US 20090020772A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2009/0020772 A1

(43) Pub. Date: Jan. 22, 2009

CHIU et al.

(54) **LIGHT-EMITTING DEVICE AND METHOD FOR MAKING THE SAME**

(76) Inventors: **Ching-Hua CHIU**, Taipei (TW); **Hung-Wen HUANG**, Taipei (TW); **Hao-Chung KUO**, Taipei (TW); **Tien-Chang LU**, Taipei (TW); **Shing-Chung WANG**, Taipei (TW); **Chih-Ming LAI**, Taipei (TW)

Correspondence Address:
ROSENBERG, KLEIN & LEE
3458 ELLICOTT CENTER DRIVE-SUITE 101
ELLICOTT CITY, MD 21043 (US)

(21) Appl. No.: **11/984,562**

(22) Filed: **Nov. 20, 2007**

(30) **Foreign Application Priority Data**

Jul. 19, 2007 (TW) 096126350

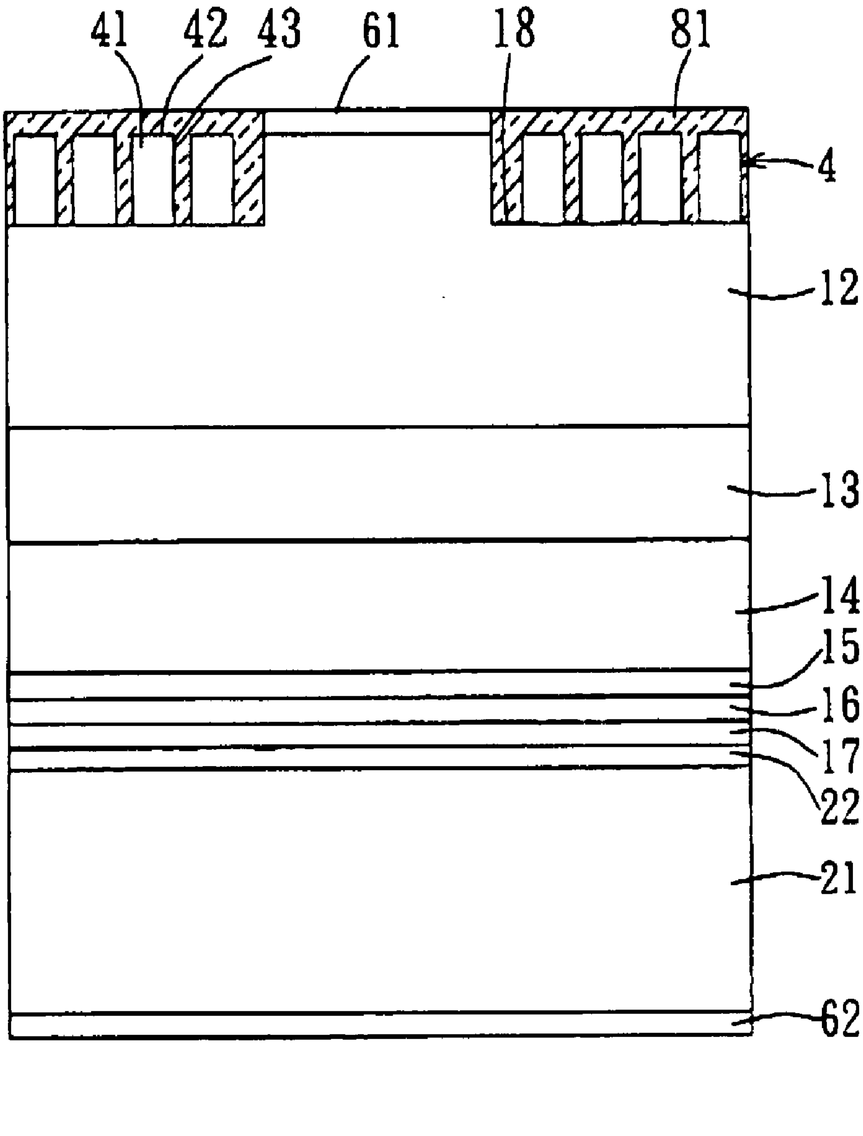
Publication Classification

(51) **Int. Cl.**
H01L 33/00 (2006.01)

(52) **U.S. Cl.** **257/98**; 438/31; 257/E33.067

(57) **ABSTRACT**

A light-emitting device is capable of emitting a light having a wavelength ranging from 300 to 550 nm, and includes: a substrate; a p-type semiconductor layer disposed on the substrate; an active layer disposed on the p-type semiconductor layer; a n-type semiconductor layer disposed on the active layer and having a waveguide-disposing surface; and a waveguide structure formed on the waveguide-disposing surface of the n-type semiconductor layer and having a plurality of spaced apart nanorods extending from the waveguide-disposing surface.



