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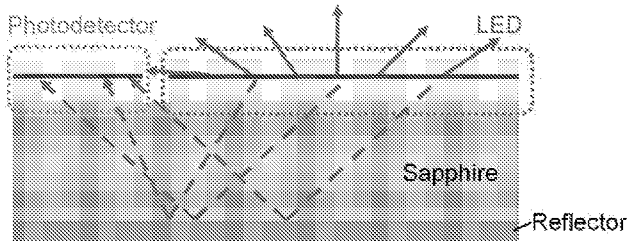

FIG. 3

(57) **Abstract:** Devices directed to light-emitting diode (LED) lighting applications and methods of fabricating the same are provided. A device can include an LED integrated with a photodetector on the same semiconductor platform, such that the photocurrent generated by the photodetector can be used to monitor the optical output of the LED, which is located adjacent to the photodetector. Compact, robust, and reliable photodetectors capable of monitoring LED emission via a low-cost approach are provided.

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DESCRIPTION

LIGHT-EMITTING DIODES (LEDS) WITH MONOLITHICALLY-INTEGRATED PHOTODETECTORS FOR IN SITU REAL-TIME INTENSITY MONITORING

FIELD OF THE INVENTION

The subject matter disclosed herein relates to light-emitting diode (LED) devices.

BACKGROUND OF THE INVENTION

Performance of solid-state lighting devices has improved tremendously in recent years, owing to the development of light-emitting diodes (LEDs) with high luminous efficacy and long lifetime. However, gradual decline of the intensity of LED output is as inevitable as it was for earlier generations of lighting devices, albeit at a much slower rate.

Specifically, the degradation mechanisms of LEDs are highly temperature-dependent as elevated junction temperature will cause reduction in light output and thus acceleration in chip degradation. Furthermore, individual LEDs within a light source can exhibit varying degradation rates even when they are subjected to the same environmental factors. Such long-term drift in light output poses one of the most significant challenges in lighting applications typically comprising a plurality of LEDs such as, for example, residential lamps and outdoor displays. In some instances, LED-based lighting devices do not generate sufficient brightness or emission uniformity, leading to a much shorter lifespan than the manufacturer-determined expectancy. Due to the intrinsically large divergence angles created by LED emission, the overall emission pattern of an LED-based lighting device is a combination of overlapping emission cones from a plurality of LEDs, as illustrated in Figure 1. As a result, discrete intensity variation from individual LEDs will cause non-uniformity in the overall emission pattern.

Apart from general lighting devices aforementioned, other LED-based applications, such as fiber light source and indoor agricultural and greenhouse lighting, require the light source to be highly stable (*i.e.*, without intensity drift in individual LEDs) against short-term environmental variations caused by factors including electrostatic breakdown, electrode deterioration, and other thermal- and humidity-related issues. One method of monitoring intensity variations in a plurality of LEDs' output is to provide a separate photodetector pointing toward the LEDs at a specific angle (Figure 1).

Although a number of semiconductor photodetectors such as Schottky barrier photodiodes, p-n, p-i-n, metal-semiconductor-metal (MSM), metal-insulator-semiconductor (MIS), and high-electron-mobility transistor (HFET) sensors, have been made available for this purpose, the off-chip integration of a photodetector together with chip carrier packages above the light source requires the use of several bulky mechanical components to maintain the detecting angle of the photodetector, leading to reduced light output and non-uniform emission. Integrating tedious photodetector configurations onto LED light sources having narrow divergence angles can be especially challenging.

Additionally, the existing solutions are only effective at a single position and/or an angle and thus unable to detect the intensity changes from a plurality of individual LEDs. Moreover, the entire off-chip system may be sensitive to other unexpected environmental factors, such as shocks or vibration, potentially reducing the reliability of the overall device.

BRIEF SUMMARY

Due to the challenges discussed above, there remains a need in the art for developing integrated light-emitting diode (LED) devices whose output can be effectively monitored by photodetectors. Embodiments of the subject invention provide devices directed to LED lighting applications and methods of fabricating the same. In some embodiments, a device can comprise an LED integrated with a photodetector on the same semiconductor platform, such that the photocurrent generated by the photodetector can be used to monitor the optical output of the LED, which is located adjacent to the photodetector. Advantageously, technologies disclosed herein can be used to provide compact, robust, and reliable photodetectors capable of monitoring LED emission via a low-cost approach.

In an embodiment, an electronic device can include an LED and a photodetector integrated onto a single semiconductor platform and positioned adjacent to each other, and the current generated by the photodetector can be used to monitor the optical output of the LED. The LED diode and the photodetector can be monolithically fabricated onto the single semiconductor platform.

In another embodiment, a method of fabricating an electronic device can include: depositing an n-type semiconductor layer on a top surface of a substrate having a coating on a bottom surface thereof; depositing an active layer on the substrate, the active layer comprising a plurality of quantum wells; depositing a p-type semiconductor layer on the active layer; depositing a current spreading layer on the active layer; depositing a layer of photoresist on the current spreading layer; masking the layer of photoresist according to a pre-defined pattern defining the size and location of an LED to be formed and the size and location a photodetector to be formed; exposing the masked photoresist to UV light; developing the UV-exposed surface of the electronic device in a bath of photoresist developer to form the LED and the photodetector; and etching away unmasked regions on the surface to form desired contact pads and trenches designed for electrical isolation between the LED and the photodetector.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram illustrating an exemplary embodiment of an LED array with an off-chip photodetector.

