGS. 25 and 26.

The first chamber 191A comprises a chamber input 192A and a chamber output 193A

with an aperture 194A communicating with a chamber interior 195A. An annular input gas port 196A surrounds the aperture 194A for introducing the wide bandgap doping gas 172G into the chamber interior 195A. An annular output gas port 198A surrounds the annular input gas port 196A for recovering excess bandgap doping gas 177 from the chamber interior 195A.

5 A thermal energy beam 172EB is directed through the aperture 194A to be concentrated between the first and second surfaces 121 and 122 of the substrate 120. In this example, the thermal energy beam 172EB is focused by the lens (not shown) between the first and second surfaces 121 and 122 of the substrate 120. The focused laser beams 172EB impinges upon the substrate 120 as the substrate 120 as the chamber 191A move relative to the substrate 120. Heat
10 provided by the thermal energy beam 172EB in the presence of the wide bandgap doping gas 172G within the chamber interior 195A converts the insulating material 124 of the substrate into the wide bandgap semiconductor material 130. The laser beam can be focused to small diameters using lenses or can be expanded by using beam expanders for large area irradiation. Furthermore, the laser beam can be scanned across the substrate 120. The laser beam can be a pulsed at a
15 specific location on the substrate 120.

The second chamber 191B is similar in design and operation as the first chamber 191A. The second chamber 191B comprises a chamber input 192B and a chamber output 193B with an aperture 194B communicating with a chamber interior 195B. An annular input gas port 196B surrounds the aperture 194B for introducing any gas into the chamber interior 195B. An annular
20 output gas port 198A surrounds the annular input gas port 196A for recovering any excess gas from the chamber interior 195B. The thermal energy beam 173EB is focused through the aperture 194B to be concentrated between the first and second surfaces 121 and 122 of the substrate 120. The focused laser beam 173EB impinges upon the substrate 120. Heat provided by the thermal energy beam 173EB converts the wide bandgap semiconductor material 130 into
25 the first conductor 141 as the chamber 191B moves relative to the substrate 120. Typically a doping gas is not used for converting the wide bandgap semiconductor material 130 into the first conductor 141.

FIG. 32 illustrates a first specific example of the solid-state energy device 105C within an insulating substrate 120C having a first surface 121C and a second surface 122C. The insulating
30 substrate 120C is formed from an insulating glass material (SiO_2) 124C.

A wide bandgap forming doping gas selected from the group consisting of acetylene (C_2H_2), ethylene (C_2H_4) and methane (CH_4) is applied to the glass substrate (SiO_2) 120C. A wide bandgap forming thermal energy is concentrated inside of the substrate 120C for converting a

region of the insulating glass material (SiO_2) 124C between the first and second surfaces 121C and 122C into a silicon carbide material (SiC) 130C. The wide bandgap forming doping gas contributes carbon (C) to form the (SiC).

5 A first conductor forming thermal energy is concentrated inside the silicon carbide material (SiC) 130C to form a first conductor 141C within the silicon carbide material (SiC) 130C. The thermal energy concentrated inside the silicon carbide material (SiC) 130C dissociates the silicon atoms from the carbon atoms to enrich the carbon content of the silicon carbide material (SiC) 130C to form the first conductor 141C.

10 The first conductor 141C can range in composition from a carbon material (C) to a silicon (Si) - carbon (C) - oxygen (O) conductive material. A complete discussion of this enrichment process is set forth in U.S Patent 5,145,741 and U.S Patent 6,670,693 which are incorporated by reference into the present specification as if fully set forth herein.

15 A first type semiconductor forming doping gas selected from the group consisting of nitrogen (N_2) and diethyl selenium $(\text{C}_2\text{H}_5)_2\text{Se}$ is applied to the silicon carbide material (SiC) 130C. A first type semiconductor forming thermal energy is concentrated inside of the silicon carbide material (SiC) 130C to form an N-type silicon carbide semiconductor material (N - SiC) 150C within the silicon carbide wide material (SiC) 130C and in Ohmic contact with the first conductor 141C.

20 A second type semiconductor forming doping gas selected from the group consisting of trimethyl aluminum $(\text{CH}_3)_3\text{Al}$ and Bis (ethyl-benzene)-chromium $(\text{C}_{16}\text{H}_{20}\text{Cr})$ is applied to silicon carbide material (SiC) 130C. A second type semiconductor thermal energy is concentrated inside of the silicon carbide material (SiC) 130C to form a P-type silicon carbide semiconductor material (P - SiC) 160C within the silicon carbide wide bandgap material (SiC) 130C forming a P-N junction the N-type silicon carbide semiconductor material (N - SiC) 150C.

25 A second conductor forming thermal energy is concentrated inside the silicon carbide material (SiC) 130C to form a second conductor 142C in Ohmic contact with the P-type silicon carbide semiconductor material (P - SiC) 160C. The thermal energy concentrated inside the silicon carbide material (SiC) 130C enriches the carbon content of the silicon carbide material (SiC) 130C to form the second conductor 142C. The second conductor 142C is formed in a
30 manner similar to the first conductor 141C.