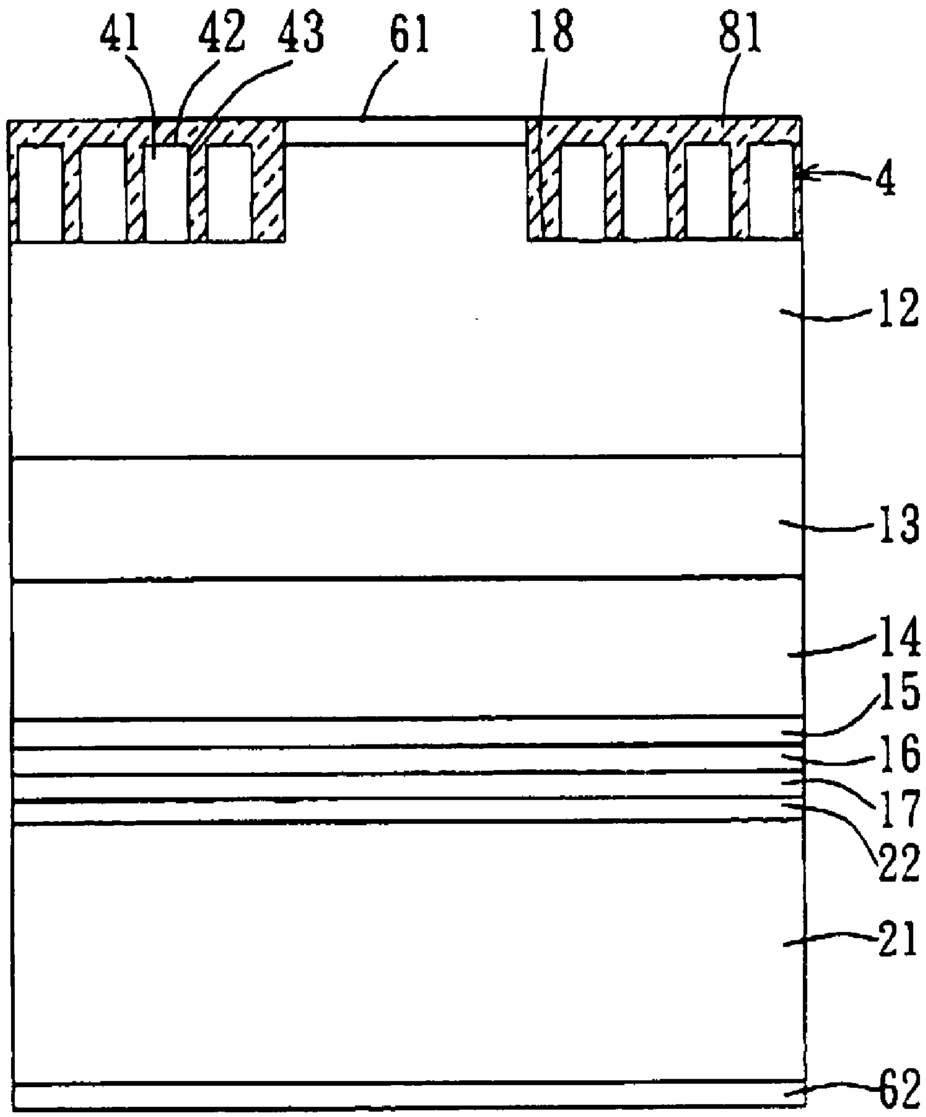


FIG. 1

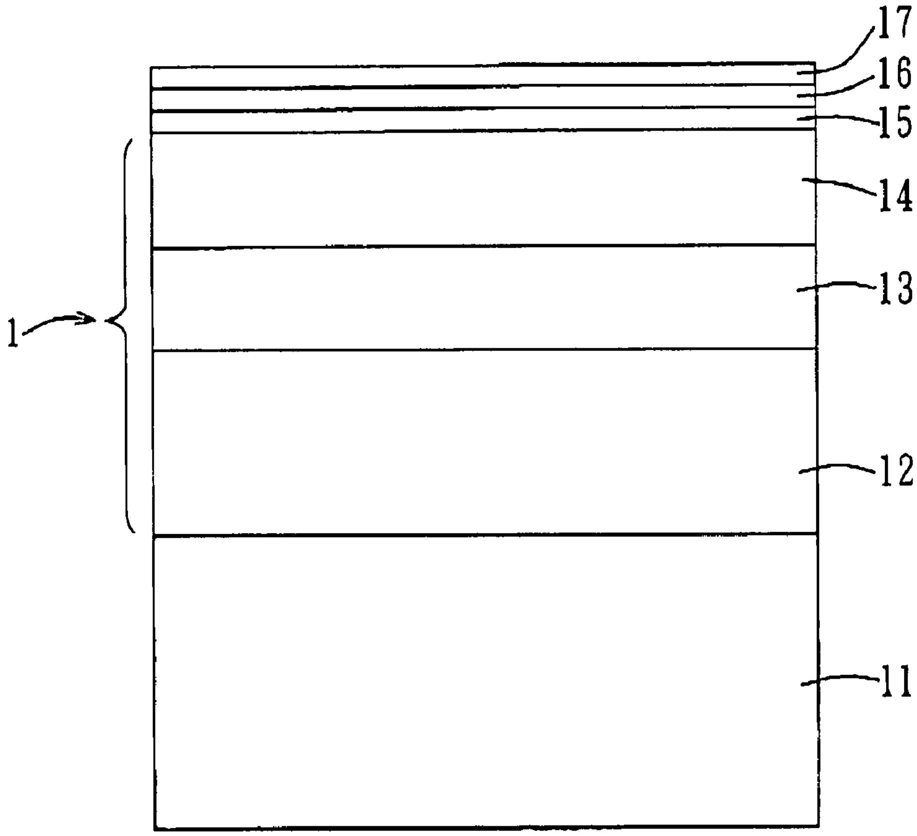


FIG. 2

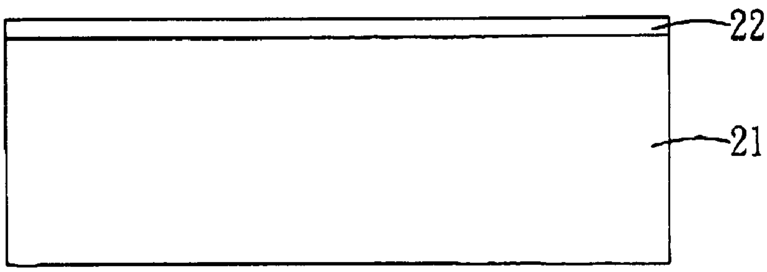


FIG. 3

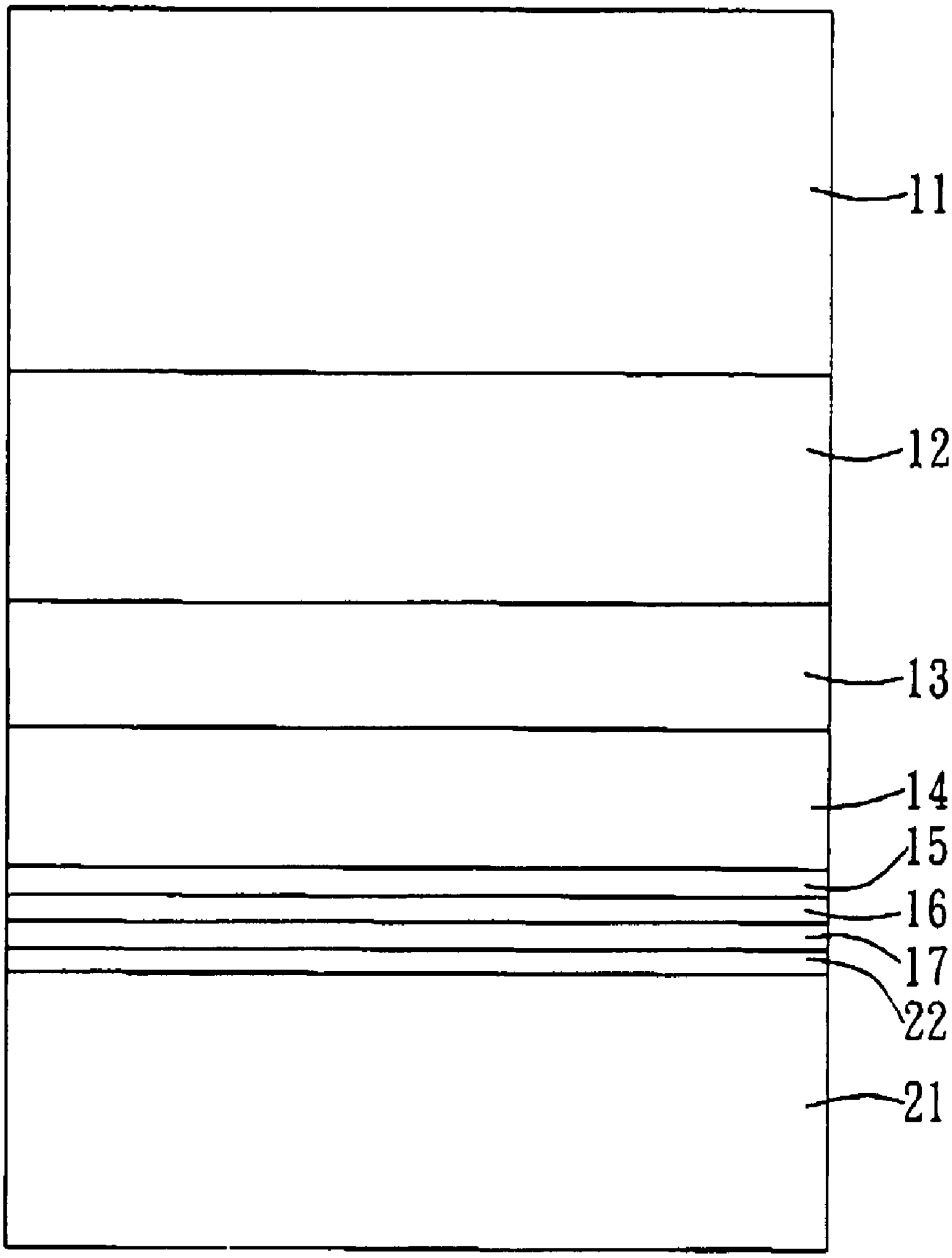


FIG. 4

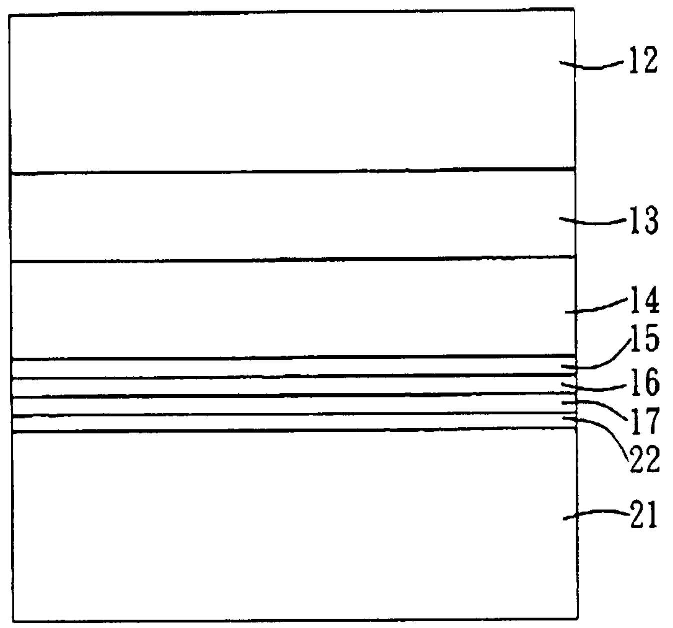


FIG. 5

