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United States Patent Application Publication	20250267984
Kind Code	A1
Publication Date	August 21, 2025
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SEMICONDUCTOR LIGHT-EMITTING DEVICE AND LIGHT-EMITTING APPARATUS HAVING THE SAME

Abstract

A semiconductor light-emitting device includes an n-type semiconductor layer, a light-emitting structure, a first electron blocking layer, a second electron blocking layer, and a p-type hole injection layer, which are sequentially stacked in such order. The light-emitting structure includes well layers and barrier layers which are stacked alternately. The first electron blocking layer contacts a last one of the barrier layers of the light-emitting structure and has an energy band gap (E.sub.g3) that is larger than an energy band gap (E.sub.g4) of the second electron blocking layer. The energy band gap (E.sub.g4) of the second electron blocking layer is larger than an energy band gap (E.sub.g2) of the barrier layers, and an energy band gap (E.sub.g5) of the p-type hole injection layer is smaller than the energy band gap (E.sub.g2) of the barrier layers.

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Family ID: **1000008616131**

Appl. No.: **19/196959**

Filed: **May 02, 2025**

Related U.S. Application Data

parent WO continuation-in-part PCT/CN2022/141499 20221223 PENDING child US 19196959

Publication Classification

Int. Cl.: **H10H20/81** (20250101); **H10H20/812** (20250101); **H10H20/816** (20250101)

U.S. Cl.:

CPC **H10H20/8215** (20250101); **H10H20/812** (20250101); **H10H20/8162** (20250101);

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application is a continuation-in-part (CIP) of International Application No. PCT/CN2022/141499, filed on Dec. 23, 2022, the entire disclosure of which is incorporated by reference herein.

FIELD
[0002] The disclosure relates to a semiconductor light-emitting device, and more particularly to a semiconductor light-emitting device and a light-emitting apparatus having the same.
BACKGROUND
[0003] A semiconductor light-emitting device is an inorganic semiconductor device, which emits light through the combination of electrons and holes. An ultraviolet (UV) light-emitting device emits UV light and is widely used in a variety of fields, e.g. curing the polymeric material, sterilization of medical equipment, a light source for generating white light, etc.
[0004] Optoelectronic performance of a conventional UV light-emitting device is directly related to characteristics of a light-emitting structure therein (e.g., quality of a quantum well, a doping concentration, an interface defect, a V-shaped groove, etc.). For example, a p-type dopant (e.g. magnesium) tends to diffuse into the quantum well under heat, thereby forming a deep level defect, which may impact relative luminance of the conventional UV light-emitting device in the aging process.
SUMMARY
[0005] Therefore, an object of the disclosure is to provide a semiconductor light-emitting device and a light-emitting apparatus having the same that can alleviate at least one of the drawbacks of the prior art.
[0006] According to one aspect of the disclosure, a semiconductor light-emitting device includes an n-type semiconductor layer, a light-emitting structure, a first electron blocking layer, a second electron blocking layer, and a p-type hole injection layer, which are sequentially stacked in such order. The light-emitting structure includes well layers and barrier layers, which are stacked alternately. The first electron blocking layer contacts a last one of the barrier layers of the light-emitting structure and has an energy band gap (E.sub.g3) that is larger than an energy band gap (E.sub.g4) of the second electron blocking layer. The energy band gap (E.sub.g4) of the second electron blocking layer is larger than an energy band gap (E.sub.g2) of each of the barrier layers, and an energy band gap (E.sub.g5) of the p-type hole injection layer is smaller than the energy band gap (E.sub.g2) of each of the barrier layers.
[0007] According to another aspect of the disclosure, a semiconductor light-emitting device includes a n-type semiconductor layer, a light-emitting structure, an electron blocking layer, and the p-type hole injection layer, which are stacked sequentially in such order. The light-emitting structure includes well layers and barrier layers which are alternatively stacked. An energy band gap of the electron blocking layer is larger than an energy band gap (E.sub.g2) of each of the barrier layers. The electron blocking layer has at least one V-shaped groove that extends into the light-emitting structure, and the p-type hole injection layer fills the at least one V-shaped groove. The p-type hole injection layer has an energy band gap (E.sub.g5) that is smaller than the energy band gap (E.sub.g2) of the barrier layers.

[0008] According to yet another aspect of the disclosure, a light-emitting apparatus includes any one of the aforesaid semiconductor light-emitting devices.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Other features and advantages of the disclosure will become apparent in the following detailed description of the embodiment(s) with reference to the accompanying drawings. It is noted that various features may not be drawn to scale.

[0010] FIG. **1** is a schematic view of an epitaxial laminate of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0011] FIG. **2** is a schematic view of a light-emitting structure of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0012] FIG. **3** is a schematic view of an epitaxial laminate of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0013] FIG. **4** is a schematic view of a light-emitting structure of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0014] FIG. **5** is fragmentary view illustrating energy band gaps of the epitaxial laminate shown in FIG. **3**.

[0015] FIG. **6** is a transmission electron microscope (TEM) image of the epitaxial laminate shown in FIG. **3**.

[0016] FIG. **7** is a schematic view of a light-emitting structure of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0017] FIG. **8** is a schematic view of a light-emitting structure of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0018] FIG. **9** is an energy-dispersive x-ray spectroscopy (EDX) spectrum of a light-emitting structure of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0019] FIG. **10** is a fragmentary view illustrating energy band gaps of the epitaxial laminate shown in FIG. **8**.

[0020] FIG. **11** is a schematic view of an embodiment of a semiconductor light-emitting device according to the present disclosure.

[0021] FIG. **12** shows scatter plots of light output power (LOP) versus wavelength of Sample **1** and Sample **2**.