Figures 2a-2d are schematic diagrams depicting a photolithography process for fabricating a monolithically integrated LED-photodetector device according to an embodiment of the subject invention. Figure 2a illustrates the starting LED wafer coated with an ITO layer. Figure 2b illustrates the result of the mesa definition and ICP etching. Figure 2c shows the metal pad coating deposited by E-beam evaporation. Figure 2d illustrates the separation between the LED and the photodetector.

Figure 3 illustrates various angles at which light beams may travel within the LED, the sapphire substrate, and the photodetector according to an embodiment of the subject invention.

Figure 4a is a microphotograph of an operating integrated LED-photodetector device according to an embodiment of the subject invention.

Figure 4b illustrates an electroluminescence (EL) spectrum (blue; the line with the peak near the center of the plot) and spectral responsivity (black; the squares that begin near the top, left-hand side of the plot) of the on-chip photodetector of a device according to an embodiment of the subject invention.

Figure 5a demonstrates the I-V characteristics of an exemplary on-chip photodetector integrated with an LED measured in darkness and illumination, respectively.

Figure 5b shows a plot of light output power (red; the line that is higher as depicted, having the square plot points) and photocurrent (blue; the line that is lower as depicted, having the circular plot points) as a function of the operation time of an exemplary device.

Figure 5c shows a plot of photocurrent (amps) versus LED current (milliamps).

Figures 6a and 6b are microphotographs of a device, according to an embodiment of the subject invention, whose surface is deposited with phosphors.

Figure 6c shows an EL spectrum of a packaged device with phosphors according to an embodiment of the subject invention.

Figures 7a and 7b are schematic diagrams of the red-, green-, and blue-light emitting diodes with monolithically integrated on-chip photodetectors arranged in a multi-chip (Figure 7a) and a chip-stacking (Figure 7b) configuration, respectively. As depicted in Figure 7a, the blue LED is the left-most, the green LED is the top-most, and the red LED is the right-most. As depicted in Figure 7b, the blue LED is on the top, the green LED is under the blue LED, and the red LED is under the green LED.

Figure 8 shows a monolithically integrated LED-photodetector device, according to an embodiment of the subject invention, comprising a GaN-based semiconductor platform.

Figure 9 shows a plot of photocurrent (amps) versus voltage (volts).

Figures 10a and 10b are schematic diagrams of the red-, green-, and blue-light emitting micro-displays with monolithically-integrated photodetectors arranged in the multi-chip (Figure 10a) and the chip-stacking (Figure 10b) configuration, respectively. As depicted in Figure 10a, starting with the top-most LED as depicted, the first left-to-right line shows red LEDs, the next line below that shows green LEDs, followed by blue, red, green, and blue LEDs, in that order. As depicted in Figure 10b, an array of blue LEDs is on the top, a green LED array is under the blue LED array, and a red LED array is under the green LED array.

Figure 11a shows a plot of voltage (V) versus current (mA); **Figure 11b** shows a plot of EL intensity (a.u.) versus wavelength (nm), and **Figure 11c** shows a plot of spectral width (nm) versus current (mA).

DETAILED DESCRIPTION

Embodiments of the subject invention provide devices directed to light-emitting diode (LED) lighting applications and methods of fabricating the same. In some embodiments, a device can comprise an LED integrated with a photodetector on the same semiconductor platform, such that the photocurrent generated by the photodetector can be used to monitor the optical output of the LED, which is located adjacent to the photodetector. Advantageously, technologies disclosed herein can be used to provide compact, robust, and reliable photodetectors capable of monitoring LED emission via a low-cost approach.

In some embodiments, the LED and the photodetector have the same semiconductor structure. Because luminesce and absorption are complementary processes, an LED that is intended for light emission can also function as a photodetector in which electron-hole pairs are generated by optical absorption, producing a substantial photocurrent flow between electrodes. By defining a region of the device as a photodetector, the photocurrent generated can be exploited for monitoring the optical output of the LED located on the same device.

In some embodiments, the LED and the photodetector are co-fabricated as a unit by a single set of micro-fabrication procedures rather than being constructed separately. This monolithic integration approach, as an alternative to the currently available external integration approach, is an attractive manufacturing strategy due to its use of smaller circuit boards, fewer discrete components, and reduced manufacturing cost.

Advantageously, the monolithic integration methods disclosed herein can improve the overall device performance by reducing the size of the photodetector and allowing the components (*e.g.*, the LED and the photodetector) to be placed in close proximity to each other, thereby maximizing the effect of optical coupling between the LED and the photodetector. Furthermore, the monolithic fabrication strategies provided herein utilize much less material than if the device were fabricated in discrete steps. In an exemplary embodiment, an LED and a photodetector having identical (or similar) structure as the LED are co-fabricated on the same semiconductor platform comprising, *e.g.*, GaN-on-sapphire, using a single set of photolithography procedures.

According to some embodiments of the subject invention, the ability for a photodetector located adjacent to an LED on the same platform to detect optical output of the LED is attributed to a light coupling mechanism involving two distinct processes (Figure 3). First, the side-by-side, *i.e.*, planar, configuration allows light emitted from the LED's etched sidewall to directly irradiate the nearby photodetector. The upward emitting light from the LED, on the other hand, is extracted from the device into free space and would not be detected by the planar photodetector located adjacent to the LED. Second, a transparent substrate, such as sapphire, can serve as a waveguide that allows a constant portion of the downward-emitting light to propagate toward the photodetector. The photodetector subsequently converts the light signal into measurable photocurrent signal. Advantageously, with the photocurrent data as the feedback signal monitoring the light intensity level of the LED, any signal drifts in the diode can be corrected for efficiency, ensuring precise monitoring of the long-term and short-term performance of the LED device.