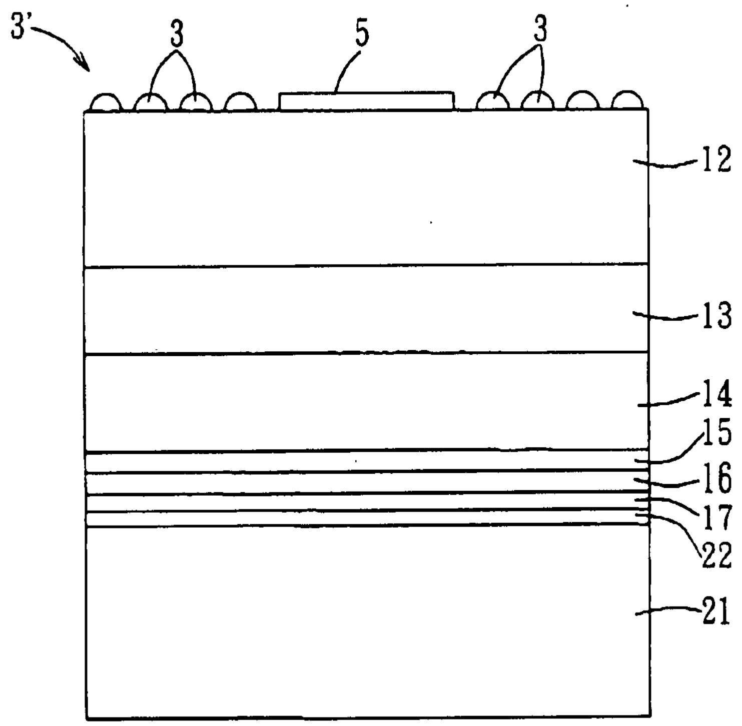


FIG. 6

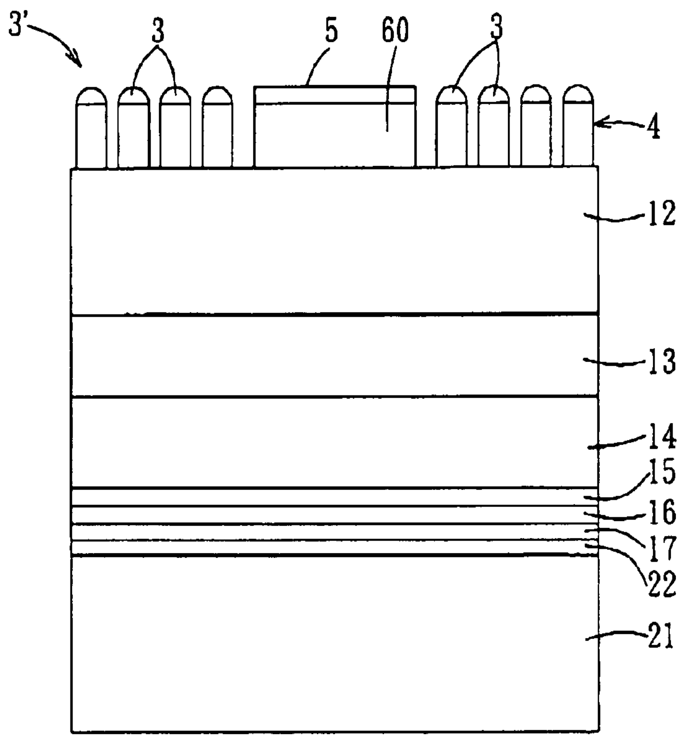


FIG. 7

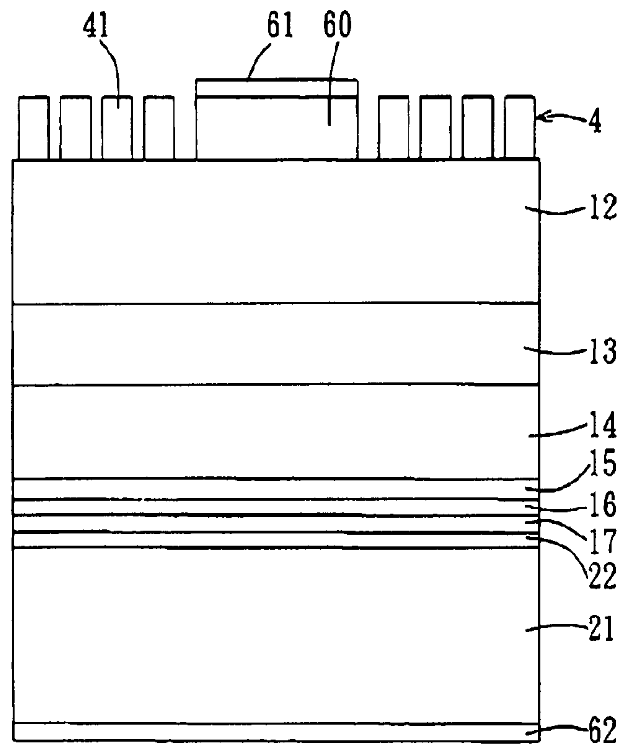


FIG. 8

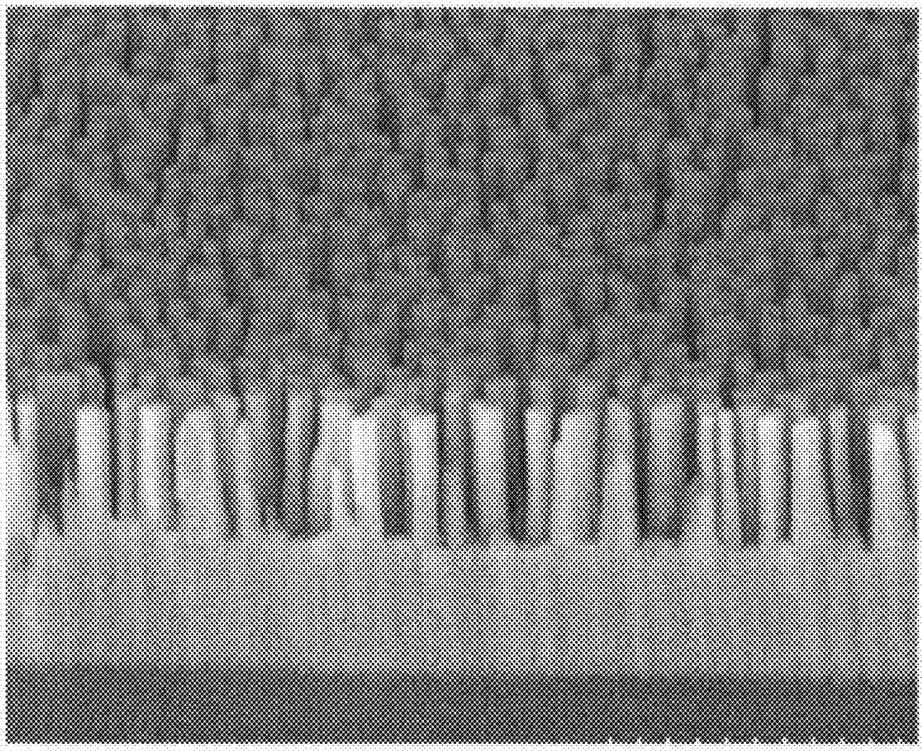


FIG. 9

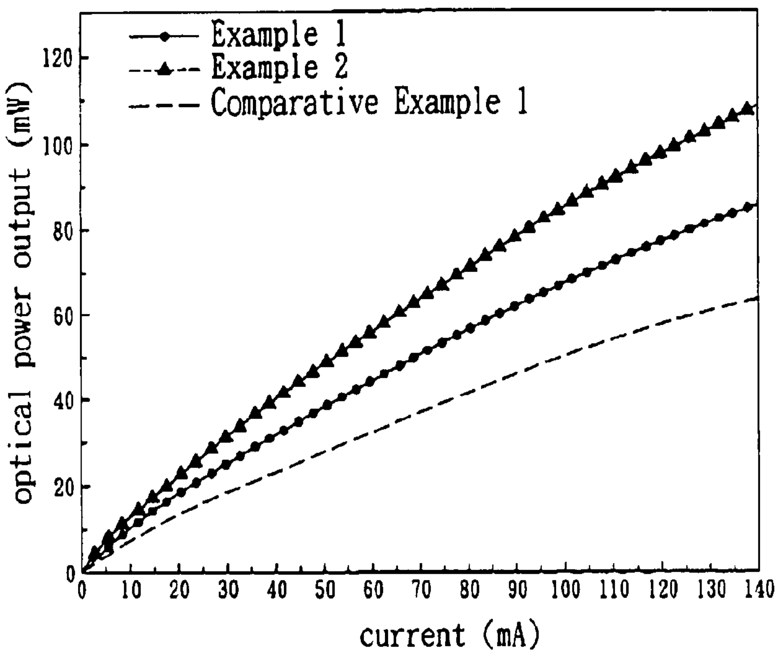

Example 1
Example 2