Table 9 set forth representative processing parameters for converting the silicon carbide (SiC) 124C to a white light emitting SiC region.

TABLE 9

Process	Laser Source	Power (W)	Pulse repetition rate (KHz)	Pulse Energy (mJ/pulse)	Fluence (J/cm ²)	Spot size (μm)	# of passes/shots	Scanning speed (mm/sec)	Gas Environment
SiO ₂ conversion to SiC	CO ₂ 9300 nm wavelength	-	-	-	<1.6x10 ⁴	-	-	-	Methane 30 psi
Conductor Synthesis	Nd:YAG 532 nm wavelength	-	2-10	3.15	-	-	1	20	Ambient
Doping (P-type)	Cr Nd:YAG 1064 nm wavelength	11.6	4	-	-	65	1	0.8	Bis (ethyl benzene)-chromium, argon 30 psi
(P-type)	Al Nd:YAG 1064 nm wavelength	11.5-12	5	-	-	65	2	0.5	Trimethyl aluminum, 30psi
(N-type)	N ArF Excimer 193 nm wavelength	-	10	200	0.556	-	1	-	N ₂ 30 psi

FIG. 33 illustrates a second specific example of the solid-state energy device 105D within an insulating substrate 120D having a first surface 121D and a second surface 122D. The insulating substrate 120D is formed from an insulating ceramic material such as aluminum oxide commonly known alumina (Al₂O₃) 124D.

A wide bandgap forming doping gas is applied to the alumina (Al₂O₃) 124D to convert a portion of the alumina (Al₂O₃) 124D into a wide bandgap aluminum nitride material (AlN). In

one example, a first carbon source gas to remove oxygen and a second nitrogen source doping gas are applied to the alumina (Al_2O_3) 124D. The first carbon source gas is selected from the group consisting of methane (CH_4), acetylene (C_2H_2) and ethylene (C_2H_4). Preferably, the second nitrogen source doping gas is nitrogen (N_2).

5 A wide bandgap forming thermal energy is concentrated inside of the substrate 120D for converting a region of the alumina material (Al_2O_3) 124D into a wide bandgap material aluminum nitride (AlN) 130D. The first carbon source gas applied to the alumina (Al_2O_3) 124D removes oxygen (O) from the alumina (Al_2O_3) 124D and produces carbon oxide, CO or CO_2 . The second nitrogen source doping gas donates nitrogen to the oxygen deficient alumina (Al_2O_3)
10 124D to form the wide bandgap aluminum nitride material (AlN) 130D. The first carbon source gas and the second nitrogen source doping gas may be applied serially or simultaneously to the alumina (Al_2O_3) 124D.

A first conductor forming thermal energy is concentrated inside the insulating substrate 120D to form a first conductor 141D within the aluminum nitride material (AlN) 130D. The
15 thermal energy concentrated inside the aluminum nitride (AlN) 130D dissociates the nitrogen atoms from the aluminum atoms to enrich the aluminum content of the aluminum nitride material (AlN) 130D to form the first conductor 141D. The first conductor 141D can range in composition from an aluminum conductive material (Al) to an aluminum (Al) - nitrogen (N)-oxygen (O) conductive material. A complete discussion of this enrichment process is set forth in
20 U.S Patent 5,145,741 and U.S Patent 6,670,693 which are incorporated by reference into the present specification as if fully set forth herein.

A first type semiconductor forming doping gas selected from the group consisting of and oxygen (O_2) and silane (SiH_4), for providing silicon, is applied to the substrate 120D.

A first type semiconductor forming thermal energy is concentrated inside of the substrate
25 120 to form an N-type aluminum nitride semiconductor material (N - AlN) 150D within the wide bandgap aluminum nitride material (AlN) 130 between the first and second surfaces of the substrate 120D. The N-type aluminum nitride semiconductor material (N - AlN) 150D is formed in Ohmic contact with the first conductor 141D.

A second type semiconductor forming doping gas selected from the group consisting of
30 ethylene (C_2H_4), methane (CH_4), acetylene (C_2H_2), for providing carbon, and Bis-magnesium dihydrate [$\text{Mg}(\text{TMHD})_2$], for providing magnesium, is applied to the substrate 120D.

A second type semiconductor thermal energy is concentrated inside of the substrate 120 to form a P-type aluminum nitride semiconductor material (P - AlN) 160D within the wide bandgap

aluminum nitride material (AlN) 130D between the first and second surfaces 121D and 122D of the substrate 120D. The P-type aluminum nitride semiconductor material (P - AlN) 160D forms a P-N junction with the N-type aluminum nitride semiconductor material (N - ALN) 150D.