DETAILED DESCRIPTION

[0022] Before the disclosure is described in greater detail, it should be noted that where considered appropriate, reference numerals or terminal portions of reference numerals have been repeated among the figures to indicate corresponding or analogous elements, which may optionally have similar characteristics.

[0023] It should be noted herein that for clarity of description, spatially relative terms such as “top,” “bottom,” “upper,” “lower,” “on,” “above,” “over,” “downwardly,” “upwardly” and the like may be used throughout the disclosure while making reference to the features as illustrated in the drawings. The features may be oriented differently (e.g., rotated 90 degrees or at other orientations) and the spatially relative terms used herein may be interpreted accordingly.

[0024] Composition and a dopant of each layer included in a semiconductor light-emitting device of the present disclosure may be analyzed by any proper instrument, such as secondary ion mass spectrometer (SIMS). A thickness of each layer included in the semiconductor light-emitting device of the present disclosure may be analyzed by any proper instrument, such as a transmission electron microscope (TEM), or a scanning electron microscope (SEM), which may be used with the SIMS.

[0025] Through SIMS or energy-dispersive x-ray spectroscopy (EDX) cooperating with TEM a ratio of contents of Group III elements (aluminum, indium, gallium, etc.) included in the semiconductor light-emitting device may be obtained. In addition, through the contents of aluminum and indium, an energy band gap may be predicted. If the aluminum content is larger than the indium content, the energy band gap is higher; if the indium content is larger than the aluminum content, the energy band gap is lower.

[0026] An embodiment of a light-emitting device of the present disclosure is a gallium nitride-based (GaN-based) semiconductor light-emitting device, but is not limited thereto. In some embodiments, the GaN-based semiconductor light-emitting device may have a lateral configuration, a vertical configuration, a flip-chip configuration, etc. FIG. **1** shows a schematic view of an epitaxial laminate of an embodiment of a semiconductor light-emitting device according to this disclosure. The epitaxial laminate of the semiconductor light-emitting device includes an n-type semiconductor layer **121**, a supper lattice layer **122**, a light-emitting structure **123**, an electron blocking layer **125**, and a p-type hole injection layer **126**, which are stacked sequentially from bottom to top in such order. The epitaxial laminate may be formed through a metal-organic chemical vapor deposition (MOCVD) method, a chemical vapor deposition (CVD) method, a plasma enhanced chemical vapor deposition method (PECVD) method, a molecular beam epitaxy (MBE) method, a hydride vapor phase epitaxy (HVPE) method, etc., but is not limited thereto. In addition, the semiconductor light-emitting device may include a substrate **110** for growing or supporting the abovementioned layers.

[0027] In some embodiments, the epitaxial laminate may be an AlGaInN-based semiconductor material. The n-type semiconductor layer **121** is configured for providing electrons to the light-emitting structure **123**, and is made of a semiconductor material having a chemical formula of In.sub.x1Al.sub.y1Ga.sub.1-x1-y1N, where $0 \leq x1 \leq 1$, $0 \leq y1 \leq 1$, $0 \leq x1+y1 \leq 1$, such as GaN, AlN, AlGaN, InGaN, InN, InAlGaN, AlInN, etc; an n-type dopant may be doped therein, such as Si, Ge, Sn, Se, Te, etc. In some embodiments where the semiconductor light-emitting device is an UV LED (light-emitting diode), the n-type semiconductor layer **121** may include AlGaN.

[0028] The supper lattice layer **122** is located between the n-type semiconductor layer **121** and the light-emitting structure **123**, and may have functions of adjusting stress and current spreading. The supper lattice layer **122** includes periodic units. Each of the periodic units includes at least two thin layers that are made of different materials. The different materials may be nitride-based semiconductor materials. In an embodiment, the supper lattice layer **122** includes periodic units each of which is AlGaN/GaN. In an embodiment, at least one of the periodic units includes a layered structure having a first sub-layer, a second sub-layer, and a third sub-layer, and may be InGaN/AlGaN/AlN, GaN/AlGaN/AlN or InGaN/GaN/AlN. The periodic units having a large energy band gap may regulate radiative recombination, thereby increasing recombination efficiency of the light-emitting structure **123** so as to improve luminance of the semiconductor light-emitting device. In addition, leakage, which is caused by holes or electrons obtaining additional energy under a high temperature, may be avoided, thereby improving luminance stability of the semiconductor light-emitting device at a high temperature with a hot/cold (H/C) factor being greater than 70%.

[0029] The light-emitting structure **123** is formed on the supper lattice layer **122**. The light-emitting structure **123** may be a single quantum well structure, one or more multiple quantum well structures, a quantum wire structure, a quantum dot structure, etc., and may be made of a Group III-V semiconductor material. In some embodiments, the light-emitting structure **123** may have a quantum well structure and be made of a material with a chemical formula of In.sub.x2Al.sub.y2Ga.sub.1-x2-y2N, where $0 \leq x2 \leq 1$, $0 \leq y2 \leq 1$, $0 \leq x2+y2 \leq 1$. The light-emitting structure **123** may have one or more multiple quantum well structures and include barrier layers **123**A, **123**D and well layers **123**B that are arranged between the barrier layers **123**A, **123**D. In some embodiments, the well layers **123**B and the barrier layers **123**A, **123**D may be stacked