In some embodiments, the integrated device comprising an LED and an adjacently located photodetector can be fabricated monolithically using standard micro-fabrication procedures, including, *inter alia*, photolithography, etching, and metal deposition. In some embodiments, layer deposition can be accomplished using a method selected from thermal evaporation, sputtering, electron beam evaporation, and a combination thereof. Figures 2a to 2d are schematic diagrams demonstrating an exemplary set of procedures in which a GaN-on-sapphire platform is used to fabricate an integrated device according to an embodiment of the subject invention. An illustration of the finished device is shown in Figure 8.

Referring to Figure 2a, the GaN-based platform can be grown by, for example, metal organic chemical vapor deposition (MOCVD) on a transparent sapphire substrate. The resulting GaN-based LED structure can include an n-type GaN layer, an active layer comprising multiple quantum wells, and a p-type GaN layer sequentially deposited onto the substrate, though embodiments are not limited thereto. A transparent current spreading layer comprising, for example, Ni/Au or indium-tin-oxide (ITO), can be deposited on top of the p-type GaN layer to ensure uniform light emission over the surface of the device (see, for example, Figure 8).

In some embodiments, the bottom surface of the GaN-based platform comprises a reflective coating selected from, for example, silver, aluminum, and a distributed Bragg reflector (DBR). In an exemplary embodiment, the coating comprises a DBR. A DBR, relying on pairs of alternating dielectric materials having different refractive indices, comprise a wavelength-selective mirror that reflects light of certain wavelengths within a reflectance band and transmits light of different wavelengths within the transmission band. The characteristics of the DBR depend on design parameters such as, for example, choice of dielectric materials and their respective thicknesses.

Figure 2b illustrates a layer of photoresist being spin-coated onto the current spreading layer, which is then exposed to UV light through a photo-mask comprising a pre-defined pattern defining the boundaries of the mesa of the various components of the integrated device. A mesa, as used herein, denotes a region on the device surface having distinct boundaries defining a specific component of the device.

In some embodiments, the UV-exposed surface of the device can be developed in a bath of photoresist developer. After development, the photoresist pattern can be hard baked at a temperature selected from a range of between about 115° C and about 170° C for duration of about 3 minutes to about 10 minutes. In an exemplary embodiment, the photoresist pattern can be hard baked at approximately 120° C for about 5 minutes. The uncoated regions of GaN can be etched away until the underlying n-type layer is exposed. In some embodiments, the etching can be achieved by a number of methods including, but not limited to, plasma etching, ion etching, and laser etching.

In some embodiments, the photoresist pattern can be used to expose areas of the p-type and n-type contact pads, shown as the p-electrodes and n-electrodes, respectively, in Figure 8, using another photolithography process. Specifically, a bi-layer structure comprising, for example, Ti/Au and/or Ni/Au can be deposited by electron beam (E-beam) evaporation and lifted off in a bath (*e.g.*, an acetone bath). Contacts can be subjected to rapid thermal annealing (RTA) at a temperature selected from a range of between about 450° C and about 600° C for duration of about 5 minutes to about 10 minutes. In an exemplary embodiment, the RTA can be carried out at about 550°C for about 5 minutes in nitrogen ambient and/or oxygen ambient.

A selective etching process can subsequently be carried out to form trenches for electrical isolation between the contact pads of the LED and the photodetector, respectively. The selective etching of the GaN epilayer over sapphire may be achieved using a plasma etching or pulsed laser etching method (Figure 2d). Each individual integrated LED-photodetector chip can be diced by laser machining and/or a diamond dicing saw.

The sidewalls of mesas of the LED and photodetector may be passivated by insulating materials such as, *e.g.*, silicon dioxide or aluminum oxide, though embodiments are not limited thereto. A layer of oxide can be coated over the entire surface using, for example, electron beam evaporation, plasma-enhanced chemical vapor deposition (PECVD), or atomic layer deposition (ALD) (Figure 2c).

In some embodiments, the integrated LED-photodetector chip can be bonded to a transistor outline (TO) metal can package using an adhesive (*e.g.*, acrylics and epoxies), and bond pads can be connected to the package by wire bonding. Four wire-bonds may be required to establish electrical connection to the chips, including the p- and n-pads of the LED and photodetector.

In some embodiments, the surface area of the LED is substantially larger than the surface area of the monolithically integrated photodetector. In an exemplary embodiment, the surface area of the LED is approximately 1000 x 1000 μm^2 (or less) and the surface area of the integrated photodetector is approximately 100 x 100 μm^2 (or less). In some embodiments, the monolithically integrated photodetector is located in the corner, adjacent to and electrically separated from the LED, of the semiconductor platform that has a predetermined size in accordance with its target application. The shapes, dimensions, and relative positions of the LED and the photodetector on a given platform are determined based on the target application of the device and are therefore not limited to the examples provided herein.

In the embodiment illustrated in Figure 4a, the LED emits visible light of blue color; however, embodiments of the subject invention can also provide LEDs emitting monochromatic light of other colors when a voltage bias is applied. For example, embodiments of the subject invention are compatible with GaN-based LEDs grown on sapphire or bulk GaN substrates. The direct band gap of semiconductors comprising InGaN (from about 0.7 eV to about 3.4 eV) or AlGaN (from about 3.4 eV to about 6.2 eV) provide quantum wells that can cover a wide spectral range such as, for example, from approximately 200 nm to approximately 1770 nm, and the emission wavelength (*i.e.*, color) can be tuned based on the composition of indium or aluminum. Figure 4a is a microphotograph of an integrated LED-photodetector device emitting monochromatic blue light, while Figure 4b shows the device's corresponding electroluminescence spectrum according to an embodiment of the subject invention.