A second conductor forming thermal energy is concentrated on the substrate 120D to form a second conductor 142D in Ohmic contact with the P-type aluminum nitride semiconductor material (P - AlN) 160D. The second conductor 142D is formed in a manner similar to the first conductor 141D.

Table 10 set forth representative processing parameters for converting the alumina material (Al₂O₃) 124D to an aluminum nitride material (AlN) 130D direct energy conversion region.

TABLE 10

Process	Laser Source	Power (W)	Pulse repetition rate (KHz)	Peak Pulse Intensity (W/cm)	Pulse Energy (mJ)	Fluence (J/cm ²)	Spot size (μm)	# of passes/shots	Scanning speed (mm/sec)	Gas Environment
AL ₂ O ₃ conversion to AlN	Nd:YAG 1064 nm wavelength	-	-	-	-	<750	-	-	-	Methane + N ₂ 30 psi
Conductor Synthesis	Nd:YAG 1064 nm wavelength	-	2-10	-	8.05	-	-	1	2	Ambient
Doping										
Si (N-type)	Nd:YAG 532 nm wavelength	15	4	-	-	-	300	1	0.9	Silane 30 psi
Mg (P-type)	Nd:YAG 532 nm wavelength	15	4.2	-	-	-	300	1	0.9	Mg(TMHD) ₂ 30psi

FIG. 34 illustrates an energy conversion device 105E. In this example, the photovoltaic

energy conversion device 105A of the present invention is coupled to a wave guide 200A. A one-piece insulating substrate 120A has a first and a second surface 121A and 122A. The photovoltaic device 105A is formed within the one-piece insulating substrate 120A between the first and second surfaces 121A and 122A.

5 A transparent wave guide 200A is defined between a first and a second surface 201A and 202A. The transparent wave guide 200A may be formed from various materials such as glass materials, polymeric materials or any other type of suitable material. The second surface 202A of the transparent wave guide 200A is bonded to the first surface 121A the one-piece insulating substrate 120A. Preferably, the transparent wave guide 100A is bonded to the first surface 121A
10 of the insulating substrate 120A by a laser fusion process or any other suitable means. A reflecting material 203A is affixed to the second surface 202A of the transparent wave guide 200A.

The transparent wave guide 200A acts as a concentrator for directing electromagnetic radiation into the photovoltaic energy device 105A formed within the one-piece insulating
15 substrate 120A. The transparent wave guide 200A effectively increases the surface area of the photovoltaic energy device 105A thus increasing the electric power of the photovoltaic energy device 105A.

FIG. 35 illustrates an energy conversion device 105F. In this example, the light emitting energy device 105B of the present invention is coupled to a wave guide 100B. A one-piece
20 insulating substrate 120B has a first and a second surface 121B and 122B. The light emitting energy device 105B is formed within the one-piece insulating substrate 120B between the first and second surfaces 121B and 122B.

A transparent wave guide 200B is defined between a first and a second surface 201B and 202B. The transparent wave guide 200B may be formed from various materials such as glass
25 materials, polymeric materials or any other type of suitable material. The second surface 202B of the transparent wave guide 200B is bonded to the first surface 121B the one-piece insulating substrate 120B. Preferably, the transparent wave guide 200B is bonded to the first surface 121B of the insulating substrate 120B by a laser fusion process or any other suitable means. A reflecting material 203B is affixed to the second surface 202B of the transparent wave guide
30 200B.

The transparent wave guide 200B acts as a diffuser for diffusing electromagnetic radiation from the light emitting energy device 105B formed within the one-piece insulating substrate 120B. The transparent wave guide 200B effectively increases the surface area of electromagnetic

radiation from the light emitting energy device 105B.

FIG. 36 illustrates a plurality of energy conversion devices 105G of the present invention located in a building structure 108G. The plurality of energy conversion devices 105G are shown located on the roof of the building structure 108G. The plurality of energy conversion devices 105G include the energy conversion devices 105G identified as units 111G and 112G. Each of the energy conversion devices 105G comprises a photovoltaic energy conversion device 105A in combination with a solar liquid heater 107G. The solar liquid heaters 107G of the plurality of energy conversion devices 105G are shown interconnected in a conventional manner for heating a liquid upon the impingement of electromagnetic radiation from the sun. Although the plurality of energy conversion devices 105G are shown mounted on the roof of the building structure 108G, it should be understood that the plurality of energy conversion devices 105G may be mounted in any appropriate location.

FIGS. 37 and 38 are more detailed views of the energy conversion device 105G and the solar liquid heater 107G of unit 111G. The energy conversion device 105G includes a frame support 210G comprising side supports 211G and 212G and end supports 213G and 214G. A back support 215G interconnects the side supports 211G and 212G and end supports 213G and 214G. Preferably, the back support 215G is made of an insulating material as best shown in FIG. 38.