Comparative Example 1
optical power output (mW)
0
20
40
60
80
100
120
current (mA)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

FIG. 10

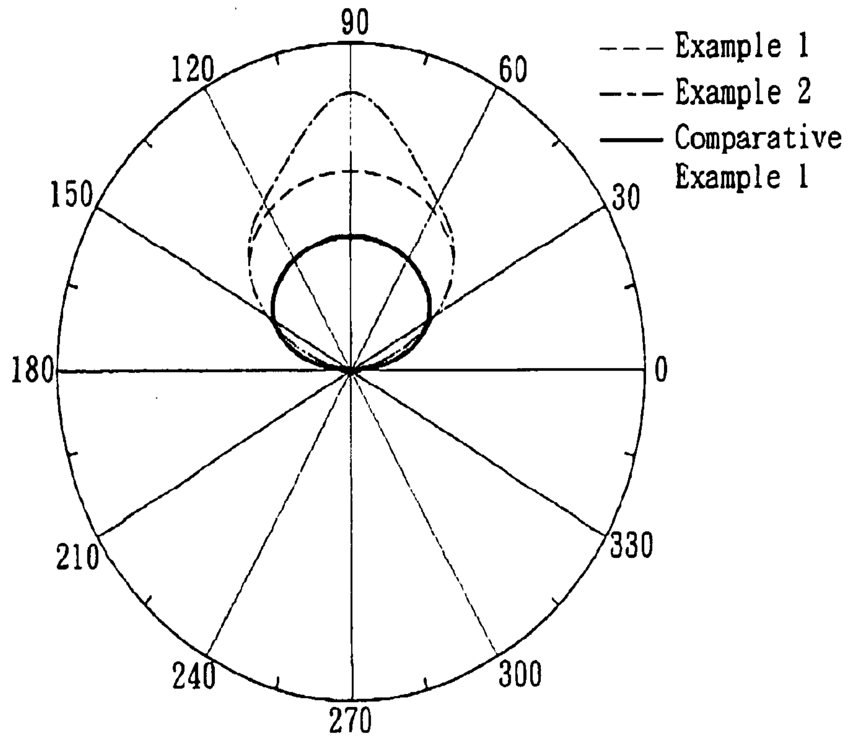

Example 1
Example 2
Comparative
Example 1
90
60
30
0
330
300
270
240
210
180
150
120