Due to the presence of stoke shift effect, there is a spectral difference between optical absorption and luminescence. For example, the absorption spectrum shown in Figure 4b indicates that the photodetector is able to respond to the shorter-wavelength-half of the LED emission spectrum. Figure 5a shows that the photocurrent level measured when the LED was in operation at 10 mA is approximately four orders of magnitude higher than that measured under conditions of darkness, revealing that the integrated photodetector is capable of robustly responding to weak illumination intensity generated by the LED. This is advantageous because the key function of the on-chip photodetector is to monitor the variation in light intensity emitted by the LED. Figure 5b shows the result of a device aging test revealing that the measured photocurrent can serve as a reliable feedback signal for monitoring the intensity of the LED emission. Advantageously, embodiments of the integrated device provided herein enable both visible light emission from the LED and visible light detection by the photodetector integrated monolithically on the same platform.

In some embodiments, a lighting device can comprise a plurality of electronic devices each comprising an LED and a photodetector integrated onto the same semiconductor platform, and the current generated by the photodetector of each individual electronic device can be used to monitor the optical output of the LED on the same electronic device. The LED and the photodetector on a given electronic device can have the same semiconductor structure and can be fabricated monolithically via a single set of photolithography procedures. In some embodiments, the lighting device is a broadband LED light source.

In one embodiment, broadband LED emission is achieved by the use of phosphors for color down-conversion. Phosphorescent materials that emit light when exposed to certain wavelengths of radiation are used for color conversion in LEDs. As a device emits a higher-energy photon (*i.e.*, shorter-wavelength), the phosphor absorbs it and then re-emits a lower-energy (*i.e.*, longer-wavelength), and thus differently colored, photon. For white light emission, yellow, green, and/or red light-emitting phosphors may be used. Although the integration of phosphor materials requires the surface deposition of phosphor powder as well as an encapsulation layer, the sensing capability of photodetector will remain unaffected due to the light coupling mechanism provided by the underlying transparent substrate (Figures 6a and 6b).

In another embodiment, broadband LED emission is achieved by mounting a plurality of LED, each integrated with a photodetector and capable of emitting the same or different visible light of primary colors (*i.e.*, red, green, and blue) as the other LEDs, in a planar (*i.e.*, a multi-chip configuration) or vertically stacked geometry (*i.e.*, a chip-stacking configuration) into a single package. A chip-stacking configuration provides optimal color by stacking a blue LED onto a green LED, which is subsequently stacked on top of a red LED. The red LED structure can be an AlInGaP alloy grown on a GaAs substrate, in which case the substrate would not be transparent to the emitted light and the photodetector will rely entirely on sidewall absorption. Each of the three stacked LEDs can be individually controllable when arranged in the chip-stacking configuration. If all three are illuminated, an optically-mixed output can result in white light emission. Optical output of each individual LED can be readily monitored by its corresponding monolithically integrated photodetector. In a multi-chip approach, discrete blue, green, and red LEDs in a broadband lighting device can be driven individually and the intensity of various color components can thus be varied. Unlike the stacked configuration, the multi-chip configuration does not produce mixed colors and thus does not constitute a color-tunable lighting device. In an embodiment, lighting sources arranged in a multi-chip or a chip-stacking configuration can be used to implement devices such as a full-color micro-display.

Overall, the integrated LED-photodetector devices and methods provided herein can offer several advantages. First, on-chip functionality and reliability are improved with reduced packaging cost, achieved by eliminating hybrid optics and other supporting components. Second, the separation between the LED and the photodetector is minimized without intercepting LED emission, resulting in an ultra-compact device structure. Third, the on-chip photodetectors can better differentiate the intensity changes from individual LEDs than their off-chip counterparts. Fourth, the sensing capability of the photodetector remains unaffected by top-surface deposition of materials such as phosphor powder and/or an encapsulation layer as the photodetector relies on downward-travelling light signals from the adjacent LED.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

CLAIMS

What is claimed is:

1. An electronic device, comprising a light-emitting diode and a photodetector integrated onto a single semiconductor platform and positioned adjacent to each other, wherein the current generated by the photodetector is used to monitor the optical output of the light-emitting diode.

2. The device according to claim 1, wherein the light-emitting diode and the photodetector have the same semiconductor structure.

3. The device according to any of claims 1-2, wherein the light-emitting diode and the photodetector are monolithically fabricated onto the single semiconductor platform.

4. The device according to any of claims 1-3, wherein the surface area of the light-emitting diode is larger than the surface area of the photodetector.

5. The device according to any of claims 1-3, wherein the surface area of the light-emitting diode is at least ten times larger than the surface area of the photodetector.

6. The device according to any of claims 1-5, wherein the single semiconductor platform comprises GaN-based materials.

7. The device according to any of claims 1-6, wherein the light-emitting diode generates light in a spectral range between about 200 nm and about 1770 nm, and the photodetector detects light within a portion of said spectral range of the light-emitting diode.