alternatively, as illustrated in FIG. **2**. The number of the well layers **123**B and the number of the barrier layers **123**A, **123**D each may range from 3 to 8. Each of the well layers **123**B may be made of a material that has an energy band gap smaller than that of each of the barrier layers **123**A, **123**D; that is, an energy band gap (E.sub.g1) of each of the well layers **123**B is smaller than an energy band gap (E.sub.g2) of each of the barrier layers **123**A, **123**D. With an increase in an Al content of the well layers **123**B, the energy band gap and a lattice constant of the well layers **123**B increase. Therefore, light-emitting efficiency of the semiconductor light-emitting device would be improved and an emission wavelength of light emitted by the semiconductor light-emitting device would be reduced. In an embodiment, one of the well layers **123**B (i.e., the last one well layer) that is nearest to the p-type hole injection layer **126** in the light-emitting structure **123** has a p-type doping concentration equal to or smaller than 5×10.sup.17 atoms/cm.sup.3, and the remaining well layers **123**B each have a p-type doping concentration equal to or smaller than 1×10.sup.17 atoms/cm.sup.3. Controlling the p-type doping concentration of each of the well layers **123**B in the light-emitting structure **123**, especially the p-type doping concentration of the last one well layer **123**B, is beneficial to improve an anti-aging capability of the semiconductor light-emitting device. If the p-type doping concentration of the last one well layer **123**B is larger than 1×10.sup.18 atoms/cm.sup.3, long-term lumen depreciation of the semiconductor light-emitting device may occur early; in particular, severe lumen depreciation may occur in a large current condition.
[0030] The emission wavelength of the light emitted by the semiconductor light-emitting device may be determined by composition and a thickness of the light-emitting structure **123**. In some embodiments, a ratio of a thickness of each of the well layers **123**B to a thickness of each of the barrier layers **123**A ranges from 1:1.7 to 1:2. Therefore, the light emitted by the semiconductor light-emitting device has the emission wavelength ranging from 340 nm to 425 nm (i.e., UV light), and internal quantum efficiency of the semiconductor light-emitting device may be enhanced.
[0031] In some embodiments, the light-emitting structure **123** has a last one of the barrier layers **123**D (i.e., the last one barrier layer) that is adjacent to the electron blocking layer **125**. The last barrier layer **123**D has a thickness ranging from 3 nm to 40 nm. If the thickness of the last one barrier layer **123**D is smaller than 3 nm, current leakage may occur. The last barrier layer **123**D may include a material with a chemical formula of In.sub.jAl.sub.kGa.sub.(1-j-k)N, where 0≤j≤1, 0≤k≤1. In an embodiment, the last barrier layer **123**D and one of the remaining barrier layers **123**A have the same material. In some embodiments, the last barrier layer **123**D has a thickness smaller than that of one of the remaining barrier layers **123**A. In some embodiments, the thickness of the last one barrier layer **123**D is smaller than the thickness of each of the remaining barrier layers **123**A. In an embodiment, the last barrier layer **123**D has a p-type doping concentration that is equal to or smaller than 1×10.sup.18 atoms/cm.sup.3. Except for the last barrier layer **123**D, the barrier layers **123**A (i.e., the remaining barrier layers **123**A) each have a p-type doping concentration that is equal to or smaller than 1×10.sup.17 atoms/cm.sup.3. In certain embodiments, the last barrier layer **123**D has the p-type doping concentration that is equal to or smaller than 5×10.sup.17 atoms/cm.sup.3. Controlling the p-type doping concentration of each of the barrier layers **123**A, **123**D in the light-emitting structure **123**, especially the p-type doping concentration of the last barrier layer **123**D, is beneficial to improve the anti-aging capability of the semiconductor light-emitting device.
[0032] The electron blocking layer **125** is located between the light-emitting structure **123** and the p-type hole injection layer **126**, and includes a semiconductor material represented by In.sub.zAl.sub.wGa.sub.1-z-w, where 0≤z≤1, 0≤w≤1, 0≤z+w≤1, and has a lattice constant greater than that of the p-type hole injection layer **126**. In some embodiments where the semiconductor light-emitting device is a UV LED, the electron blocking layer **125** includes AlGaN. The electron blocking layer **125** may have an energy band gap that is larger than an energy band gap of the light-emitting structure **123**. When high current is applied to the semiconductor light-emitting device, the electron blocking layer **125** may prevent electrons, which are injected into the light-emitting

structure **123** from the n-type semiconductor layer **121**, from further flowing into the p-type hole injection layer **126**. Therefore, a probability of recombination of electrons and holes in the light-emitting structure **123** may increase, thereby preventing current leakage.

[0033] In some embodiments, the electron blocking layer **125** includes the semiconductor material represented by In.sub.zAl.sub.wGa.sub.1-z-wN, where 0≤z≤0.05, 0<w≤1. In certain embodiments, the electron blocking layer **125** has a p-type doping concentration that is equal to or smaller than 5×10.sup.19 atoms/cm.sup.3. In certain embodiments, the p-type doping concentration of the electron blocking layer **125** ranges from 5×10.sup.17 atoms/cm.sup.3 to 2×10.sup.19 atoms/cm.sup.3. If the p-type doping concentration of the electron blocking layer **125** is smaller than 5×10.sup.17 atoms/cm.sup.3, a voltage of the semiconductor light-emitting device may increase. In certain embodiments, the p-type doping concentration of the electron blocking layer **125** ranges from 1×10.sup.18 atoms/cm.sup.3 to 2×10.sup.19 atoms/cm.sup.3; therefore, a voltage of the semiconductor light-emitting device may be better controlled, and the p-type doping quality of the light-emitting structure **123** may be better controlled, so that the semiconductor light-emitting device may have a good anti-lumen depreciation capacity.