FIG. 11

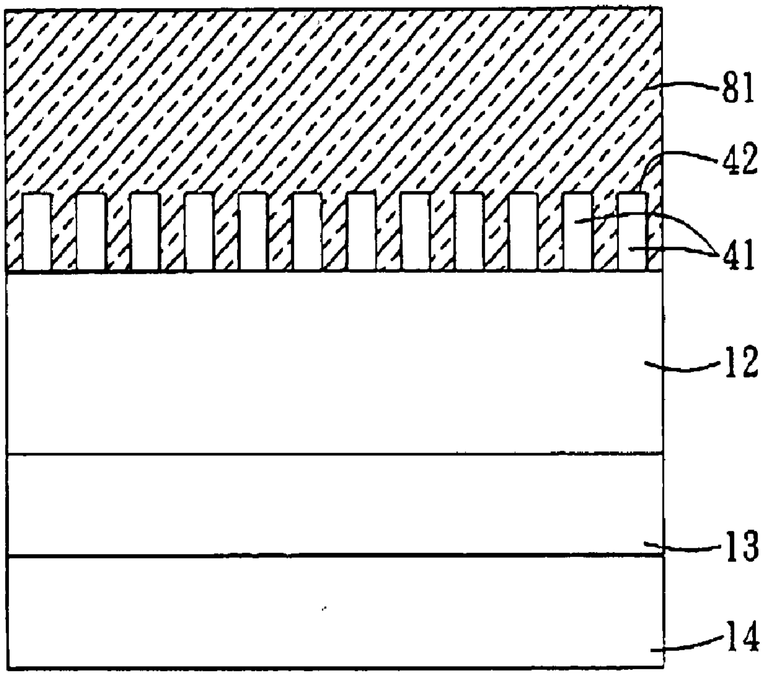


FIG. 12

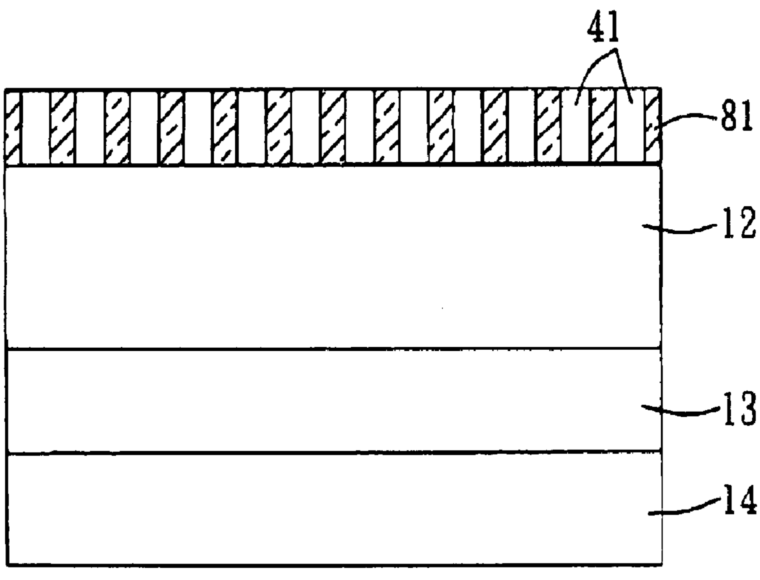


FIG. 13

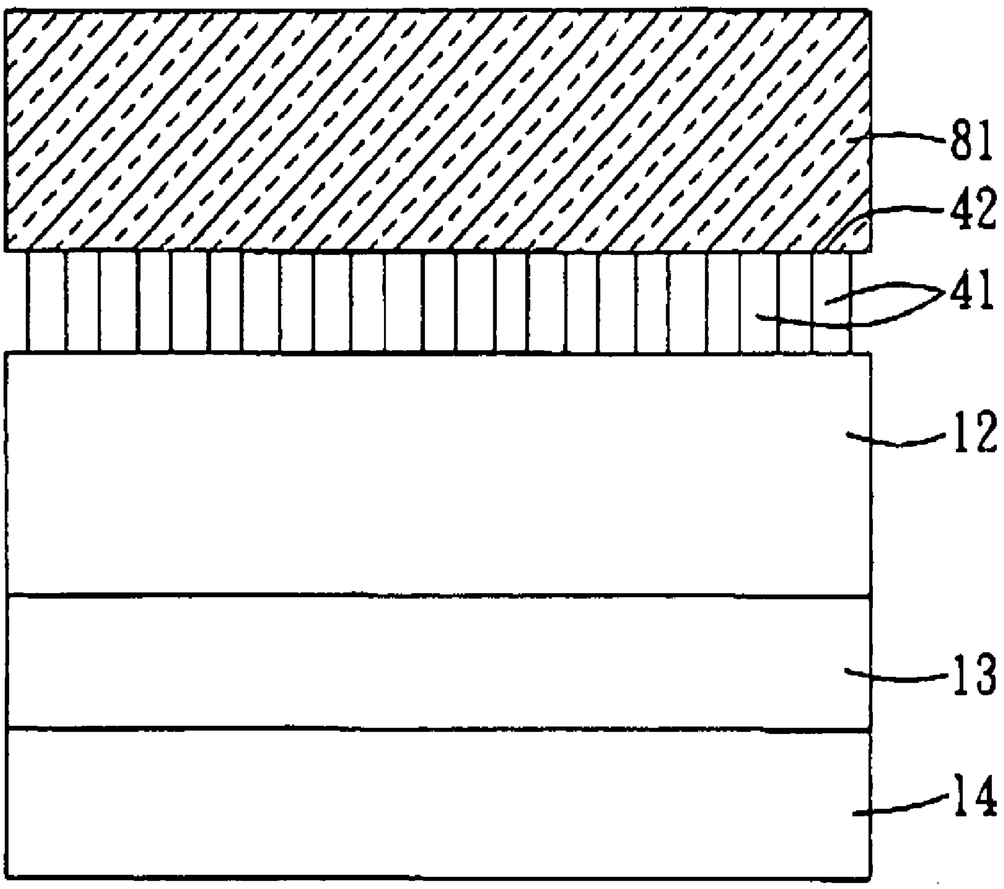


FIG. 14

LIGHT-EMITTING DEVICE AND METHOD FOR MAKING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority of Taiwanese application no. 096126350, filed on Jul. 19, 2007.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention relates to a light-emitting device, more particularly to a light-emitting device including a waveguide structure having a plurality of nanorods formed on a n-type semiconductor layer.

[0004] 2. Description of the Related Art

[0005] It is known in the art that light extraction efficiency of a light-emitting diode is considerably limited due to the laminated layered structure of the light-emitting diode, which can cause total internal reflection of light generated from an active layer of the light-emitting diode, which, in turn, can result in a decrease in the light extraction efficiency. Conventional methods for enhancing light extraction efficiency normally involve increasing surface roughness of the laminated layered structure of the light-emitting diode so as to reduce total internal reflection of light in the light-emitting diode. However, in UV, blue, or green light emitting diodes, since the p-cladding layer thereof is relatively thin, which has a layer thickness required to be not greater than 200 nm, surface roughening of the same tends to cause short-circuiting of the light emitting diode and has an adverse effect on the electrical properties of the light emitting diode. U.S. Pat. No. 7,132,677 discloses a light emitting device including a plurality of nanorods, each of which has a n-cladding layer, an active layer formed on the n-cladding layer, and a p-cladding layer formed on the active layer. Although the light-emitting diode thus formed can enhance the light extraction efficiency, manufacturing of the same is complex and expensive.