8. A method of fabricating an electronic device, the method comprising:

depositing an n-type semiconductor layer on a top surface of a substrate having a coating on a bottom surface thereof;

depositing an active layer on the substrate, the active layer comprising a plurality of quantum wells;

depositing a p-type semiconductor layer on the active layer;

depositing a current spreading layer on the active layer;

depositing a layer of photoresist on the current spreading layer;

masking the layer of photoresist according to a pre-defined pattern defining the size and location of a light-emitting diode to be formed and the size and location a photodetector to be formed;

exposing the masked photoresist to UV light;

developing the UV-exposed surface of the electronic device in a bath of photoresist developer to form the light-emitting diode and the photodetector; and

etching away unmasked regions on the surface to form desired contact pads and trenches designed for electrical isolation between the light-emitting diode and the photodetector.

9. The method according to claim 8, wherein the coating on the bottom surface of the substrate comprises at least one of silver, aluminum, and a distributed Bragg reflector.

10. The method according to any of claims 8-9, wherein the substrate is optically transparent.

11. The method according to any of claims 8-10, wherein the current spreading layer is optically semi-transparent.

12. The method according to any of claims 8-10, wherein the current spreading layer is optically transparent.

13. A lighting device, comprising a plurality of electronic devices, each electronic device comprising a light-emitting diode and a photodetector integrated onto a single semiconductor platform and positioned adjacent to each other, wherein the current generated by the photodetector of each electronic device is used to monitor the optical output of the light-emitting diode of the same electronic device.

14. The device according to claim 13, wherein each light-emitting diode has the same semiconductor structure as the photodetector of the same electronic device.

15. The device according to any of claims 13-14, wherein all light-emitting diodes and all photodetectors have the same semiconductor structure.

16. The device according to any of claims 13-15, wherein, for each electronic device, the light-emitting diode and the photodetector are monolithically fabricated onto the single semiconductor platform of said electronic device.

17. The device according to any of claims 13-16, wherein, for each electronic device, the surface area of the light-emitting diode is larger than the surface area of the photodetector of said electronic device.

18. The device according to any of claims 13-17, wherein the surface area of each light-emitting diode is larger than the surface area of each photodetector.

19. The device according to any of claims 13-16, wherein, for each electronic device, the surface area of the light-emitting diode is at least ten times larger than the surface area of the photodetector of said electronic device.

20. The device according to any of claims 13-19, wherein the surface area of each light-emitting diode is at least ten times larger than the surface area of each photodetector.

21. The device according to any of claims 13-20, wherein each electronic device of the plurality of electronic devices is individually controlled.

22. The device according to any of claims 13-21, wherein each electronic device of the plurality of electronic devices is configured to emit light of the same spectral range as light emitted from all other electronic devices.

23. The device according to any of claims 13-21, wherein at least one electronic device of the plurality of electronic devices is configured to emit light of a spectral range that is different from the spectral range of light at least one of the other electronic devices is configured to emit.

24. The device according to any of claims 13-21, wherein all electronic devices are configured to emit light of a spectral range that is different from the spectral range of light all other electronic devices are configured to emit.

25. The device according to any of claims 13-24, wherein, for each electronic device, the single semiconductor platform comprises GaN-based materials.

26. The device according to any of claims 13-25, wherein the light-emitting diode of each electronic device generates light in a spectral range of from 200 nm to 1770 nm, and the photodetector detects light within a portion of said spectral range of the light-emitting diode.

27. The device according to any of claims 13-26, wherein all electronic devices of the plurality of electronic devices are mounted onto a single package in a side-by-side configuration.

28. The device according to any of claims 13-26, wherein all electronic devices of the plurality of electronic devices are mounted onto a single package in a vertically stacked configuration.

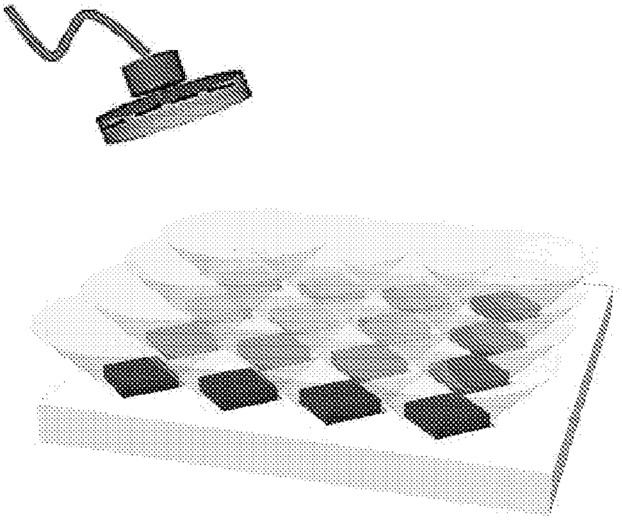
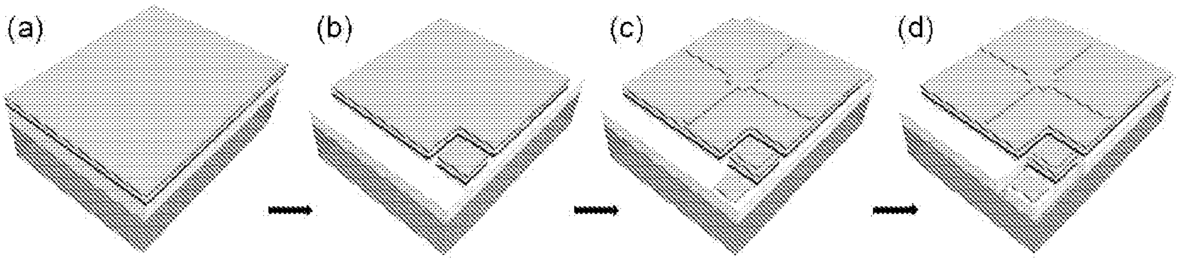