[0034] The p-type hole injection layer **126** is formed on the electron blocking layer **125**, and is made of a semiconductor compound to inject holes into the light-emitting structure **123**. The p-type hole injection layer **126** is made of a semiconductor material represented by In.sub.x3Al.sub.y3Ga.sub.1-x3-y3N, where 0≤x2≤1, 0≤y2≤1, 0≤x2+y2≤1. The semiconductor material of the p-type hole injection layer **126** may be GaN, AlN, AlGaN, InGaN, InN, InAlGaN, AlInN, etc., and may be doped with a p-type dopant, e.g., Mg, Zn, Ca, Sr, Ba, etc. In some embodiments where the semiconductor light-emitting device is a UV LED, the p-type hole injection layer **126** may include AlGaN. In addition, a contact layer (not depicted in the drawings) may be formed on the p-type hole injection layer **126**. The contact layer may be a highly doped p-type GaN layer or a highly doped p-type AlGaN layer. For example, the contact layer may be a p-type AlGaN layer having a p-type doping concentration larger than 1×10.sup.20 atoms/cm.sup.3, which is beneficial to form a good ohmic contact with an electrode. In an embodiment, the p-type hole injection layer **126** has a doping concentration that is equal to or smaller than 1×10.sup.20 atoms/cm.sup.3. In an embodiment, the p-type hole injection layer **126** has an energy band gap (E.sub.g5), which is larger than the energy band gap (E.sub.g1) of the well layers **123**B. In an embodiment, the energy band gap (E.sub.g5) of the p-type hole injection layer **126** is smaller than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D.

[0035] In an embodiment, the electron blocking layer **125** has at least one V-shaped groove **140** that extends into the light-emitting structure **123**, and the p-type hole injection layer **126** fills the at least one V-shaped groove **140**. Since the at least one V-shaped groove **140** extends into and is formed in the light-emitting structure **123**, electrons and holes that are injected into the light-emitting structure **123** may not reach threading dislocations, which is beneficial to inhibit non-emitting recombination in the light-emitting structure **123**. In addition, the at least one V-shaped groove **140** has an upper end that is located in a top surface of the electron blocking layer **125** and a lower end (A). The lower end (A) is located not lower than a lower surface of the light-emitting structure **123** (specifically, the lower end (A) is located not lower than a lower surface of a lowest one of the well layers **123**B that is adjacent to the n-type semiconductor layer **121**). In some embodiments, the lower end (A) is located in the light-emitting structure **123** so that a path of current leakage in the epitaxial laminate may be reduced, thereby enhancing the light-emitting efficiency. At least a part of the at least one V-shaped groove **140** is located in the light-emitting structure **123**, and is filled (e.g., completely filled) by the p-type hole injection layer **126**. Controlling a depth of the at least one V-shaped groove **140** is beneficial to control the p-type doping concentration of the light-emitting structure **123**. In an embodiment, the upper end of the at least one V-shaped groove **140** has a maximum width that is equal to or smaller than 160 nm and the depth of the at least one V-shaped groove **140** is smaller than 120 nm, so that the p-type doping

concentration of the light-emitting structure **123** may be well controlled to be smaller than 5×10.sup.17 atoms/cm.sup.3.
[0036] Generally, in the embodiment where the semiconductor light-emitting device is a UV LED, to reduce light absorption by the semiconductor layers of the UV LED, energy band gaps of the semiconductor layers are to be increased. By controlling the Al contents in the semiconductor layers, the energy band gaps of the semiconductor layers may be adjusted. However, the semiconductor layer with a high Al content is unfavorable to filling of the at least one V-shaped groove **140**. In this embodiment, by controlling the energy band gap (E.sub.g5) of the p-type hole injection layer **126** to be higher than the energy band gap (E.sub.g1) of the well layers **123**B and to be lower than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D, the p-type hole injection layer **126** may fill the at least one V-shaped groove **140** well, thereby reducing current leakage and improving an anti-aging capability of the semiconductor light-emitting device.
[0037] In this embodiment, forming the at least one V-shaped groove **140** in the epitaxial laminate is beneficial to increase the recombination efficiency of holes and electrons in the light-emitting structure **123**. By controlling the position of the lower end (A) and the depth of the at least one V-shaped groove **140**, and by adjusting the energy band gap (E.sub.g5) of the p-type hole injection layer **126** to be smaller than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D so as to fill the at least one V-shaped groove **140** well, the p-type doping concentration of the light-emitting structure **123** may be well controlled so that the anti-aging capability of the light-emitting device may be enhanced.
[0038] FIGS. **3** and **4** show an epitaxial laminate of another embodiment of the semiconductor light-emitting device of the present disclosure. The epitaxial laminate in this embodiment is the same as that shown in FIG. **1** except for the electron blocking layer **125**. In this embodiment, the electron blocking layer **125** includes a first electron blocking layer **125***a* and a second electron blocking layer **125***b*.
[0039] As shown in FIG. **4**, the first electron blocking layer **125***a* directly contacts the last barrier layer **123**D. The first electron blocking layer **125***a* has an energy band gap (E.sub.g3), and the second electron blocking layer **125***b* has an energy band gap (E.sub.g4), where E.sub.g3>E.sub.g4. The first electron blocking layer **125***a* includes a material represented by Al.sub.gGa.sub.1-gN, where 0.5<g≤1. In certain embodiments, g is larger than 0.7 and is equal to or smaller than 1. In an embodiment, the first electron blocking layer **125***a* includes AlN. In this embodiment, the first electron blocking layer **125***a* has a thickness ranging from 0.5 nm to 15 nm, e.g., from 0.5 nm to 10 nm. Within this range, diffusion of the p-type dopant into the light-emitting structure **123** may be alleviated. If the thickness of the first electron blocking layer **125***a* is smaller than 0.5 nm, there will be a decrease in the capability of blocking diffusion of the p-type dopant into the light-emitting structure **123**, and the electrostatic protection capability of the semiconductor light-emitting device may be adversely affected. If the thickness of the first electron blocking layer **125***a* is larger than 15 nm, the electric properties of the semiconductor light-emitting device, e.g., positive voltage, current leakage, would be deteriorated. In certain embodiments, the first electron blocking layer **125***a* has a p-type doping concentration that is equal to or smaller than 1×10.sup.18 atoms/cm.sup.3.
[0040] In certain embodiments, the energy band gap (E.sub.g4) of the second electron blocking layer **125***b* is larger than the energy band gap (E.sub.g2) of one of the barrier layers **123**A, **123**D. In some embodiments, the energy band gap (E.sub.g4) of the second electron blocking layer **125***b* is larger than the energy band gap (E.sub.g2) of a first one of the barrier layers **123**A that is adjacent to the supper lattice layer **122**. The second electron blocking layer **125***b* includes a material represented by In.sub.aAl.sub.bGa.sub.1-a-bN, where 0≤a≤0.05, 0<b≤1. If b is smaller than 0.05, the electrostatic protection capability of the semiconductor light-emitting device would be deteriorated. The second electron blocking layer **125***b* may cooperate with the first electron blocking layer **125***a* to improve the light-emitting efficiency of the semiconductor light-emitting device. In certain embodiments, the second electron blocking layer **125***b* has a p-type doping

