Method of Fabricating Solid State Gas Dissociating Device By Laser Doping

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A solid state energy conversion device and method of making is disclosed 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 thermal energy beam is directed onto the first doped region of the wide bandgap semiconductor material in the presence of a 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 one embodiment, 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 embodiment, 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 Claims, 13 Drawing Sheets
OTHER PUBLICATIONS


* cited by examiner
FIG. 1

FIG. 2
FIG. 5

FIG. 6

FIG. 7
Indium contact

Laser doped (Al and Cr)

6H:SiC (n-type)

Indium contact

FIG. 8A

6H:SiC (n-type) doped with Cr and Al

FIG. 8B
Indium contact

Laser doped (Cr)

6H:SiC (n-type)

Laser doped (N region)

Indium contact

FIG. 9A

4H:SiC (p-type) doped with Cr and N

FIG. 9B
Indium contact -- Laser doped (Cr region) -- 4H:SiC (P-type)

**FIG. 10A**

![Diagram of a device with labeled parts](image)

**FIG. 10B**

4H:SiC (Al-p-type) doped with Cr

![Graph showing intensity vs. wavelength](image)
Indium contact -- Laser doped (Al region) -- 6H:SiC (n-type) -- Indium contact

**FIG. 11A**

6H:SiC (n-type) doped with Cr

**FIG. 11B**
FIG. 12A

Indium contact

Laser doped (Cr region) -

4H:SiC (n-type)

20 K

FIG. 12B

4H:SiC (n-type) doped with Cr and Al

Intensity (arbitrary units)

Wavelength (nm)
FIG. 13A

6H:SiC (n-type) doped with Al

FIG. 13B
FIG. 14A

6H:SiC (n-type) doped with Br

FIG. 14B
Ohmic contact

Laser doped chemical catalyst region

Laser doped LED (p-type)

LED (n-type)

Ohmic contact

Laser doped element is both the chemical catalyst and p-type LED dopant

Ohmic contact
OPTICAL METER

High Voltage Power Line

LED Device

Light Emitted by LED

Power Meter

FIG. 19

TRANSFORMER

$V_1$ $N_1$

$V_2$ $N_2$

FIG. 20
1

METHOD OF FABRICATING SOLID STATE GAS DISSOCIATING DEVICE BY LASER DOPING

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of U.S. provisional application No. 60/994,161 filed Sep. 18, 2007. All subject matter set forth in provisional application No. 60/994,161 is hereby incorporated by reference into the present application as if fully set forth herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to solid state devices and more particularly to solid state devices for converting energy between electromagnetic and electrical energy such as light emitting device and photovoltaic device.

2. Background of the Invention

A variety of semiconductors including GaN (Gallium Nitride), GaP (Gallium Phosphide), AlGaN (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. 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.


U.S. Pat. No. 5,063,421 to Suzuki et al discloses a silicon carbide light emitting diode having a p-n junction which is doped with a dopant and ion implantation. Maximum dopant concentration is limited by the solubility 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 and is limited in SiC to nitrogen (N) or phosphorus (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 used for wide bandgap semiconductor devices. This process generates implantation-induced defect centers including amorphization 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].

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 5x1016 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 at a concentration of 5x1016 cm-3 or lower. 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. Pat. No. 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 thick-
ness at which internal absorption in said second layer would substantially reduce the light emitted from said top surface of the diode.

U.S. Pat. No. 6,900,465 to Nakamura et al. discloses a nitride semiconductor light-emitting device has 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. Pat. No. 6,998,690 to Nakamura et al. discloses a gallium nitride-based III-V Group compound semiconductor device has 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 of a metallic material, and has been annealed.

U.S. Pat. No. 7,045,375 to Wu et al. discloses a white-light emitting device comprising a first 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 AlGaNp. 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-rod of AlGaNp of same or different compositions.

Discussion of wide bandgap materials and the processing thereof are discussed in U.S. Pat. No. 5,145,741; U.S. Pat. No. 5,391,841; U.S. Pat. No. 5,793,042; U.S. Pat. No. 5,837,607; U.S. Pat. No. 6,025,609; U.S. Pat. No. 6,054,375; U.S. Pat. No. 6,271,576; U.S. Pat. No. 6,670,693, U.S. Pat. No. 6,930,009 and U.S. Pat. No. 6,939,748 are hereby incorporated by reference into the present application.