FIG. 1



FIGS. 2a-2d

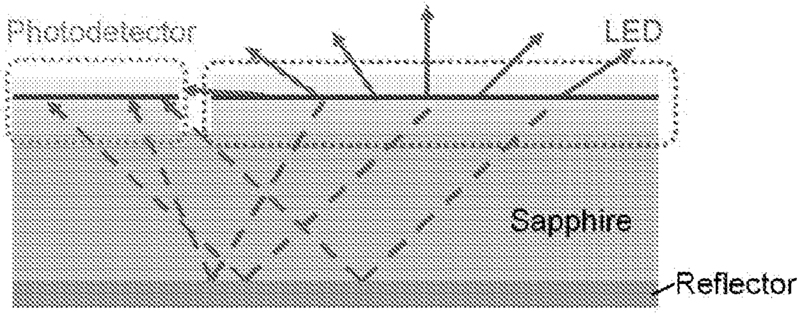
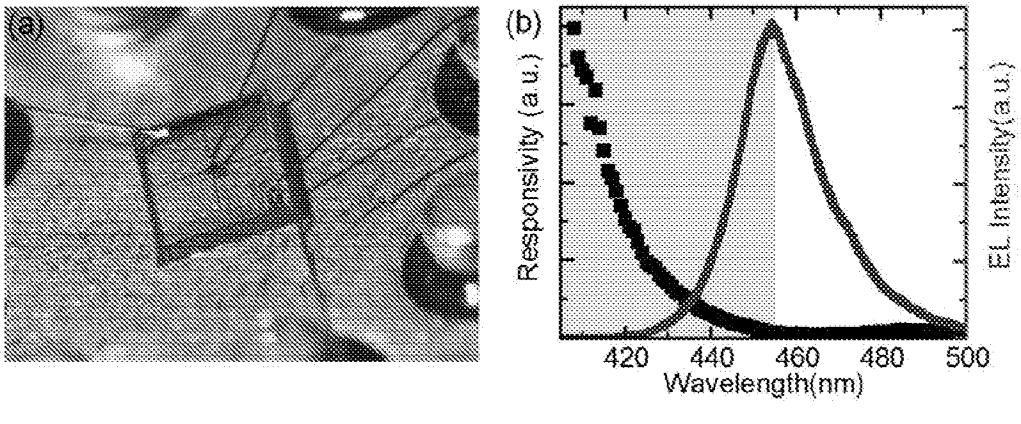
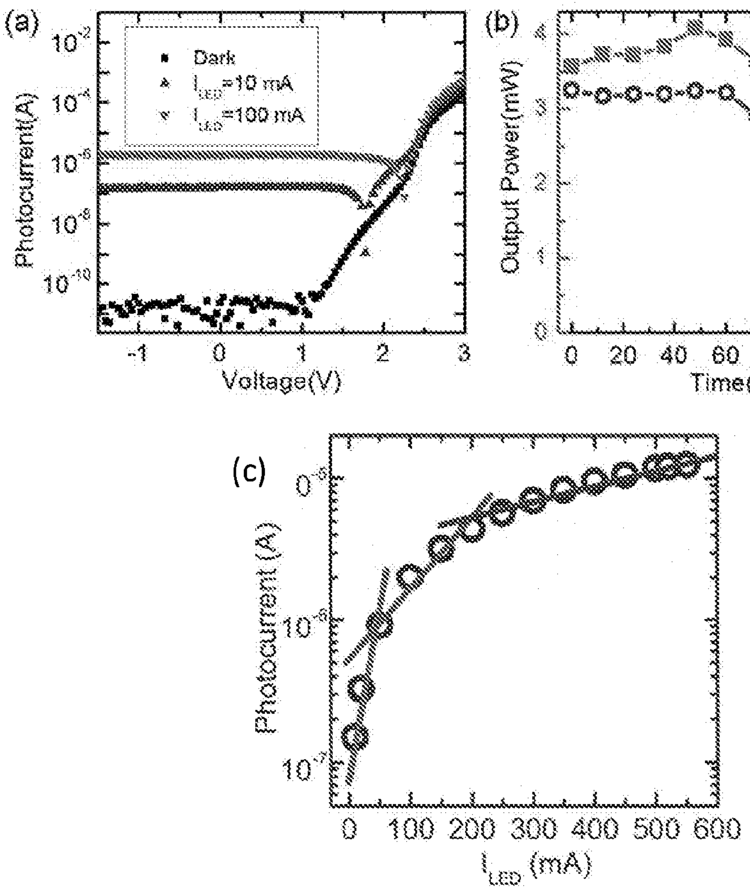