The solar liquid heater 107G comprises a liquid conduit 220G extending between an input 221G and an output 222G. Preferably, the liquid conduit 220G is formed in a serpentine path and in thermal contact with a solar collector 225G. The inputs 221G and the outputs 222G enable a plurality of the solar liquid heater 107G to be interconnected as shown in FIG. 36. The solar collector 225G provides support for the liquid conduit 220G. In addition, the solar collector 225G provides an increased surface area for receiving and collecting solar electromagnetic radiation. The frame support 210G supports the solar collector 225G and the liquid conduit 220G within the side supports 211G and 212G and end supports 213G and 214G.

The energy conversion device 105G comprises an insulating substrate 120G formed from an insulating glass material 124G. The frame support 210G supports the insulating substrate 120G with the photovoltaic energy conversion device 105A disposed within the insulating glass material 120G. The insulating glass material 120G is spaced from the solar collector 225G creating an air space 230G.

A first wavelength of the electromagnetic radiation propagates through the glass substrate 120G to impinge upon the liquid conduit 220G and the solar collector 225G to heat the liquid

within the liquid conduit 220G. A second wavelength of the electromagnetic radiation is absorbed by the photovoltaic device 105A for generating electrical power.

Typically, the first wavelength of the electromagnetic radiation absorbed by the liquid conduit 220G and the solar collector 225G is in the-wavelength range of 750 nm- 10^6 nm. In the example, of the insulating substrate 120G formed from an insulating glass material 124G and a silicon carbide (SiC) photovoltaic energy conversion device 105G. The second wavelength of the electromagnetic radiation absorbed by the photovoltaic device 105A is in the wavelength range of 10^{-3} nm- 10^{12} nm.

FIG. 40 illustrates an energy conversion device 105H of the present invention in the form of a combined photovoltaic device 105A and a solar heater 107H for treating water. The energy conversion device 105H is similar to the energy conversion device 105G shown in FIGS. 36-38.

The energy conversion device 105H includes a frame support 210H comprising supports 211H-215H. The solar liquid heater 107H includes a liquid conduit 220H formed in a serpentine path extending between an input 221H and an output 222H. The liquid conduit 220H is in thermal contact with a solar collector 225H supported by the frame support 210H.

The energy conversion device 105H comprises an insulating substrate 120H formed from an insulating glass material 124H with the photovoltaic energy conversion device 105A disposed within the insulating glass material 120H. A first wavelength of the electromagnetic radiation propagates through the glass substrate 120H to impinge upon the liquid conduit 120H and the solar collector 125H to heat the water within the liquid conduit 120H. A second wavelength of the electromagnetic radiation is absorbed by the photovoltaic device 105A for generating electrical power.

The energy conversion device 105H comprises a water input 240H, a water output 250H and a water recirculator 260H. The energy conversion device 105H is controlled by a control 270H. The photovoltaic energy conversion device 105A charges a battery 280H for powering the control 270H. The water input 240H comprises an input conduit 241H connected to an input valve 243H in fluid communication with the input 221H of the liquid conduit 220H. An optional input pump 245H may be interposed in the input conduit 241H.

The water output 250H comprises an output conduit 251H connected to an input valve 253H in fluid communication with the output 222H of the liquid conduit 220H. A temperature sensor 255H is located for measuring the water exiting the output 222H of the liquid conduit 220H. An optional UV treatment stage 257H may be interposed in the output conduit 251H

The water recirculator 260H comprises conduits 261H and 262H interconnecting the

output valve 253H to the input valve 243H. A recirculating pump 263H is interposed between the conduits 261H and 262H.

Untreated water is directed into the input conduit 241H of the water input 240H. Preferably, the untreated water is passed through a conventional filter prior to entering input
5 conduit 241H. The optional pump 245H may be an electrically operated or a manually pump. In the alternative, the untreated water may flow by action of gravity into the input conduit 241H of the water input 240H.

Untreated water is heated within the liquid conduit 220H for heat treating the untreated water. The temperature sensor 255H measures the temperature of the water exiting the output
10 222H of the liquid conduit 220H. If the temperature of the water is sufficient to properly treat the water, the treated water is discharged from the output conduit 251H. An optional UV treatment stage 257H irradiates the treated water with ultraviolet radiation to further purify the water. The preferred UV radiation source is a wide bandgap material processed as disclosed herein and tuned to UV emission.

15 FIG. 40 illustrates the apparatus of FIG. 39 with the valves position to circulate the water. In the event the temperature of the water exiting the output 222H of the liquid conduit 220H, the control 270H actuates the input valve 243H, the output valve 253H and the recirculating pump 263H into the positions shown in FIG. 40. The water is recirculated through the liquid conduit 220H until the temperature of the water is sufficient to properly treat the water. Thereafter, the
20 control 270H actuates the input valve 243H, the output valve 253H into the positions shown in FIG. 39 and deactivates the recirculating pump 263H to discharge the treated water from the output conduit 251H.