SUMMARY OF THE INVENTION

[0006] Therefore, the object of the present invention is to provide a light-emitting device that can overcome the aforesaid drawbacks associated with the prior art.

[0007] Another object of this invention is to provide a method for making the light-emitting device.

[0008] According to one aspect of the present invention, a light-emitting device capable of emitting a light having a wavelength ranging from 300 to 550 nm comprises: a substrate; a p-type semiconductor layer disposed on the substrate; an active layer disposed on the p-type semiconductor layer; a n-type semiconductor layer disposed on the active layer and having a waveguide-disposing surface; first and second electrodes coupled electrically to the n-type semiconductor layer and the substrate, respectively; and a waveguide structure formed on the waveguide-disposing surface of the n-type semiconductor layer and having a plurality of spaced apart nanorods extending from the waveguide-disposing surface.

[0009] According to another aspect of this invention, there is provided a method for making a light-emitting device capable of emitting a light having a wavelength ranging from 300 to 550 nm. The method comprises: (a) forming a multilayered structure on a first substrate, the multilayered structure including a n-type semiconductor layer disposed on the first substrate, an active layer disposed on the n-type semiconductor layer, and a p-type semiconductor layer disposed on the active layer; (b) attaching the multilayered structure to a second substrate and removing the first substrate from the multilayered structure so as to expose the n-type semiconductor layer; and (c) etching the n-type semiconductor layer to form a waveguide structure thereon. The waveguide structure includes a plurality of spaced apart nanorods extending from the n-type semiconductor layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Other features and advantages of the present invention will become apparent in the following detailed description of the preferred embodiment of this invention, with reference to the accompanying drawings, in which:

[0011] FIG. **1** is a fragmentary schematic view of the preferred embodiment of a light-emitting device according to this invention;

[0012] FIGS. **2** to **8** are schematic views to illustrate consecutive steps of the preferred embodiment of a method for making the light-emitting device;

[0013] FIG. **9** is a scanning electron microscopic view of a plurality of nanorods formed on a n-type semiconductor layer of the preferred embodiment;

[0014] FIG. **10** is a graph showing output power/current relation of Comparative Example 1 and Examples 1 and 2 of the preferred embodiment;

[0015] FIG. **11** is a graph showing Far-Field Pattern of Comparative Example 1 and Examples 1 and 2 of the preferred embodiment;

[0016] FIG. **12** is a schematic view to illustrate a protective layer formed on the n-type semiconductor layer of the preferred embodiment;

[0017] FIG. **13** is a schematic view to illustrate the protective layer filled among and flush with free ends of the nanorods on the n-type semiconductor layer of the preferred embodiment; and

[0018] FIG. **14** is a schematic view to illustrate the protective layer formed on the free ends of the nanorods of the preferred embodiment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0019] FIG. **1** illustrates the preferred embodiment of a light-emitting device capable of emitting UV, blue, or green light, i.e., a light having a wavelength ranging from 300 to 550 nm, according to this invention.

[0020] The light-emitting device includes: a substrate **21**; a p-type semiconductor layer **14** disposed on the substrate **21**; an active layer **13** disposed on the p-type semiconductor layer **14**; a n-type semiconductor layer **12** disposed on the active layer **13** and having a waveguide-disposing surface **18**; first and second electrodes **61**, **62** coupled electrically to the n-type semiconductor layer **12** and the substrate **21**, respectively, for applying a working voltage thereto; and a waveguide structure **4** formed on the waveguide-disposing surface **18** of the n-type semiconductor layer **12** and having a plurality of spaced apart nanorods **41** extending from the waveguide-disposing surface **18**. Each of the nanorods **41** has a length not less than 200 nm. The p-type semiconductor layer **14** has a layer thickness not greater than 200 nm.

[0021] In this embodiment, each of the nanorods **41** has a free end **42** and a peripheral surface **43** extending from the waveguide-disposing surface **18** of the n-type semiconductor layer **12** to the free end **42** of the nanorod **41** in a normal direction relative to the substrate **21**. Preferably, the nanorods **41** are cylindrical in shape.

[0022] In this embodiment, the light-emitting device further includes a protective layer **81** disposed on the n-type semiconductor layer **12**, enclosing the waveguide structure **4**, and having a refractive index greater than that of air (n=1) and smaller than that of the n-type semiconductor layer **12** (n=2.4~2.5) so as to reduce total internal reflection of light in the light-emitting device.

[0023] Preferably, the protective layer **81** is transparent and is made from an insulator material selected from the group consisting of SiO_2 and silicon nitride-based compound (Si_xN_Y).

[0024] Preferably, the substrate **21** is made from a conductive material, or from a material selected from the group consisting of Si, SiC, GaAs, GaP, MgO, ZnO, GaN, AlN, InN, Cu, Mo, W, Al, Au, Zn, Sn, and combinations thereof. In this embodiment, the substrate **21** is made from Si.

[0025] In this embodiment, the light-emitting device further includes a reflective layer **16** disposed between the substrate **21** and the p-type semiconductor layer **14**, and a current diffusion layer **15** disposed between the reflective layer **16** and the p-type semiconductor layer **14** so as to enhance light extraction efficiency.

[0026] Preferably, the reflective layer **16** is made from metal. The current diffusion layer **15** is transparent.

[0027] In this embodiment, the active layer **13** is capable of generating a light having a wavelength of about 450 nm.

[0028] Preferably, each of the n-type and p-type semiconductor layers **12**, **14** is made from a material selected from the group consisting of GaN, AlN, InN, and combinations thereof.

[0029] A method for making the light-emitting device according to this invention is described as follows. Referring to FIGS. **2** to **8**, the method includes the steps of: (a) forming a multilayered structure **1** on a first substrate **11** (see FIG. **2**), the multilayered structure **1** including a n-type semiconductor layer **12** disposed on the first substrate **11**, an active layer **13** disposed on the n-type semiconductor layer **12**, a p-type semiconductor layer **14** disposed on the active layer **13**, a current diffusion layer **15** disposed on the p-type semiconductor layer **14**, a reflective layer **16** disposed on the current diffusion layer **15**, and a first Au—Sn alloy layer **17** disposed on the reflective layer **16**; (b) attaching the multilayered structure **1** to a second substrate **21** through a second Au—Sn alloy layer **22** (see FIGS. **3** and **4**) by eutectic bonding the first and second Au—Sn alloy layers **17**, **22** together, and removing the first substrate **11** from the multilayered structure **1** so as to expose the n-type semiconductor layer **12** (see FIG. **5**); (c) forming a patterned mask **3'** on the n-type semiconductor layer **12** and etching the n-type semiconductor layer **12** to form a waveguide structure **4** thereon (see FIGS. **6** and **7**), the waveguide structure **4** including a plurality of the nanorods **41** extending from the n-type semiconductor layer **12** in a normal direction relative to the second substrate **21** or the multilayered structure **1**; and (a) removing the patterned mask **3'** from the waveguide structure **4**.

[0030] In this embodiment, the etching operation in step (c) is conducted through dry etching techniques using a particle-containing material as the patterned mask **3'**. Preferably, the dry etching operation is conducted through inductively coupled plasma reactive ion etching (ICPRIE) techniques.