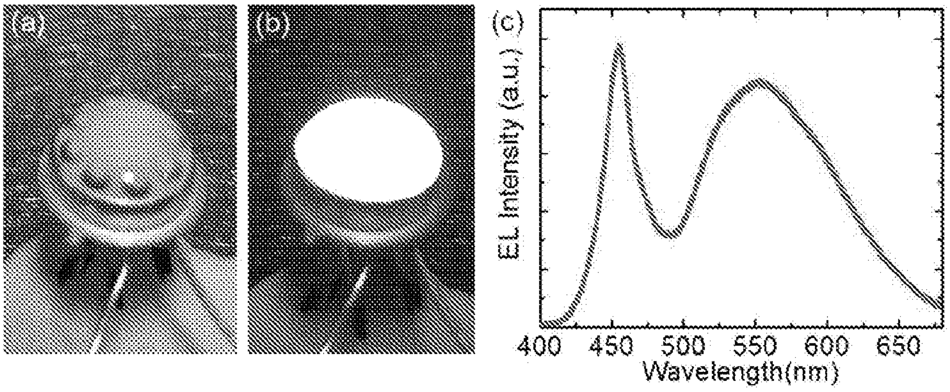
FIG. 3



FIGS. 4a-4b


(a)
Dark
I_{LED}=10 mA
I_{LED}=100 mA
Photocurrent(A)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
-1
0
1
2
3
Voltage(V)
(b)
Output Power(mW)
Photocurrent(uA)
0
1
2
3
4
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
20
40
60
80
100
120
Time(h)
(c)
Photocurrent (A)
10^{-5}
10^{-6}
10^{-7}
0
100
200
300
400
500
600
I_{LED} (mA)

FIGS. 5a-5c


(a)
(b)
(c)
EL Intensity (a.u.)
400
450
500
550
600
650
Wavelength(nm)