Although the invention has been described in its preferred form with a certain degree of particularity, it is understood that the present disclosure of the preferred form has been made only
25 by way of example and that numerous changes in the details of construction and the combination and arrangement of parts may be resorted to without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. The process of making a solid state energy conversion device for converting energy between electromagnetic and electrical energy, comprising the steps of:
providing a wide bandgap semiconductor material having a first doped region;
applying a doping gas to the first doped region of the wide bandgap semiconductor material;
directing a thermal energy beam onto the first doped region of the wide bandgap semiconductor material in the presence of the doping gas for converting a portion of the first doped region into a second doped region in the wide bandgap semiconductor material; and
applying a first and a second Ohmic contact to the first and the second doped regions of the wide bandgap semiconductor material.
2. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step of providing a wide bandgap semiconductor material having a first doped region comprises providing a wide bandgap semiconductor material selected from the group consisting of silicon carbide, gallium nitride, aluminum nitride, diamond, diamond like carbon, boron nitride and gallium phosphide.
3. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step of providing a wide bandgap semiconductor material having a first doped region comprises providing a wide bandgap semiconductor material having a p-type doped region; and
the step of directing a thermal energy beam onto the first doped region of the wide bandgap semiconductor material in the presence of the doping gas comprises directing a thermal energy beam onto the p-type doped region of the wide bandgap semiconductor material in the presence of the doping gas for converting a portion of the p-type doped region into a n-type doped region in the wide bandgap semiconductor material.
4. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step of providing a wide bandgap semiconductor material having a first

doped region comprises providing a wide bandgap semiconductor material having a n-type doped region; and

the step of directing a thermal energy beam onto the first doped region of the wide bandgap semiconductor material in the presence of the doping gas comprises directing a thermal energy beam onto the n-type doped region of the wide bandgap semiconductor material in the presence of the doping gas for converting a portion of the n-type doped region into a p-type doped region in the wide bandgap semiconductor material.

5. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step of applying a doping gas to the first doped region of the wide bandgap semiconductor material comprises applying a doping gas selected from the group consisting of nitrogen, trimethylaluminum, Bis (ethyl benzene)-chromium, Europium 2,2,6,6, Tetramethyl 3,5, heptanedionate and diethyl selenium.
6. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step of applying a doping gas to the first doped region of the wide bandgap semiconductor material comprises using a dopant selected from the group comprised of nitrogen, aluminum, chromium, boron, europium, selenium, gallium, thulium, carbon, cobalt, erbium, magnesium and oxygen.
7. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step applying of a doping gas to the first doped region of the wide bandgap semiconductor material comprises applying a doping gas containing a dopant atom having a valence sufficiently greater than the valence of the wide bandgap semiconductor material to provide a multi-hole acceptor within the first doped region of the wide bandgap semiconductor material.
8. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step applying of a doping gas to the first doped region of the wide bandgap semiconductor material comprises applying a doping gas containing a dopant atom having a valence sufficiently less than the valence of the wide bandgap semiconductor material to provide a multi-electron donor within the first doped region of the wide

bandgap semiconductor material.

9. The process of making a solid state energy conversion device as set forth in claim 1, wherein the step of applying the first and second Ohmic contact comprises applying the first and second Ohmic contact selected from the group consisting of indium, aluminum and laser synthesized carbon rich conductor.
10. The process of making a solid state energy conversion device as set forth in claim 1, wherein the solid state energy conversion device produces electromagnetic radiation upon the application of electrical power to said first and second Ohmic contacts to operate as a light emitting device.
11. The process of making a solid state energy conversion device as set forth in claim 1, wherein the solid state energy conversion device produces electrical power between the first and second Ohmic contacts upon the application of electromagnetic radiation to operate as a photovoltaic device.
12. A solid state energy conversion device, comprising:
 - a wide bandgap semiconductor material having a first doped region;
 - a second doped region formed in situ within a portion of said first doped region by directing a thermal energy beam onto said first doped region in the presence of a doping gas for converting a portion of said first doped region into a second doped region; and
 - a first and a second Ohmic contact connected to said first and the second doped regions of said wide bandgap semiconductor material.
13. A solid state energy conversion device as set forth in claim 12, wherein the solid state energy conversion device operates as a light emitting device to produce electromagnetic radiation upon the application of electrical power to said first and second Ohmic contacts.
14. A solid state energy conversion device as set forth in claim 12, wherein the solid state energy conversion device operates as a photovoltaic device to produce electrical power