concentration that is equal to or smaller than 5×10.sup.19 atoms/cm.sup.3, e.g., equal to or smaller than 2×10.sup.19 atoms/cm.sup.3.

[0041] FIG. **5** shows a relationship of the energy band gaps of the light emitting structure **123**, the electron blocking layer **125** and the p-type hole injection layer **126** in the epitaxial laminate shown in FIG. **3**, where E.sub.g3>E.sub.g4>E.sub.g2>E.sub.g5>E.sub.g1. FIG. **6** is a TEM image of the epitaxial laminate shown in FIG. **3**, which includes the n-type semiconductor layer **121**, the supper lattice layer **122**, the light-emitting structure **123**, the first electron blocking layer **125***a*, the second electron blocking layer **125***b*, and the p-type hole injection layer **126** from bottom to top. The at least one V-shaped groove **140** in the first electron blocking layer **125***a* and the second electron blocking layer **125***b* extends into the light-emitting structure **123**, and the p-type hole injection layer **126** fills the at least one V-shaped groove **140**. The lower end (A) of the at least one V-shaped groove **140** is located in the middle of the light-emitting structure **123**. In this embodiment, through controlling the energy band gap (E.sub.g5) of the p-type hole injection layer **126** to be smaller than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D, the p-type hole injection layer **126** may fill the at least one V-shaped groove **140** well, thereby reducing current leakage of the semiconductor light-emitting device. Moreover, the first electron blocking layer **125***a* and the second electron blocking layer **125***b* may restrict the p-type doping concentration in the light-emitting structure **123**, which may improve the light-emitting efficiency and the anti-aging capability of the semiconductor light-emitting device.

[0042] FIG. **7** shows an epitaxial laminate of yet another embodiment of the semiconductor light-emitting device of the present disclosure. The epitaxial laminate in this embodiment is the same as that shown in FIG. **3** except for the design of the light-emitting structure **123**. Referring to FIG. **7**, in this embodiment, the light-emitting structure **123** includes a blocking interlayer **123**C; specifically, the blocking interlayer **123**C is located between one of the barrier layers **123**A and one of the well layers **123**B. In certain embodiments, the light-emitting structure **123** includes a plurality of layer units each containing a distinct one of the barrier layers **123**A and a distinct one of the well layers **123**B. At least two of the layer units each further include the blocking interlayer **123**C, and in each of the at least two layer units, the blocking interlayer **123**C is disposed between the barrier layer **123**A and the well layer **123**B. The blocking interlayer **123**C has an energy band gap (E.sub.g6), which is larger than the energy band gap (E.sub.g4) of the second electron blocking layer **125***b*. In certain embodiments, the blocking interlayer **123**C may be made of a material represented by Al.sub.cGa.sub.1-cN, where 0.95≤c≤1. In some embodiments, the energy band gap (E.sub.g6) of the blocking interlayer **123**C is larger than the energy band gap (E.sub.g2) of the barrier layers **123**A. When the semiconductor light-emitting device is operating under a condition that an energy band is bent due to an applied bias voltage, and when the blocking interlayer **123**C with the energy band gap (E.sub.g6) that is 1.5 eV larger than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D is introduced into the semiconductor light-emitting device, potential barrierspike may be generated, thereby preventing overflow of carriers and increasing radiative recombination efficiency.

[0043] FIG. **8** shows an epitaxial laminate of an embodiment of the semiconductor light-emitting device of the present disclosure. The epitaxial laminate in this embodiment is the same as that shown in FIG. **7** except for the design of the light-emitting structure **123**. Referring to FIG. **8**, in this embodiment, in at least two layer units of the light-emitting structure **123**, the well layer **123**B of each of the at least two layer units includes a first layer **123**B**0** and a second layer **123**B**1**. The first layer **123**B**0** is located between the blocking interlayer **123**C and the second layer **123**B**1**. That is to say, each of the at least two layer units sequentially includes the barrier layer **123**A, the blocking interlayer **123**C, the first layer **123**B**0**, and the second layer **123**B**1**. In other words, each of the well layers **123**B that is located between corresponding two of the barrier layers **123**A includes the first layer **123**B**0** and the second layer **123**B**1**. The first layer **123**B**0** is mainly used for reducing a lattice difference between the blocking interlayer **123**C and the second layer **123**B**1**, and the second layer **123**B**1** is mainly used for emitting light. In this embodiment, the first layer **123**B**0** has a lattice constant that is between a lattice constant of the blocking interlayer **123**C and a lattice constant of the second layer **123**B**1**, thereby alleviating a problem caused by lattice-mismatch between different materials, so that the optoelectronic properties may be further improved. In certain embodiments, the first layer **123**B**0** has an energy band gap (E.sub.g7), which is larger than the energy band gap (E.sub.g1) of the well layers **123**B, and which is smaller than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D. The first layer **123**B**0** may be made of a material represented by Al.sub.dGa.sub.1-dN, where 0≤d≤0.5. Therefore, an emission wavelength of the light emitted by the light-emitting structure **123** may be well controlled. In addition, radiative recombination of holes and electrons in the second layer **123**B**1** may be enhanced. Thus, the radiative recombination efficiency of the light-emitting structure **123** may be improved simultaneously and the lumen depreciation effect of the semiconductor light-emitting device due to a plenty of interfacial defects may be avoided.