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

The following 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 modifying the invention within the scope of the invention. Accordingly other objects in a full understanding of the invention may be had by referring to the summary of the invention, the detailed description describing the preferred embodiment in addition to the scope of the invention defined by the claims taken in conjunction with the accompanying drawings.

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 solid state energy conversion device produces electromagnetic radiation. The solid state energy conversion device 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.

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

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 Ohmic contact is 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 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 of the claims 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 as set forth in the appended claims.

**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 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. 3B 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. 4A 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. 4B 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. 4C 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. 5 is a graph of conventional dopant diffusivity in SiC as a function of reciprocal temperature for conventional processing.

FIG. 6 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. 7 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. 8A 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. 8B is a graph of light intensity as a function of wavelength for the solid state light emitting device of FIG. 8A;

FIG. 9A is a side sectional view of a second example of a white light solid state emitting device fabricated on 4H-SiC (p-type) substrate by doping with nitrogen and chromium;
FIG. 9B is a graph of light intensity as a function of wave-length for the solid state light emitting device of FIG. 9A.

FIG. 10A 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. 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 fourth example of a green light solid state light emitting device fabricated on 6H:SiC (n-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 fifth example of a red 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 sixth example of a blue light solid state light emitting device fabricated on 6H:SiC (n-type) substrate by doping with aluminum;

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 seventh example of a blue-green solid state light emitting device fabricated on 6H:SiC (n-type) substrate by doping with boron; and

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

FIG. 15 is a graph of operational temperature as a function of band gap for various solid state devices;

FIG. 16 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. 17 is a first embodiment of a gas splitter of the present invention;

FIG. 18 is a second embodiment of a gas splitter of the present invention;

FIG. 19 illustrates an optical meter incorporating the present invention; and

FIG. 20 illustrates a transformer incorporating the present invention.

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

DETAILED DISCUSSION

FIG. 1 is a side view of an apparatus for forming a solid state energy conversion device 10 on a wide-bandgap semiconductor substrate 20. The wide-bandgap semiconductor substrate 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 side wall 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.

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 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.

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.

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 20 Nd:YAG laser 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 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 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.

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 for creating the solid state energy conversion device 10 of the present invention.
Properties of Parent Substrates for SiC Energy Conversion Device Fabrication

<table>
<thead>
<tr>
<th>Parent Substrate</th>
<th>Typical Resistivity (ohm-cm)</th>
<th>Principle Dopant</th>
<th>Typical principle dopant concentration (cc)</th>
<th>Notes:</th>
</tr>
</thead>
<tbody>
<tr>
<td>6H-SiC n-type</td>
<td>0.05</td>
<td>Nitrogen</td>
<td>10^{16}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a) acceptor impurities may be present</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) defects can behave as acceptors</td>
<td></td>
</tr>
<tr>
<td>6H-SiC p-type</td>
<td>0.1-0.2</td>
<td>Aluminum</td>
<td>10^{17}-10^{20}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a) Nitrogen (donor) impurities may be present.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) defects can behave as donors</td>
<td></td>
</tr>
<tr>
<td>6H-SiC semi-insulating</td>
<td>10^{5}-10^{11}</td>
<td>Vanadium</td>
<td>&lt;10^{14}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a) Vanadium can behave as a donor or acceptor.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) Vanadium can complex with defects creating local strains, which create local dipoles which behave as electron carriers.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>e) Nitrogen can be on the order of 10^{10}cc</td>
<td></td>
</tr>
<tr>
<td>4H-SiC n-type</td>
<td>0.044</td>
<td>Nitrogen</td>
<td>10^{16}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a) acceptor impurities may be present</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) defects can behave as acceptors</td>
<td></td>
</tr>
<tr>
<td>4H-SiC p-type</td>
<td>0.1-0.2</td>
<td>Aluminum</td>
<td>10^{17}-10^{20}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a) Nitrogen (donor) impurities may be present.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) point defects can behave as acceptors</td>
<td></td>
</tr>
</tbody>
</table>

Notes:

- a) acceptor impurities may be present
- b) defects can behave as acceptors
- c) Nitrogen can be on the order of 10^{10}cc
- d) Vanadium can behave as a donor or acceptor.
- e) Vanadium can complex with defects creating local strains, which create local dipoles which behave as electron carriers.
- f) Nitrogen can be on the order of 10^{10}cc