[0031] Preferably, the particle-containing material contains hemispherical particles **3** having a diameter less than 0.8 μm.

[0032] The hemispherical particles **3** are preferably made from an inorganic oxide compound, and are more preferably made from a material selected from the group consisting of TiO, SiO_2, and Al_2O_3, and combinations thereof. In this embodiment, the particles **3** are made from TiO material.

[0033] In this embodiment, the formation of each of the n-type and p-type semiconductor layers **12**, **14**, and the active layer **13** of the multilayered structure **1** in step (a) is conducted through epitaxial growth techniques. The removing operation in step (b) is conducted through laser lift-off techniques.

[0034] Preferably, a protective Layer **81** is formed on the n-type semiconductor layer **12** (see FIG. **1**) through plasma enhanced chemical vapor deposition (PECVD) techniques or spin-on-glass coating (SOG) techniques.

[0035] Preferably, the formation of each of the current diffusion layer **15** and the reflective layer **16** of the multilayered structure **1** in step (a) is conducted through evaporation deposition techniques.

[0036] The merits of the method of making the light-emitting device of this invention will become apparent with reference to the following Examples and Comparative Example.

EXAMPLES

Example 1

[0037] The light-emitting device of Example 1 was prepared by the following steps.

[0038] First, an epitaxial layered structure **1**, which includes a n-type GaN semiconductor layer **12**, an active layer **13** (a multi quantum well having ten pairs InGaN/GaN), and a p-type GaN semiconductor layer **14** having a layer thickness of about 200 nm, was grown on a sapphire substrate **11** (Al_2O_3) having a diameter of 2 inches and a layer thickness of 500 μm through metal organic vapor phase epitaxy (MOVPE) techniques.

[0039] It is noted that formation of the epitaxial layered structure can also be conducted by molecular beam epitaxy (MBE) techniques or hydride vapor phase epitaxy (HVPE) techniques.

[0040] Subsequently, a current diffusion layer **15** made from ITO and having a thickness of approximately 200 nm was deposited on the p-type GaN semiconductor layer **14** by e-beam evaporation. A reflective layer **16** made from Al and having a thickness of approximately 500 nm was deposited on the current diffusion layer **15** by e-beam evaporation. A first Au—Sn alloy layer **17** having a layer thickness of 2 μm was deposited or the reflective layer **16** by evaporation deposition techniques.

[0041] In addition, a second Au—Sn alloy layer **22** having a layer thickness of 2 μm was deposited on a silicon substrate **21**, which has a diameter of 2 inches and a thickness of 500 μm, by evaporation deposition techniques(see FIG. **3**).

[0042] The first and second Au—Sn alloy layers **17**, **22** were subjected to eutectic bonding under a temperature of 350° C. to bond them together (see FIG. **4**). A laser having a wavelength of 248 nm (25×10^9s pulse period, laser spot size=1.2 mm×1.2 mm) was applied to a boundary between the sapphire substrate **11** and the n-type GaN semiconductor layer **12** so as to break bonding therebetween and so as to separate the sapphire substrate **11** from the n-type GaN semiconductor layer **12** for exposing the n-type GaN semiconductor layer **12** (see FIG. **5**). Hydrochloric acid was then used to clean the boundary, followed by inductively coupled plasma reactive ion etching of the boundary so as to completely remove residue of the sapphire substrate **11** thereon.

[0043] An etching mask material of a plurality of hemispherical particles **3** having a diameter less than 0.8 μm and made from TiO was dispersed in an alcohol solvent to form a particle-containing solution which was then applied onto the n-type GaN semiconductor layer **12** by spin coating techniques at a rotation speed of 6000 rps. After evaporation of the solvent, the hemispherical particles **3** were adhered firmly to the n-type GaN semiconductor layer **12** as an etching mask and had a distributed density of 3×10^9 particles/cm^2.

[0044] The n-type GaN semiconductor layer **12** having the hemispherical particles **3** disposed thereon was then subjected to inductively coupled plasma reactive ion etching (ICPRIE) for an etching time of about 2 minutes so as to form a plurality of nanorods **41** thereon. Each of the nanorods **41** had a length of approximately 200 nm. Hydrofluoric acid was then used to remove the hemispherical particles **3** from the nanorods **41**. FIG. **9** is a scanning electron microscope (SEM) image showing the nanorods **41** on the n-type GaN semiconductor layer **12** at 20000× magnification.

[0045] Referring to FIGS. **6** to **8**, the first and second electrodes **61**, **62** were then formed on the n-type GaN semiconductor layer **12** and the silicon substrate **21**, respectively. Specifically, in order to form the first electrode **61**, a pre-formed SiO_2 layer **5** having a thickness of 3000 Å was deposited on a portion **60** of the n-type GaN semiconductor layer **12** prior to the step of forming the hemispherical particles **3** thereon so that the portion **60** of the n-type GaN semiconductor layer **12** was prevented from being etched during formation of the nanorods **41**. The pre-formed SiO_2 was then removed by hydrofluoric acid after the step of forming the plurality of nanorods **41**. The first electrode **61** was formed on the portion **60** of the n-type GaN semiconductor layer **12** by evaporation deposition techniques.

[0046] Preferably, the first electrode **61** is a Ti/Al/Ti/Au contact electrode, and the second electrode **62** is a Ti/Au contact electrode.

Example 2

[0047] The light-emitting device of Example 2 was prepared by steps similar to those of Example 1, except that the etching time was about 5 minutes and that the nanorods **41** thus formed had a length of approximately 1000 nm.

Comparative Example 1

[0048] The light-emitting device of Comparative Example 1 was prepared by steps similar to those of Example 1, except that Comparative Example 1 was not formed with the nanorods **41** on the n-type GaN semiconductor layer **12**.

[0049] FIG. **10** is a graph showing optical power outputs for the light-emitting devices of Example 1, Example 2 and Comparative Example 1. The optical power outputs of Example 1 and Example 2 are higher than that of Comparative Example 1. Moreover, the optical power output of Example 2 is higher than that of Example 1. For example, the optical power output is 22.3 mW for Example 2 and 17.5 mW for Example 1 at a current of 20 mA.

[0050] The results show that the nanorods **41** on the n-type GaN semiconductor layer **12** can improve considerably the optical power output, especially when the nanorods **41** have a length not less than 200 nm.

[0051] FIG. **11** is a graph showing Far-field Patterns of the light-emitting devices of Example 1, Example 2 and Comparative Example 1. The results show that each of Examples 1 and 2 has a higher light extraction efficiency (encircled areas by the dashed lines) compared to that of Comparative Example 1 (encircled area by the solid line), and a higher intensity in the normal direction relative to the multilayered structure **1**.

[0052] As illustrated in the aforesaid light-emitting tests, the longer the nanorods **41** on the n-type GaN semiconductor layer **12** are, the higher will be the light extraction efficiency.

[0053] The merits of forming the protective layer **81** on the n-type semiconductor layer **12** will become apparent with reference to the following simulations.