[0044] FIG. **9** shows an EDX spectrum of the light-emitting structure **123** shown in FIG. **8**, which specifically shows a profile of the Al content. In FIG. **9**, the x-axis represents a thickness of each layer, and the y-axis represents concentration intensity. The profile includes a plurality of groups each including a platform (G), a crest area (P), and a trough area (T). The platform (G) indicates an area where the fluctuation is smaller than that in each of the crest area (P) and the trough area (T). The fluctuation may be caused either by noise during testing or by change of the Al content that is intentionally adjusted. The platform (G) has a certain width and has a concentration between a concentration of the crest area (P) and a concentration of the trough area (T). In some embodiments, the Al content in the platform (G) may be gradually changed, e.g., may be gradually increased in a direction from the trough area (T) to the crest area (P). In this embodiment, the platform (G) corresponds to the barrier layer **123**A and has a largest thickness. The crest area (P) corresponds to the blocking interlayer **123**C and has a smallest thickness. The trough area (T) corresponds to the well layer **123**B and has a thickness between the thickness of the crest area (P) and the thickness of the platform (G). That is to say, full width at half maximum (FWHM) of the trough area (T) is larger than FWHM of the crest area (P). Furthermore, the trough area (T) has an unsymmetrical shape, which includes a line segment (T**1**) and a line segment (T**2**). The line segment (T**1**) is close to the platform (G) and has a relatively small slope, and the line segment (T**2**) is close to the crest area (P) and has a first portion (L**1**) and a second portion (L**2**). The first portion (L**1**) is connected to the crest area (P), and the second portion (L**2**) is connected to the first portion (L**1**) and the line segment (T**1**). In this embodiment, formation of the second portion (L**2**) may be accomplished by inserting the first layer **123**B**0** that has an middle energy band gap into the blocking interlayer **123**C and the second layer **123**B**1**, and that may be, for example, a GaN layer or a AlGaN layer with a low Al content, so as to form a buffer region. In an embodiment, the second portion (L**2**) forms a small step. The step may avoid a sudden change in Al content between the crest area (P) and the trough area (T), thereby reducing the lattice difference between the blocking interlayer **123**C and the well layer **123**B, and may well confine electrons and holes that flow into the light-emitting structure **123** in the second layer **123**B**1** to perform radiative illumination, thereby increasing the radiative recombination efficiency and maintaining the consistency of the emission wavelength of light.

[0045] FIG. **10** shows a relationship of the energy band gaps of an epitaxial laminate that has the light-emitting structure **123** shown in FIG. **8**. It can be noted that the energy band gaps in the layer units satisfy a relationship of E.sub.g1<E.sub.g7<E.sub.g2<E.sub.g6. Furthermore, in order to alleviate lattice-mismatch between the well layers **123**B and the barrier layers **123**A, a portion of each of the barrier layers **123**A that is close to the adjacent well layer **123**B may have an Al content that is gradually increased and then maintains at a particular level (i.e., remains unchanged).

[0046] FIG. **11** shows a schematic view of an embodiment of a semiconductor light-emitting device according to the present disclosure. Referring to FIG. **11**, the semiconductor light-emitting device has a vertical structure and includes a conductive substrate **400** and a semiconductor layer sequence **100** that is disposed on the conductive substrate **400**. In some embodiments, the semiconductor light-emitting device may further include a connecting layer **200**, e.g., a metal bonding layer or an insulating layer that is disposed between the conductive substrate **400** and the semiconductor layer sequence **100**.

[0047] The semiconductor layer sequence **100** includes a sidewall and a first surface and a second surface opposite to the first surface. The first surface is a front side and the second surface is a rear side. The semiconductor layer sequence **100** includes the n-type semiconductor layer **121**, the supper lattice layer **122**, the light-emitting structure **123**, the first electron blocking layer **125***a*, the second electron blocking layer **125***b* and the p-type hole injection layer **126**, which are arranged sequentially in such order. The light-emitting structure **123** may have the structure shown in FIG. **2**. The second surface of the semiconductor layer sequence **100** is formed with at least one recess G**2** that at least penetrates the p-type hole injection layer **126**, the second electron blocking layer **125***b*, the first electron blocking layer **125***a*, the light-emitting structure **123**, the supper lattice layer **122**, and a part of the n-type semiconductor layer **121**. The semiconductor light-emitting device may further include a first electrical connection layer **210**, a second electrical connection layer **220**, and an insulating layer that has a first insulating layer **310**, a second insulating layer **320**, and a third insulating layer **330**. The first electrical connection layer **210** is electrically connected to the p-type hole injection layer **126**. The second electrical connection layer **220** includes a transparent conductive layer **221** that contacts the semiconductor layer sequence **100**, a metal reflection layer **222**, and a metal connection layer **223**. The first electrical connection layer **210** has a protrusion that is formed in the recess G**2**, and is electrically connected to the n-type semiconductor layer **121**. Through the second insulating layer **320** and the third insulating layer **330**, the first electrical connection layer **210** and the second electrical connection layer **220** are electrically insulated from each other. The first electrical connection layer **210** and/or the second electrical connection layer **220** may include metal. The conductive substrate **400** serves as a first electrode and is electrically connected to the first electrical connection layer **210**. The semiconductor light-emitting device further includes a second electrode **420** that is disposed on an upper surface of the second electrical connection layer **220**. The first electrode and the second electrode **420** are used for external electrical connection. Furthermore, the first insulating layer **310** is disposed between the second electrical connection layer **220** and the semiconductor layer sequence **100**, which is beneficial to improve the optoelectronic performance of the semiconductor light-emitting device.