Wide bandgap semiconductors (WBGs) have been laser doped with both n- 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 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 laser-doped regions were formed on the 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, (CH3)3Al), Bis (ethyl benzene)-chromium and boron 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, 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 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 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 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 levels due to acceptor (holes) states in a chromium-doped 4H-SiC (n-type-N) 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 1.94 x 10^{19} cm^{-3} which is almost twice the average dopant concentration (-10^{18} 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 x 10^{19} 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 heptanediominate precursor vapor decomposes upon laser heating and is diffused into SiC substrate using the process described for Cr laser doping. Selenium derived from a diethylselenide precursor also behaves as a multi-electron donor.
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 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 is converted into a photon (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 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 transfer of electron-hole recombination between the conduction and valence bands with no additional momentum.

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 electron components in monolithic or thin film geometries.

FIG. 3A 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 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. 4A is a side sectional view of a fourth example of a solid state light emitting 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. 5 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 5x10^-15 cm^2/sec at a temperature greater than 2500°C, and aluminum diffusivity in silicon carbide SiC is 3x10^-14 to 6x10^-13 cm^2/sec 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 2x10^-15 and 9x10^-14 cm^2/sec and increases aluminum diffusivity in silicon carbide SiC between 1x10^-12 and 1x10^-11 cm^2/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...
13 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 (1x10^15 cm^-3), Cr-implanted SiC standard (1x10^16 cm^-3), N-doped SiC standard (5x10^16 cm^-3), as received 4H-SiC (p-type) and an as-received 6H-SiC (n-type) (5x10^18 cm^-3) were also analyzed for reference and background concentrations.

FIG. 6 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 2x10^20 cm^-3 was measured for Al at the surface decreasing gradually to 1x10^18 cm^-3 to a depth of 700 nm, while a concentration of 1x10^19 cm^-3 was measured for Cr at the surface decreasing gradually to the background concentration of 1x10^16 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 SiC vacancies the penetration is accompanied by lattice strain. Additionally, the solid solubility limits in SiC for Al (2x10^13 cm^-3) is much higher than Cr (3x10^11 cm^-3). G. L. Harris, "Properties of silicon carbide", IEE Inspect 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. 7 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 1x10^19 cm^-3 was obtained for N at the surface decreasing gradually to 3x10^17 cm^-3 to a depth of 8.5 µm, while a concentration of 1.5x10^19 cm^-3 was obtained for Cr at the surface decreasing gradually to the background concentration of 1x10^15 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 (6x10^20 cm^-3) is much higher than Cr (3x10^17 cm^-3), the 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.

Since crystalline SiC is chemically inert and has good thermo-mechanical properties at high temperatures, photovoltaic device made of p-n regions in SiC can be located at the walls of combustion chambers, particularly in power plants, to directly convert radiative energy, e.g., heat, into electrical energy. Burning fuels and the resultant flame 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.

Light Emitting Device

FIG. 8A 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. 8A. 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 in LEDs   | Dopant | Power (W) | Pulse repetition rate (KHz) | Focal Length (mm) | Spot size (µm) | Scanning speed (mm/sec) | Dopant medium |
| 6H:SiC n-type   | White, Green    | Cr     | 11.6      | 4                           | 150               | 65             | 1                            | 0.8            | Ba (ethyl benzene) - chromium, argon 30 psi |
|                 | White, Blue     | Al     | 11.5-12   | 5                           | 150               | 65             | 2                            | 0.5            | Trimethyl aluminum, Methane 30 psi |

FIG. 8B is a graph of light intensity as a function of wavelength for the light emitting device 10G of FIG. 8A. The graph of FIG. 8B illustrates the distribution of light intensity, in arbitrary units, as a function of frequency for the light emitting device 10G of FIG. 8A. The sum of the distribution of light intensity of 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 donor-acceptor pair recombination between N—Cr and N—Al, respectively. This red-green-blue (RGB) combination produces an observed broadband white light.
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 its 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 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. 9A is a side sectional view of a first example of a light emitting device 101 fabricated on 4H:SiC (p-type) substrate 201 by doping with chromium. The substrate 201 defines a first and a second side 211 and 221 and a peripheral edge 231. A first and a second Ohmic contact 611 and 621 are electrically connected to the first and second side 211 and 221 of the substrate 201.