- between the first and second Ohmic contacts upon the application of electromagnetic radiation.
15. The process of making a solid state light emitting device in a substrate of a wide bandgap semiconductor material, comprising the steps of:
providing a wide bandgap semiconductor material having a first doped region;
applying a doping gas to the first doped region of the wide bandgap semiconductor material;
directing a thermal energy beam onto the first doped region of the wide bandgap semiconductor material in the presence of the doping gas for converting a portion of the first doped region into a second doped region in the wide bandgap semiconductor material; and
applying a first and a second Ohmic contact to the first and the second doped regions of the wide bandgap semiconductor material.
16. The process of making a solid state light emitting device as set forth in claim 15, wherein the solid state energy conversion device produces electromagnetic radiation upon the application of electrical power to said first and second Ohmic contacts to operate as a light emitting device having a color temperature that is between bright midday daylight and average daylight.
17. The process of making a solid state light emitting device as set forth in claim 15, wherein the solid state energy conversion device produces electromagnetic radiation upon the application of electrical power to said first and second Ohmic contacts to operate as a light emitting device having a color temperature that is between bright midday daylight and average daylight.
18. A solid state light emitting device, comprising:
a wide bandgap semiconductor material having a first doped region;
a second doped region formed in situ within a portion of said first doped region by directing a thermal energy beam onto said first doped region in the presence of a doping gas for converting a portion of said first doped region into a second doped region; and

- a first and a second Ohmic contact connected to said first and the second doped regions of said wide bandgap semiconductor material.
19. A solid state light emitting device as set forth in claim 18, wherein the solid state energy conversion device produces electromagnetic radiation upon the application of electrical power to said first and second Ohmic contacts to operate as a light emitting device having a color temperature that is between bright midday daylight and average daylight.
20. A solid state photovoltaic device, comprising:
a wide bandgap semiconductor material having a first doped region;
a second doped region formed in situ within a portion of said first doped region by directing a thermal energy beam onto said first doped region in the presence of a doping gas for converting a portion of said first doped region into a second doped region; and
a first and a second Ohmic contact connected to said first and the second doped regions of said wide bandgap semiconductor material.
21. The process for making a solid-state energy device from an insulating substrate, comprising the steps of:
providing a substrate of an insulating material having a first surface and a second surface;
converting a portion of the insulating material of the substrate into a first type wide bandgap semiconductor material;
converting an adjacent portion of the insulating material of the substrate into a second type wide bandgap semiconductor material in contact with the first type wide bandgap semiconductor material;
providing a first conductor in electrical contact with the first type wide bandgap semiconductor material; and
providing a second conductor in electrical contact with the second type wide bandgap semiconductor material.
22. The process for making a solid-state energy device as set forth in claim 21, wherein the

- solid-state energy device is a photovoltaic energy device for providing electrical power between the first and second conductors upon impingement of electromagnetic radiation.
23. The process for making a solid-state energy device as set forth in claim 21, wherein the solid-state energy device is a light emitting energy device for emitting electromagnetic radiation upon the application of electrical power between the first and second conductors.
24. The process for making a solid-state energy device as set forth in claim 21, wherein the step of converting the insulating material into the second type wide bandgap semiconductor material comprises converting the insulating material into the second type wide bandgap semiconductor material to form a P-N junction between the first and second type wide bandgap semiconductor materials.
25. The process for making a solid-state energy device as set forth in claim 21, wherein the step of providing the first conductor comprises forming a first conductor in Ohmic contact with the first type wide bandgap semiconductor material; and the step of providing the second conductor comprises forming a second conductor in Ohmic contact with the second type wide bandgap semiconductor material.
26. The process for making a solid-state energy device from an insulating substrate, comprising the steps of:
providing a substrate of an insulating material having a first surface and a second surface;
converting a region of the insulating material of the substrate into a wide bandgap semiconductor material;
forming a first conductor in the wide bandgap semiconductor material;
converting a first portion of the wide bandgap semiconductor material into a first type wide bandgap semiconductor material in contact with the first conductor;
converting a second portion of the wide bandgap semiconductor material into a second type wide bandgap semiconductor material in contact with the first wide bandgap semiconductor material; and

- forming a second conductor in contact with the second type wide bandgap semiconductor material.
27. The process for making a solid-state energy device as set forth in claim 26, wherein the step of providing a substrate of an insulating material comprises providing a substrate of an insulating material selected from the group consisting of silicon oxide (SiO_2) and alumina (Al_2O_3).
28. The process for making a solid-state energy device as set forth in claim 26, wherein the step of providing a substrate of the insulating material comprises providing a glass substrate (SiO_2);
the step of converting a region of the insulating material of the substrate into a wide bandgap semiconductor material comprising converting a region of the glass substrate (SiO_2) into silicon carbide (SiC);
the step of forming the first conductor comprises forming a carbon rich silicon carbide (SiC);
the step of converting the first portion of the wide bandgap semiconductor material into a first type wide bandgap semiconductor material comprises converting the first portion of the wide bandgap semiconductor material into a N-type silicon carbide material (SiC);
the step of converting the second portion of the wide bandgap semiconductor material into a second type wide bandgap semiconductor material comprises converting the second portion of the wide bandgap semiconductor material into a P-type silicon carbide material (SiC); and
the step of forming the second conductor comprises forming a carbon rich silicon carbide (SiC).
29. The process for making a solid-state energy device as set forth in claim 26, wherein the step of providing a substrate of the insulating material comprises providing a ceramic substrate (Al_2O_3);
the step of converting a region of the insulating material of the substrate into a wide bandgap semiconductor material comprising converting a region of the ceramic substrate (Al_2O_3) into aluminum nitride (AlN);