FIGS. 6a-6c

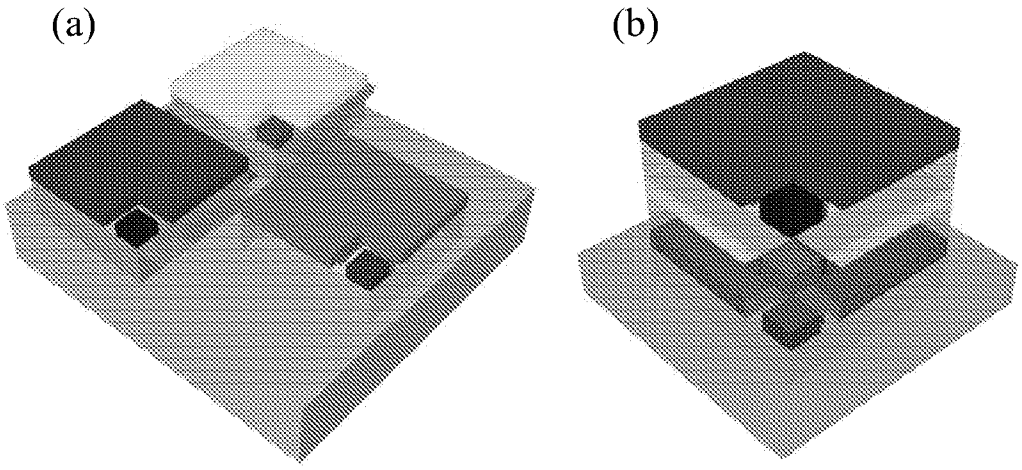


FIG. 7a-7b

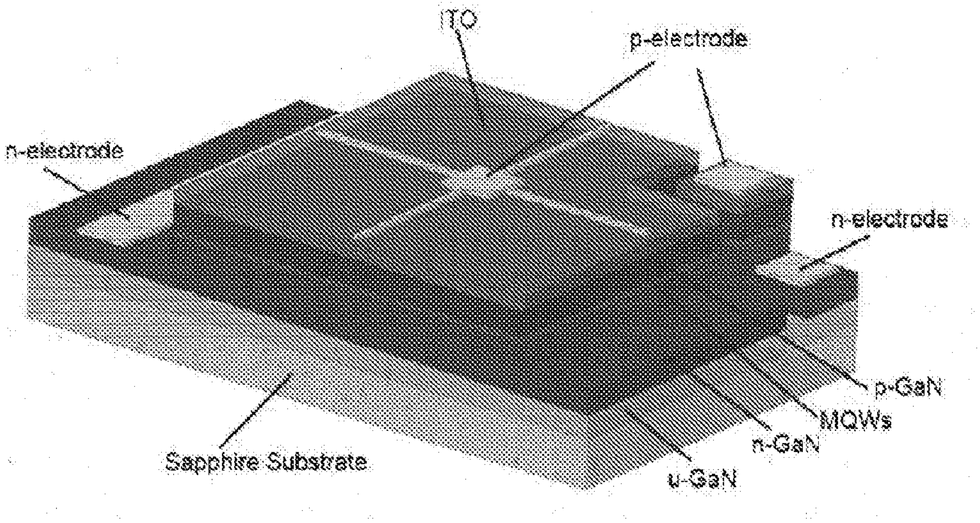


FIG. 8

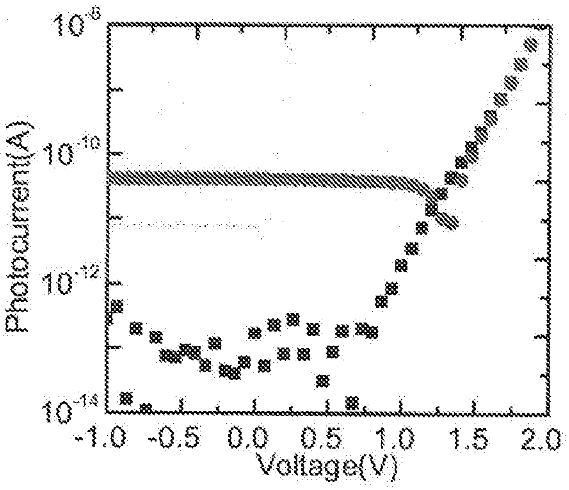


FIG. 9

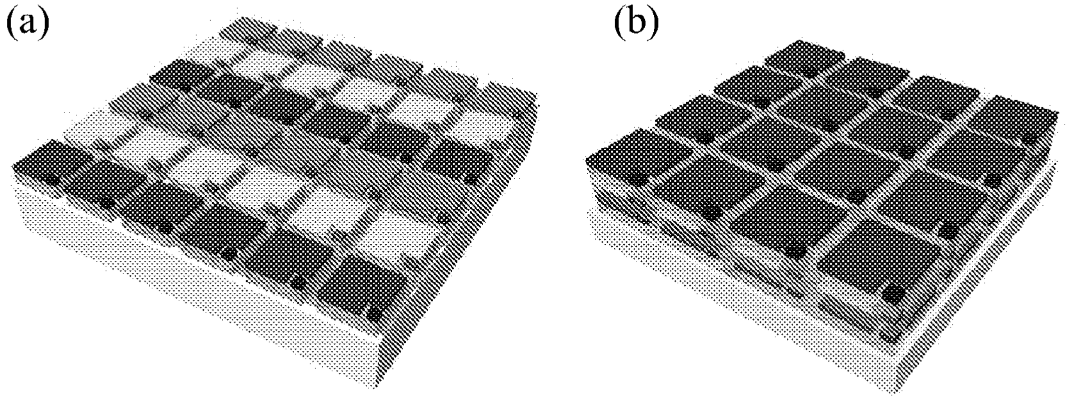


FIG. 10a-10b

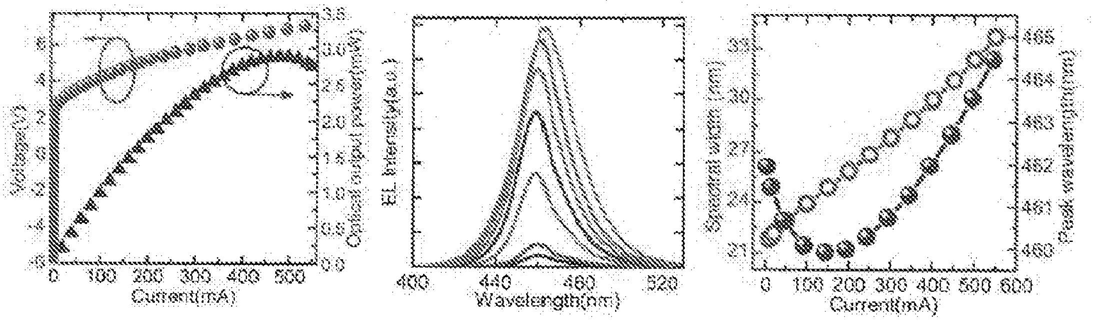

Voltage(V)
6
4
2
0
-2
-4
-6
0 100 200 300 400 500
Current(mA)
Optical output power(mW)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
EL Intensity(a.u.)
400 440 480 520
Wavelength(nm)
Spectral width (nm)
33
30
27
24
21
Peak wavelength(nm)
465
464
463
462
461
460
0 100 200 300 400 500 600
Current(mA)

FIG. 11a-11c

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2016/082320

A. CLASSIFICATION OF SUBJECT MATTER

H01L 21/761(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L

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

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

CNPAT, CNKI, WPI, IEEE, EPODOC: HONG KONG UNIVERSITY, CHOI HOI WAI, LED, light, emit+, diode, photodetect +, monitor, detect, measur+, in w situ, monolithic, single, common, substrate, platform, PD, phototransistor, degradat+, optical, photocurrent, photoconduct+, watch+, guard+

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 105428305 A (NANJING UNIVSITY OF POSTS AND TELECOMMUNICATIONS) 23 March 2016 (2016-03-23) description, paragraphs [0033]-[0051], Figs. 1-3	1-28
X	GB 1456120 A (RIDEOUT, VINCENT LEO ET AL.) 17 November 1976 (1976-11-17) description, from page 1, line 52 to page 2, line 64, Figs. 1-2	1-7, 13-28
X	JP S6114752 A (TOSHIBA K.K.) 22 January 1986 (1986-01-22) description, pages 301-302, Figs. 1-3	1-7, 13-28
A	JP 2010278151 A (PANASONIC ELEC. WORKS CO., LTD.) 09 December 2010 (2010-12-09) the whole document	1-28
A	US 5298735 A (EASTMAN KODAK CO.) 29 March 1994 (1994-03-29) the whole document	1-28

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

*	Special categories of cited documents:
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"E"	earlier application or patent but published on or after the international filing date
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"O"	document referring to an oral disclosure, use, exhibition or other means
"P"	document published prior to the international filing date but later than the priority date claimed
"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&"	document member of the same patent family

Date of the actual completion of the international search **15 December 2016**	Date of mailing of the international search report **28 December 2016**
Name and mailing address of the ISA/CN **STATE INTELLECTUAL PROPERTY OFFICE OF THE P.R.CHINA** **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088** **China** Facsimile No. **(86-10)62019451**	Authorized officer **ZHOU,Zhongtang** Telephone No. **(86-10)53318981**

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/CN2016/082320

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
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		JP S5098291 A	05 August 1975
		US 3881113 A	29 April 1975
		FR 2256544 B1	22 October 1976
		DE 2458745 A1	10 July 1975
JP S6114752 A	22 January 1986	None	
JP 2010278151 A	09 December 2010	JP 5249856 B2	31 July 2013
US 5298735 A	29 March 1994	None	