Table 3 sets forth the parameters for the fabrication of the light emitting device 101 of FIG. 9A. 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>
<thead>
<tr>
<th>Sample</th>
<th>Color Contribution in LEDs</th>
<th>Dopant</th>
<th>Power (W)</th>
<th>Pulse repetition rate (KHz)</th>
<th>Focal Length (mm)</th>
<th>Spot size (µm)</th>
<th># of passes</th>
<th>Scanning speed (mm/sec)</th>
<th>Dopant medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>4H:SiC</td>
<td>White, Orange-Red</td>
<td>Cr</td>
<td>12.5-13</td>
<td>5</td>
<td>150</td>
<td>65</td>
<td>1</td>
<td>0.5</td>
<td>Bis (ethyl benzene)-chromium, argon 30 psi</td>
</tr>
</tbody>
</table>

FIG. 10A is a side sectional view of a first example of a light emitting device 101 fabricated on 4H:SiC (p-type) substrate 201 by doping with chromium. The substrate 201 defines a first and a second side 211 and 221 and a peripheral edge 231. A first and a second Ohmic contact 611 and 621 are electrically connected to the first and second side 211 and 221 of the substrate 201.

Table 4 sets forth the parameters for the fabrication of the light emitting device 101 of FIG. 10A. The graph of FIG. 10B is a graph of light intensity as a function of wavelength for the light emitting device 101 of FIG. 10A. The graph of FIG. 10B illustrates the distribution of light intensity as a function of frequency for the light emitting device 101 of FIG. 10A. The sum of the distribution of light intensity of the light emitting device 101 results in an orange-red light.

FIG. 11A is a side sectional view of a first example of a light emitting device 101 fabricated on 4H:SiC (n-type) substrate 201 by doping with chromium. The substrate 201 defines a first and a second side 211 and 221 and a peripheral edge 231. A first and a second Ohmic contacts 611 and 621 are electrically connected to the first and second side 211 and 221 of the substrate 201.

Table 5 sets forth the parameters for the fabrication of the light emitting device 101 of FIG. 11A. 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.
FIG. 11B is a graph of light intensity as a function of wavelength for the light emitting device 10J of FIG. 11A. The graph of FIG. 11B illustrates the distribution of light intensity as a function of frequency for the light emitting device 10J of FIG. 11A. The sum of the distribution of light intensity of the light emitting device 10J results in a green light.

FIG. 12A 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. 12A. 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.

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

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

FIG. 14A 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.

Table 8 sets forth the parameters for the fabrication of the light emitting device 10M of FIG. 11A. 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

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

Photovoltaic Device


An optical device with p and n regions can produce electric current when light or electromagnetic radiation is incident 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 5x1018 cm-3) and p-type 4H-SiC (Al doped) (as received aluminum concentration 1x1019 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, (CH3)3Al) 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.

FIG. 16 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 first and second Ohmic contacts 61N and 62N upon receiving electromagnetic radiation as indicated by the ammeter 72N.

Photocurrent measurements were conducted using a Keithley pic-o-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 light source was a 50 W 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 50 W tungsten filament light source produced a greater than 220% voltage boost and a greater than 15.
45350% current output boost in the laser doped 4H-SiC device. A greater than 540% voltage boost and a greater than 1250% current output boost was observed in the laser doped 6H-SiC device. The mechanism for the observed photocurrent SiC as is 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 excited from the valence band (or from impurity levels created by dopants Cr, Al, N) to the conduction band (or some 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 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.

FIGS. 17 and 18 illustrate a solid state device incorporated into a Gas Splitting Catalyst. The laser doped optical device can be used to create a light emitting device (LED) that activates catalysts that dissociate or split gases such as carbon dioxide. The laser doped optical device can also directly dissociate or directly or assist the splitting of gases by photocatalysis. Devices fabricated in wide bandgap semiconductors such as silicon carbide, gallium nitride, aluminum nitride, diamond and boron nitride can be inserted in high temperature environments allowing the high temperature to also contribute to gas dissociation or splitting. A principal application is the dissociation or splitting of carbon dioxide to alleviate global warming. The objective is the conversion of power generation, turbine and auto CO₂ emissions to CO and O₂ and further to C and O₂ for fuel and structural uses. Laser doping technology allows the combined use of photolysis, chemical catalysis, thermal catalysis and electrical catalysis to drive gas dissociation/splitting.