[0048] Two chip samples (Samples **1** and **2**) of a UV LED, each of which has a vertical structure shown in FIG. **11**, has a chip size of 45 mil×45 mil and emits light with an emission wavelength mainly ranging from 365 nm to 370 nm, were prepared. A silicon substrate was used as the conductive substrate **400**. Sample **1** had the epitaxial laminate shown in FIG. **7**, in which the n-type semiconductor layer **121** was made of AlGaN, the p-type hole injection layer **126** was made of AlGaN, and the light-emitting structure **123** included five layer units each having an Al.sub.z3Ga.sub.1-z3N layer (z being 8 at %, and the Al.sub.z3Ga.sub.1-z3N layer having an thickness of 12 nm), an AlN layer (having an thickness of 0.7 nm), and an In.sub.x3Ga.sub.1-x3N layer (x3 being 0.5 at %, and the In.sub.x3Ga.sub.1-x3N layer having an thickness of 7 nm) (i.e., Al.sub.z3Ga.sub.1-z3N/AlN/In.sub.x3Ga.sub.1-x3N). Sample **2** had the epitaxial laminate shown in FIG. **8**, in which the light-emitting structure **123** included five layer units each having an Al.sub.z3Ga.sub.1-z3N layer (z being 8 at %, and the Al.sub.z3Ga.sub.1-z3N layer having an thickness of 11 nm), an AlN layer (having an thickness of 0.7 nm), a GaN layer (having an thickness of 2 nm), and an In.sub.x3Ga.sub.1-x3N layer (x3 being 0.5 at %, and the In.sub.x3Ga.sub.1-x3N layer having an e thickness of 5 nm) (i.e., Al.sub.z3Ga.sub.1-z3N/AlN/GaN/In.sub.x3Ga.sub.1-x3N). The configurations of other layers of Sample **2** were the same as those of Sample **1**.

[0049] FIG. **12** shows scatter plots of light output power (LOP) versus wavelength of Sample **1** and

Sample **2** under a current of 500 mA. A circle-shaped carrier plate is used to support a substrate which is for growth of epitaxial laminates in an MOCVD process, and the epitaxial laminates grown on different positions of the carrier plate (i.e., different positions of the substrate) may have different epitaxial qualities. To eliminate the influence caused by growth on different positions, Sample **1** and Sample **2** were respectively obtained from different manufacturing batches at the same position on the carrier plate. According to FIG. **12**, Samples **1** and **2** have light emission wavelengths ranging from 365 nm to 370 nm. The light output power (LOP) of Sample **2** is significantly larger than that of Sample **1**, which indicates that Sample **2** has improved brightness.

[0050] Sample **1** and Sample **2** were subjected to an aging test under a temperature of 45° C. and a current of 3000 mA for 48 hours. The results show that the brightness of Sample **1** is decreased to 87.71% and the brightness of Sample **2** is decreased to 90.91%. That is to say, under a large current, lumen depreciation of Sample **2** was retarded.

[0051] Furthermore, a hot/cold factor of each of Sample **1** and Sample **2** was determined. The results are presented in Table 1. It is noted that brightness stability of Sample **2** at the high temperature working condition is significantly improved.

TABLE-US-00001 TABLE 1 Hot/cold (H/C) factor 25° C. 95° C. 120° C. Sample 1 100% 77% 66% Sample 2 100% 86% 80%

[0052] An embodiment of a light-emitting apparatus according to the present disclosure includes a circuit substrate and a semiconductor light-emitting device disposed on the circuit substrate. The semiconductor light-emitting device may be any one of the aforesaid semiconductor light-emitting devices. The light-emitting apparatus exhibits a good anti-aging capability.

[0053] In summary, the first electron blocking layer **125***a* that contacts the last one barrier layer **123**D has the energy band gap (E.sub.g3) larger than the energy band gap (E.sub.g4) of the second electron blocking layer **125***b*. The energy band gap (E.sub.g4) of the second electron blocking layer **125***b* is larger than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D. In addition, the p-type hole injection layer **126** has the energy band gap (E.sub.g5) that is smaller than the energy band gap (E.sub.g2) of the barrier layers **123**A, **123**D. Through the aforesaid particular design in the energy band gaps, the p-type doping concentration of the light-emitting structure **123** may be well controlled, and thus, the anti-aging capability of the semiconductor light-emitting device may be effectively improved.

[0054] In the description above, for the purposes of explanation, numerous specific details have been set forth in order to provide a thorough understanding of the embodiment(s). It will be apparent, however, to one skilled in the art, that one or more other embodiments may be practiced without some of these specific details. It should also be appreciated that reference throughout this specification to “one embodiment,” “an embodiment,” an embodiment with an indication of an ordinal number and so forth means that a particular feature, structure, or characteristic may be included in the practice of the disclosure. It should be further appreciated that in the description, various features are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of various inventive aspects; such does not mean that every one of these features needs to be practiced with the presence of all the other features. In other words, in any described embodiment, when implementation of one or more features or specific details does not affect implementation of another one or more features or specific details, said one or more features may be singled out and practiced alone without said another one or more features or specific details. It should be further noted that one or more features or specific details from one embodiment may be practiced together with one or more features or specific details from another embodiment, where appropriate, in the practice of the disclosure.