SIMULATION

[0054] The following simulation examples and simulation comparative example were carried out using a simulation tool, i.e., a software named ASAP® developed by Breault Research Organization for analyzing light extraction efficiency of a light-emitting device.

Simulation Example 1 (SE1)

[0055] In this simulation, the parameters set for the light-emitting device having a structure shown in FIG. **12** are as follows: The semiconductor material was GaN. The p-type semiconductor layer **14** has a layer thickness of 200 nm. The active layer **13** has a layer thickness of 200 nm. The n-type semiconductor layer **12** has a layer thickness of 2 μm (including the length of the nanorods **41**). The nanorods **41** have a length of 200 nm. The protective layer **81** has a portion disposed above the free ends **42** of the nanorods **41** and having a thickness of 2 μm.

Simulation Example 2 (SE2)

[0056] Simulation Example 2 differs from the previous simulation example in that the protective layer **81** is substantially flush with the free ends **42** of the nanorods **41** (see FIG. **13**).

Simulation Example 3 (SE3)

[0057] Simulation Example 3 differs from the previous simulation examples in that the protective layer **81** is formed on the free ends **42** of the nanorods **41** (see FIG. **14**).

Simulation Example 4 (SE4)

[0058] Simulation Example 4 differs from the previous simulation examples in that the light-emitting device of this simulation example does not include the protective layer **81**.

Simulation Comparative Example 1 (SC1)

[0059] Simulation Comparative Example 1 differs from the previous simulation examples in that the light-emitting device does not include the nanorods **41** and the protective layer **81**.

[0060] Table 1 shows the simulation results of light intensity for Simulation Examples 1-4 and Simulation Comparative Example 1.

[0061] Improvement was calculated based on the following equation,

$$Improvement=[(SE-SCE)/SCE]\times 100\%,$$

where SE represents the intensity of the Simulation Example and SCE represents the intensity of Simulation Comparative Example calculated from the simulation.

TABLE 1

	Intensity			Improvement		
	Top (a.u.)	Sidewall (a.u.)	Total (a.u.)	Top (%)	Sidewall (%)	Total (%)
SE1	0.486435	0.177715	0.66415	195.2026	1740.46	280.74
SE2	0.444151	0.086726	0.530877	169.5415	798.156	204.3375
SE3	0.338945	0.141123	0.480068	105.6954	1361.51	175.2103
SE4	0.292899	0.021928	0.317564	77.7514	127.092	80.4823
SCE1	0.164780	0.009656	0.174437	—	—	—

[0062] The simulation results show that the improvement of the light-emitting device having the nanorods **41** can reach 80% in intensity and even reach 280% when the light-emitting device further includes the protective layer **81** disposed on the n-type semiconductor layer **12**.

[0063] It has thus been shown that, by forming the nanorods **41** on the n-type semiconductor layer **12** as a waveguide structure **4** and the protective layer **81** disposed on the n-type semiconductor layer **12** as a buffer layer for reducing difference in refraction index between the light-emitting device and air, the aforesaid drawbacks associated with the prior art can be eliminated.

[0064] With the invention thus explained, it is apparent that various modifications and variations can be made without departing from the spirit of the present invention. It is therefore intended that the invention be limited only as recited in the appended claims.

What is claimed is:

1. A light-emitting device capable of emitting a light having a wavelength ranging from 300 to 550 nm, comprising:
- a substrate;
- a p-type semiconductor layer disposed on said substrate;
- an active layer disposed on said p-type semiconductor layer;
- a n-type semiconductor layer disposed on said active layer and having a waveguide-disposing surface;
- first and second electrodes coupled electrically to said n-type semiconductor layer and said substrate, respectively; and
- a waveguide structure formed on said waveguide-disposing surface of said n-type semiconductor layer and having a plurality of spaced apart nanorods extending from said waveguide-disposing surface.

2. The light-emitting device of claim **1**, wherein said p-type semiconductor layer has a layer thickness not greater than 200 nm.

3. The light-emitting device of claim **1**, wherein each of said nanorods has a length not less than 200 nm.

4. The light-emitting device of claim **1**, wherein each of said nanorods is cylindrical in shape.

5. The light-emitting device of claim **1**, further comprising a protective layer disposed on said n-type semiconductor layer and having a refractive index greater than that of air and smaller than that of said n-type semiconductor layer.

6. The light-emitting device of claim **1**, further comprising a protective layer formed on said n-type semiconductor layer, enclosing said waveguide structure, and having a refractive index greater than that of air and smaller than that of said n-type semiconductor layer.

7. The light-emitting device of claim **6**, wherein said protective layer is transparent.

8. The light-emitting device of claim **6**, wherein said protective layer is made from an insulator material.

9. The light-emitting device of claim **6**, wherein said protective layer is made from a material selected from the group consisting of SiO_2 and silicon nitride-based compound (Si_xN_Y).

10. The light-emitting device of claim **1**, wherein said substrate is made from a conductive material.

11. The light-emitting device of claim **10**, wherein said substrate is made from a material selected from the group consisting of Si, SiC, GaAs, GaP, MgO, ZnO, GaN, AlN, InN, Cu, Mo, W, Al, Au, Zn, Sn, and combinations thereof.

12. The light-emitting device of claim **1**, further comprising a reflective layer disposed between said substrate and said p-type semiconductor layer, and a current diffusion layer disposed between said reflective layer and said p-type semiconductor layer.

13. The light-emitting device of claim **12**, wherein said reflective layer is made from metal.

14. The light-emitting device of claim **12**, wherein said current diffusion layer is transparent.

15. A method for making a light-emitting device capable of emitting a light having a wavelength ranging from 300 to 550 nm, comprising:
- (a) forming a multilayered structure on a first substrate, the multilayered structure including a n-type semiconductor layer disposed on the first substrate, an active layer disposed on the n-type semiconductor layer, and a p-type semiconductor layer disposed on the active layer;
- (b) attaching the multilayered structure to a second substrate and removing the first substrate from the multilayered structure so as to expose the n-type semiconductor layer; and
- (c) etching the n-type semiconductor layer to form a waveguide structure thereon, the waveguide structure including a plurality of spaced apart nanorods extending from the n-type semiconductor layer.

16. The method of claim **15**, wherein said p-type semiconductor layer has a layer thickness not greater than 200 nm.

17. The method of claim **15**, wherein each of the nanorods extends in a normal direction relative to the second substrate and has a length not less than 200 nm.

18. The method of claim **15**, wherein the etching operation in step (c) is conducted through dry etching techniques using a particle-containing material as a mask on the n-type semiconductor layer.

19. The method of claim **18**, wherein the dry etching operation in step (c) is conducted through inductively coupled plasma reactive ion etching (ICPRIE) techniques.

20. The method of claim **18**, wherein the particle-containing material contains particles having a diameter less than 0.8 μm.

21. The method of claim **20**, wherein the particles are made from an inorganic oxide compound.

22. The method of claim **20**, wherein the particles are made from a material selected from the group consisting of TiO, SiO_2, and Al_2O_3, and combinations thereof.

23. The method of claim **15**, wherein the attaching and removing operations in step (b) are conducted through metal bonding techniques and laser lift-off techniques, respectively.

* * * * *