Prior art references include (1) Science Daily, Apr. 18, 2007: CO₂ splitting semiconductor/catalyst device under construction (gallium phosphate) at University of California San Diego. (Prof. Clifford Kubiak). The semiconductor is used as a solar cell to generate electricity. This system catalyzed is electrical plus chemical. (2) Chung-lei Zhang et al, “Splitting the decomposing carbon dioxide into carbon with oxygen deficient magnetite”, Materials Chemistry and Physics, Volume 62, Issue 1, Jan. 14, 2000, pgs. 52-61. This system is chemical plus thermal. (3) Bruce H. Mahan, Photolysis of Carbon Dioxide, Journal of Chemical Physics, 1960, pgs. 959-965). This system is photolysis.

Example 1

In an example a semiconductor region is first laser doped to create an LED tuned to emit in the electromagnetic spectrum range that dissociates CO₂ and activates chemical catalysts. The top of the semiconductor is laser doped with a chemical catalyst that dissociates CO₂. The semiconductor is preferably a wide bandgap semiconductor (WBGS) such as SiC. The semiconductor can be a porous membrane structure, thin film, fiber or fibrous media. The LED wavelength emission tuning dopants can include Al, Cr, Eu, Se, N and P. The chemical catalyst dopants can include Cr, Ti, Ni, Pd, Fe, and their oxides. The chemical dopants can also include precious metals including Pd and Pt. All dopant precursors for laser doping are preferably gases or metal-organics.

Example 2

In a further example silicon can be used as the substrate. The Silicon’s top region can be laser doped with the chemical catalysts. The Silicon’s bottom region can be converted to SiC by laser doping carbon into silicon. The SiC region is then laser doped to create the wavelength emitting tuned LED.

Example 3

Referring to Example 2 silicon may be converted to SiC during the dissociation of CO₂. Silicon acts a getter to capture carbon.

Example 4

In another example the laser doped WBGS (SiC) is used as an energy conversion device (ECD) to convert heat to electricity. The doping steps are the same as example 1. In this concept CO₂ splitting is electrical plus chemical. The device can be placed in hot exhausts such as produced by turbines are internal combustion engines.

Example 5

In a further example the LED region irradiation can be used solely to increase the activity of the catalyst. This allows the use of conventional wavelengths (248-10640 nm) which are readily available as opposed to the specific 147 nm defined in prior art for photolysis of CO₂. (Bruce H. Mahan, Photolysis of Carbon Dioxide, Journal of Chemical Physics, 1960, pgs. 959-965).

Example 6

In a further example laser doping can be used to enhance hole (positive charge carrier) concentration in the WBGS to chemically reduce CO₂. In effect the hole acts as a positive charged hydrogen atom (a proton). An energy conversion device created by laser doping will create the electrical bias.

FIG. 19 illustrates an optical voltmeter, an optical ammeter and/or an optical power meter. This device is a light-emitting diode (LED) that emits light of a particular wavelength when voltage is applied across the diode. The LED can be fabricated by laser doping silicon carbide (SiC) substrates with p-type and n-type dopants to certain depths of the substrate. The range of the voltage, current and power that can be measured with this device will depend on the dimensions of the parent substrate, its dopant concentrations (intrinsic, extrinsic or semi-insulating), and the type and amount of laser-doped dopants. Very high voltages (MV) and currents (hundreds of kAmp) can be measured with this device.

FIG. 20 illustrates a transformer utilizing the present invention. This device is based on the principle of step-down and step-up transformers having armatures with different number of windings of conductive wires. The device can be fabricated using the laser metallization process to create two conductive (laser-metallized) windings of different number of turns inside a SiC substrate.

\[ V_{AB} = \sqrt{\frac{P_R}{\eta}} \]

Where

\[ P_R = \text{Power of the output light from the LED device} \]

\[ \eta = \text{Efficiency of the LED device for converting the input power to output power} \]

\[ R = \text{Resistance of the LED device} \]

\[ V_{AB} = \text{Voltage of the power line between points A and B in FIG. 1} \]
The present disclosure includes that contained in the appended claims as well as that of the foregoing description. Although this 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 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. A method of fabricating a solid state gas dissociating/splitting device, comprising the steps:
   providing a wide bandgap semiconductor;
   laser doping a first region of the wide bandgap semiconductor material to create a light emitting region tuned in the electromagnetic spectrum range that dissociates carbon oxides and activates chemical catalysts; and
   laser doping a second region to create a chemical catalyst region that dissociates carbon oxides.