[0055] While the disclosure has been described in connection with what is (are) considered the exemplary embodiment(s), it is understood that this disclosure is not limited to the disclosed embodiment(s) but is intended to cover various arrangements included within the spirit and scope of the broadest interpretation so as to encompass all such modifications and equivalent arrangements.

Claims

1. A semiconductor light-emitting device, comprising an n-type semiconductor layer, a light-emitting structure, a first electron blocking layer, a second electron blocking layer, and a p-type hole injection layer, which are sequentially stacked in such order, wherein said light-emitting structure includes well layers and barrier layers that are stacked alternately, said first electron blocking layer contacts a last one of said barrier layers of said light-emitting structure and has an energy band gap (E.sub.g3) that is larger than an energy band gap (E.sub.g4) of said second electron blocking layer, the energy band gap (E.sub.g4) of said second electron blocking layer is larger than an energy band gap (E.sub.g2) of each of said barrier layers, and an energy band gap (E.sub.g5) of said p-type hole injection layer is smaller than the energy band gap (E.sub.g2) of each of said barrier layers.
2. The semiconductor light-emitting device as claimed in claim 1, wherein light emitted by said semiconductor light-emitting device has an emission wavelength ranging from 340 nm to 425 nm.
3. The semiconductor light-emitting device as claimed in claim 1, wherein said well layers have an energy band gap (E.sub.g1), where E.sub.g3>E.sub.g4>E.sub.g2>E.sub.g5>E.sub.g1.
4. The semiconductor light-emitting device as claimed in claim 1, wherein one of said well layers, which is nearest to said p-type hole injection layer, has a p-type doping concentration that is equal to or smaller than 5×10.sup.17 atoms/cm.sup.3.
5. The semiconductor light-emitting device as claimed in claim 1, wherein said second electron blocking layer has at least one V-shaped groove that extends into said light-emitting structure, said p-type hole injection layer filling said at least one V-shaped groove.
6. The semiconductor light-emitting device as claimed in claim 5, wherein said at least one V-shaped groove has an upper end that is located at a top surface of said second electron blocking layer and a lower end that is located in said light-emitting structure.
7. The semiconductor light-emitting device as claimed in claim 1, wherein except for said last one of said barrier layers, said barrier layers each has a p-type doping concentration that is equal to or smaller than 1×10.sup.17 atoms/cm.sup.3.
8. The semiconductor light-emitting device as claimed in claim 1, wherein said first electron blocking layer has a p-type doping concentration that is equal to or smaller than 1×10.sup.18 atoms/cm.sup.3.
9. The semiconductor light-emitting device as claimed in claim 1, wherein said second electron blocking layer has a p-type doping concentration that is equal to or smaller than 5×10.sup.19 atoms/cm.sup.3.
10. The semiconductor light-emitting device as claimed in claim 1, wherein said p-type hole injection layer has a doping concentration that is equal to or smaller than 1×10.sup.20 atoms/cm.sup.3.
11. The semiconductor light-emitting device as claimed in claim 1, wherein said first electron blocking layer has a thickness ranging from 0.5 nm to 15 nm.
12. The semiconductor light-emitting device as claimed in claim 1, wherein said light-emitting structure further includes a blocking interlayer that is located between one of said barrier layers and one of said well layers, and that contacts said one of said barrier layers, said blocking interlayer having an energy band gap (E.sub.g6) that is larger than the energy band gap (E.sub.g4) of said second electron blocking layer.
13. The semiconductor light-emitting device as claimed in claim 1, wherein a ratio of a thickness of said well layers to a thickness of said barrier layers ranges from 1:1.5 to 1:2.0.
14. A semiconductor light-emitting device, comprising an n-type semiconductor layer, a light-

emitting structure, an electron blocking layer, and a p-type hole injection layer, which are stacked sequentially in such order, said light-emitting structure including well layers and a barrier layers that are alternatively stacked, wherein an energy band gap of said electron blocking layer is larger than an energy band gap (E.sub.g2) of each of said barrier layers, said electron blocking layer having at least one V-shaped groove that extends into said light-emitting structure, said p-type hole injection layer filling said at least one V-shaped groove, said p-type hole injection layer having an energy band gap (E.sub.g5) that is smaller than the energy band gap (E.sub.g2) of said barrier layers.

15. The semiconductor light-emitting device as claimed in claim 14, wherein one of said well layers, which is nearest to said p-type hole injection layer, has a p-type doping concentration that is equal to or smaller than 5×10.sup.17 atoms/cm.sup.3.

16. The semiconductor light-emitting device as claimed in claim 14, wherein said at least one V-shaped groove has an upper end that is located at a top surface of said electron blocking layer and a lower end that is located in said light-emitting structure.

17. The semiconductor light-emitting device as claimed in claim 14, wherein said at least one V-shaped groove has a depth that is equal to or smaller than 120 nm.

18. The semiconductor light-emitting device as claimed in claim 14, wherein said p-type hole injection layer has a doping concentration that is equal to or smaller than 1×10.sup.20 atoms/cm.sup.3.

19. The semiconductor light-emitting device as claimed in claim 14, wherein a last one of said barrier layers, which is adjacent to said electron blocking layer, has a p-type doping concentration that is equal to or smaller than 5×10.sup.17 atoms/cm.sup.3.

20. A light-emitting apparatus, comprising said semiconductor light-emitting device as claimed in claim 1.