- the step of forming the first conductor comprises forming aluminum (Al);
- the step of converting the first portion of the wide bandgap semiconductor material into a first type wide bandgap semiconductor material comprises converting the first portion of the wide bandgap semiconductor material into N-type aluminum nitride (AlN);
- the step of converting the second portion of the wide bandgap semiconductor material into a second type wide bandgap semiconductor material comprises converting the second portion of the wide bandgap semiconductor material into a P-type aluminum nitride (AlN); and
- the step of forming the second conductor comprises forming aluminum (Al).
30. The process for making a solid-state energy device from an insulating substrate, comprising the steps of:
- providing a substrate of an insulating material having a first surface and a second surface;
- concentrating a first conductor forming thermal energy inside of the substrate to form a first conductor between the first and second surfaces of the substrate;
- concentrating a first type semiconductor forming thermal energy inside of the substrate to form a first type wide bandgap semiconductor material between the first and second surfaces of the substrate and in electrical contact with the first conductor;
- concentrating a second first type semiconductor forming thermal energy inside of the substrate to form a second type wide bandgap semiconductor material between the first and second surfaces of the substrate and adjacent to the second wide bandgap semiconductor material; and
- concentrating a second conductor forming thermal energy on the first surface of the substrate to form a second conductor in electrical contact with the second type wide bandgap semiconductor material.
31. The process for making a solid-state energy device as set forth in claim 30, wherein the steps of concentrating thermal energy includes focusing an energy beam between the first and second surfaces of the substrate.

32. The process for making a solid-state energy device as set forth in claim 30, wherein the steps of concentrating the thermal energy includes directing a plurality of intersecting energy beams between the first and second surfaces of the substrate.
33. The process for making a solid-state energy device as set forth in claim 30, wherein the thermal energy is a laser beam.
34. The process for making a solid-state energy device from an insulating substrate, comprising the steps of:
providing a substrate of an insulating material having a first surface and a second surface;
applying a wide bandgap forming doping gas to the substrate;
concentrating wide bandgap forming thermal energy inside of the substrate for converting a region of the insulating material between the first and second surfaces into a wide bandgap semiconductor material;
concentrating a first conductor forming thermal energy inside of the substrate to form a first conductor between the first and second surfaces of the substrate;
applying a first type semiconductor doping gas to the substrate;
concentrating a first type semiconductor forming thermal energy inside of the substrate to form a first type wide bandgap semiconductor material between the first and second surfaces of the substrate and adjacent to the first conductor;
applying a second type semiconductor doping gas to the substrate;
concentrating a second type semiconductor forming thermal energy inside of the substrate to form a second type wide bandgap semiconductor material between the first and second surfaces of the substrate and adjacent to the first type wide bandgap semiconductor material; and
concentrating a second conductor forming thermal energy on the first surface of the substrate to form a second conductor in electrical contact with the second type wide bandgap semiconductor material.
35. The process for making a solid-state energy device from an insulating glass substrate, comprising the steps of:
providing a substrate of an insulating glass material having a first surface and a second

surface;
converting a portion of the insulating glass material of the substrate into one of an N-type and a P-type silicon carbide wide bandgap semiconductor material;
converting an adjacent portion of the insulating glass material of the substrate into the other one of the N-type and the P-type silicon carbide wide bandgap semiconductor material and forming an electrical contact between the N-type and the P-type silicon carbide wide bandgap semiconductor materials;
providing a first conductor in electrical contact with one of the N-type and the P-type silicon carbide wide bandgap semiconductor materials; and
providing a second conductor in electrical contact with the other of the N-type and the P-type silicon carbide wide bandgap semiconductor materials.

36. The process for making a solid-state energy device from a glass substrate, comprising the steps of:
providing a substrate of a glass material having a first surface and a second surface;
applying a wide bandgap forming doping gas selected from the group consisting of acetylene, ethylene and methane to the glass substrate;
concentrating a wide bandgap forming thermal energy inside of the substrate for converting a region of the glass material between the first and second surfaces into a silicon carbide material;
concentrating a first conductor forming thermal energy inside of the substrate to form a first conductor within the silicon carbide material between the first and second surfaces of the substrate;
applying a first type semiconductor forming doping gas selected from the group consisting of nitrogen (N_2) and diethyl selenium ($(C_2H_5)_2Se$) to the substrate;
concentrating a first type semiconductor forming thermal energy inside of the substrate to form an N-type silicon carbide semiconductor material within the silicon carbide wide material between the first and second surfaces of the substrate and in electrical contact with the first conductor;
applying a second type semiconductor forming doping gas selected from the group consisting of trimethyl aluminum ($(CH_3)_3Al$) and Bis(ethylbenzene)-chromium ($C_{16}H_{20}Cr$) to the substrate;
concentrating a second type semiconductor thermal energy inside of the substrate to

form a P-type silicon carbide semiconductor material within the silicon carbide wide bandgap material between the first and second surfaces of the substrate and in electrical contact with the N-type silicon carbide semiconductor material; and

concentrating a second conductor forming thermal energy on the substrate to form a second conductor in electrical contact with the P-type silicon carbide semiconductor material.