2. The method as set forth in claim 1, wherein the step of providing the wide bandgap semiconductor includes providing a wide bandgap semiconductor selected from the group consisting of silicon carbide, gallium nitride, aluminum nitride, boron nitride and diamond.

3. The method as set forth in claim 1, wherein the step of doping the first region includes doping with material selected from the group consisting of Al, Cr, Eu, Se, N, P and the step of doping the second region includes doping with material selected from the group consisting of Cr, Ti, Ni, Pd, Fe.

4. The method as set forth in claim 1, wherein the step of doping the first region includes doping a lower region; and the step of doping the second region includes doping an upper region.

5. The method as set forth in claim 1, wherein the step of doping the first region includes doping with material selected from the group consisting of Al, Cr, Eu, Se, N, P, and the step of doping the second region includes doping with material selected from the group consisting of Cr, Ti, Ni, Pd, Fe.

6. The method as set forth in claim 1, wherein the step of doping the second region includes doping with materials selected from the group consisting of Cr, Ti, Ni, Pd, Fe.

7. The method as set forth in claim 1, wherein the step of doping the second region includes doping with material selected from the group consisting of Pd and Pt.

8. The method as set forth in claim 1, wherein the step of doping of a first and second regions includes doping with material selected from the group consisting of precious metals.

9. The method as set forth in claim 1, wherein the step of providing a wide bandgap semiconductor substrate includes a monolithic, thin film, fiber or fibrous media substrate.

10. A method of fabricating a solid state gas dissociating/splitting device, comprising the steps of:
   providing a non-wide bandgap semiconductor;
   laser doping a non-wide bandgap semiconductor material first region to create a wide bandgap semiconductor;
   laser doping the wide bandgap semiconductor to create light emitting second region tuned in the electromagnetic spectrum range that dissociates carbon oxides and activates chemical catalysts; and
   laser doping a second region to create a chemical catalyst region that dissociates carbon oxides.

11. The method as set forth in claim 10, wherein the step of providing the non-wide bandgap semiconductor includes providing a silicon semiconductor; and
   converting a portion of the silicon semiconductor to a silicon carbide wide bandgap semiconductor.

12. A method of fabricating a solid state gas dissociating/splitting device, comprising the steps of:
   providing a wide bandgap semiconductor;
   laser doping a first region of the wide bandgap semiconductor material to create a light emitting region tuned in the electromagnetic spectrum range that dissociates carbon oxides and activates chemical catalysts; and
   laser doping a second region to create a chemical catalyst region that dissociates carbon oxides.

13. A method of fabricating a solid state gas dissociating/splitting device, comprising the steps of:
   providing a wide bandgap semiconductor;
   laser doping a wide bandgap semiconductor to create a light emitting region tuned in the electromagnetic spectrum range that dissociates carbon oxides and activates chemical catalysts; and
   laser doping a second region to create a chemical catalyst region that dissociates carbon oxides.

14. A method of fabricating a solid state gas dissociating/splitting device, comprising the steps of:
   providing a non-wide bandgap semiconductor;
   laser doping a non-wide bandgap semiconductor material first region to create a wide bandgap semiconductor;
   laser doping the wide bandgap semiconductor to create light emitting second region tuned in the electromagnetic spectrum range that dissociates selected gases and activates chemical catalysts; and
   laser doping a second region to create a chemical catalyst region that dissociates selected gases.

15. A method of fabricating a solid state gas dissociating/splitting device, comprising the steps of:
   providing a wide bandgap semiconductor;
   laser doping a first region of the wide bandgap semiconductor material to create a light emitting region tuned in the electromagnetic spectrum range that dissociates selected gases and activates chemical catalysts; and
   laser doping a second region to create a chemical catalyst region that dissociates selected gases.