37. The process for making a solid-state energy device from aluminum oxide ceramic substrate, comprising the steps of:
- providing a substrate of an aluminum oxide having a first surface and a second surface;
 - applying a carbon source to react with the oxide to form a carbon oxide for removing oxygen from the aluminum oxide;
 - applying a wide bandgap forming doping gas selected from the group consisting of nitrogen to the substrate;
 - concentrating a wide bandgap forming thermal energy inside of the substrate for converting a region of the aluminum oxide material between the first and second surfaces into an aluminum nitride material (AlN);
 - concentrating a first conductor forming thermal energy inside of the substrate to form a first conductor within the aluminum nitride material (AlN) between the first and second surfaces of the substrate;
 - applying a first type semiconductor forming doping gas selected from the group consisting of oxygen (O₂) and silane (SiH₄) to the substrate;
 - concentrating a first type semiconductor forming thermal energy inside of the substrate to form an N-type aluminum nitride semiconductor material within the aluminum nitride wide bandgap material between the first and second surfaces of the substrate and in electrical contact with the first conductor;
 - applying a second type semiconductor forming doping gas selected from the group consisting of methane (CH₄) and Bis-magnesium dihydrate [Mg(TMHD)₂] to the substrate;
 - concentrating a second type semiconductor thermal energy inside of the substrate to form a P-type aluminum nitride semiconductor material within the aluminum nitride bandgap material between the first and second surfaces of the substrate

- and in electrical contact with the N-type *aluminum nitride* semiconductor material semiconductor material; and
- concentrating a second conductor forming thermal energy on the substrate to form a second conductor in electrical contact with the P-type aluminum nitride semiconductor material.
38. A solid-state energy device, comprising:
- a substrate of an insulating material having a first surface and a second surface;
 - a first conductor located inside of the substrate between the first and second surfaces of the substrate;
 - a first type wide bandgap semiconductor material located inside of the substrate in contact with the first conductor;
 - a second type wide bandgap semiconductor material located inside of the substrate forming a junction with said first wide bandgap semiconductor material; and
 - a second conductor in contact with the second type wide bandgap semiconductor material.
39. A solid-state energy device as set forth in claim 38, wherein the solid-state energy device converts electromagnetic energy into electrical energy.
40. A solid-state energy device as set forth in claim 38, wherein the solid-state energy device converts electrical energy into electromagnetic energy.
41. A solid-state energy conversion device, comprising
- a one-piece insulating substrate; and
 - a photovoltaic device formed within said one-piece insulating substrate for enabling electromagnetic radiation propagating into said one-piece insulating substrate to impinge upon said photovoltaic device for generating electrical power.
42. A solid-state energy conversion device, comprising
- a one-piece insulating substrate; and
 - a light generating device formed within said one-piece insulating substrate for propagating electromagnetic radiation from said one-piece insulating substrate

to impinge upon the application of electrical power.

43. A solid-state energy conversion device, comprising
a one-piece insulating substrate; and
an energy conversion device formed within said one-piece insulating substrate for
converting energy between electromagnetic radiation and electrical power; and
a transparent wave guide affixed to said one-piece insulating substrate for directing
electromagnetic radiation relative to said energy conversion device formed
within said one-piece insulating substrate.
44. An energy device for heating a liquid and for generating electrical power upon the
impingement of electromagnetic energy, comprising:
a conduit for receiving the liquid;
a glass substrate;
a support for positioning said glass substrate adjacent to said conduit; and
a photovoltaic device disposed within said glass substrate for enabling a first
wavelength of the electromagnetic radiation to propagate through said glass
substrate to impinge upon said conduit to heat the liquid and for enabling a
second wavelength of the electromagnetic radiation be absorbed by said
photovoltaic device for generating electrical power.
45. An energy device for treating water and for generating electrical power upon the
impingement of electromagnetic energy, comprising:
a conduit for receiving untreated water;
a glass substrate;
a support for positioning said glass substrate adjacent to said conduit; and
a photovoltaic device disposed within said glass substrate for enabling a first
wavelength of the electromagnetic radiation to propagate through said glass
substrate to impinge upon said conduit to heat treat the untreated water and for
enabling a second wavelength of the electromagnetic radiation be absorbed by
said photovoltaic device for generating electrical power.