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(54) **LIGHT EMITTING DIODES USING ULTRA-THIN QUANTUM HETEROSTRUCTURES**

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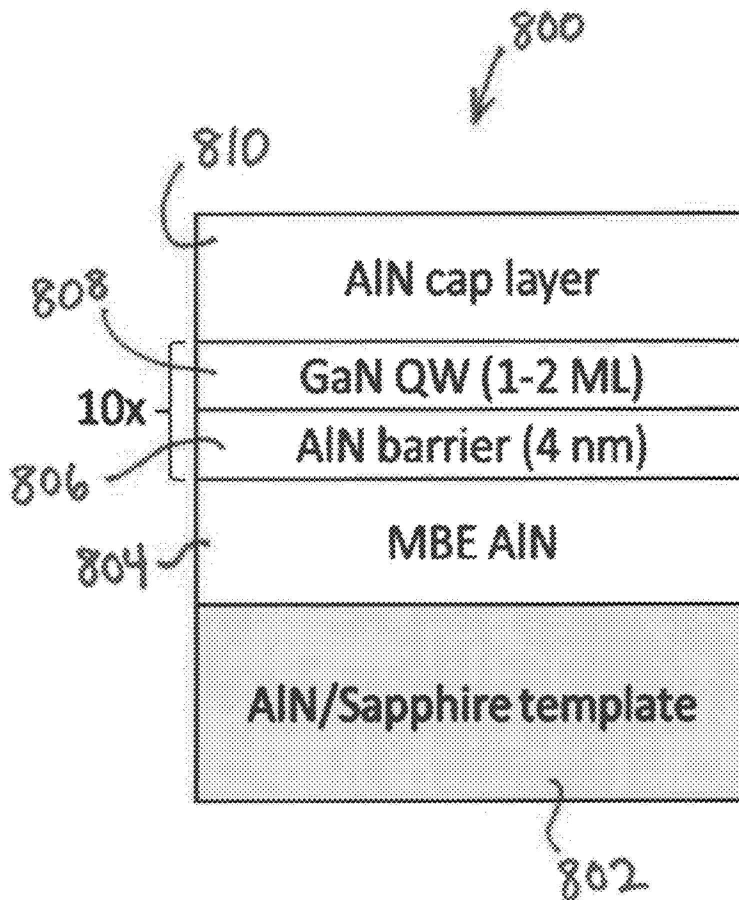
(57) **ABSTRACT**

A DUV-LED including a bottom substrate, a n-contact/injection layer formed on the bottom substrate, a p-contact region, and an emitting active region between the n-contact/injection layer and the contact region. The emitting active region includes at least one GaN quantum heterostructure. The at least one GaN quantum heterostructures is sized and shaped to determine a certain emission wavelength. Preferably, the certain emission wavelength is in a range of approximately 219-280 nm. In one embodiment, the size is controlled by precisely controlling parameters selected from the group consisting of: an epitaxial deposition time; a Ga/N ratio; a thermal annealing time; a temperature during deposition; and combinations thereof.



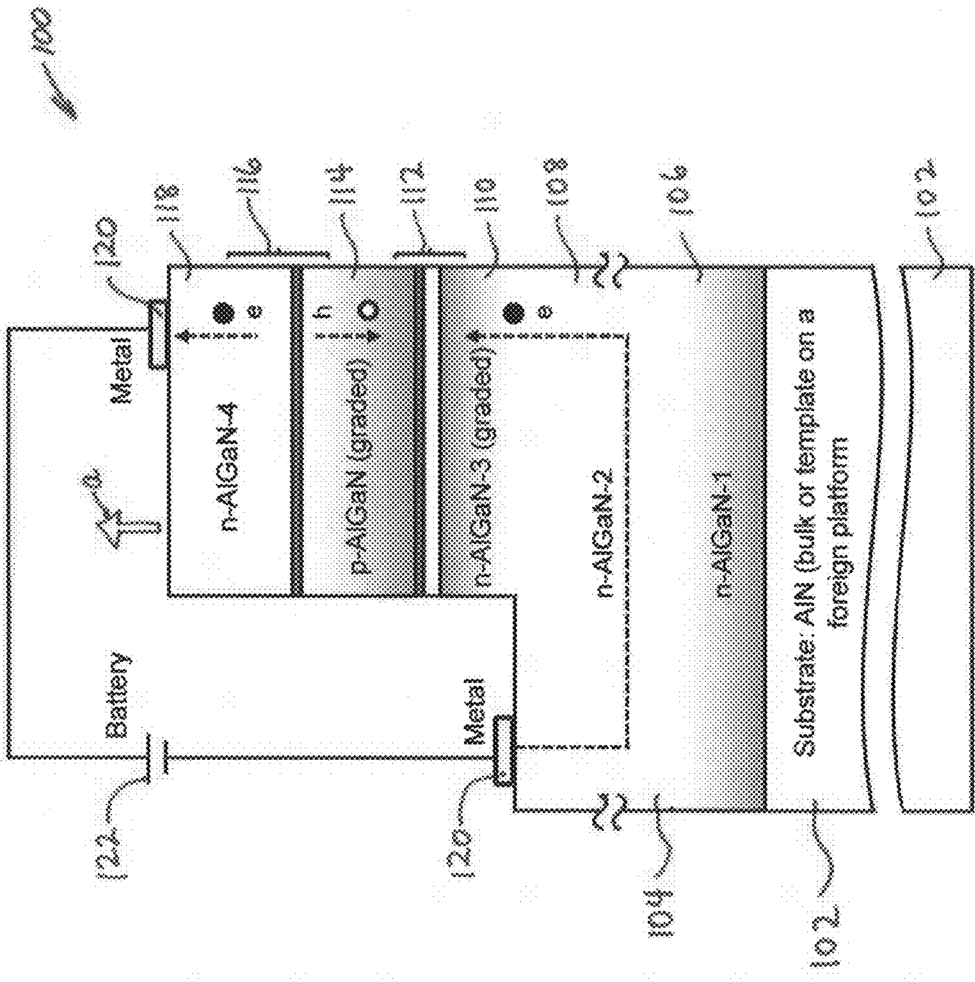


Figure 1

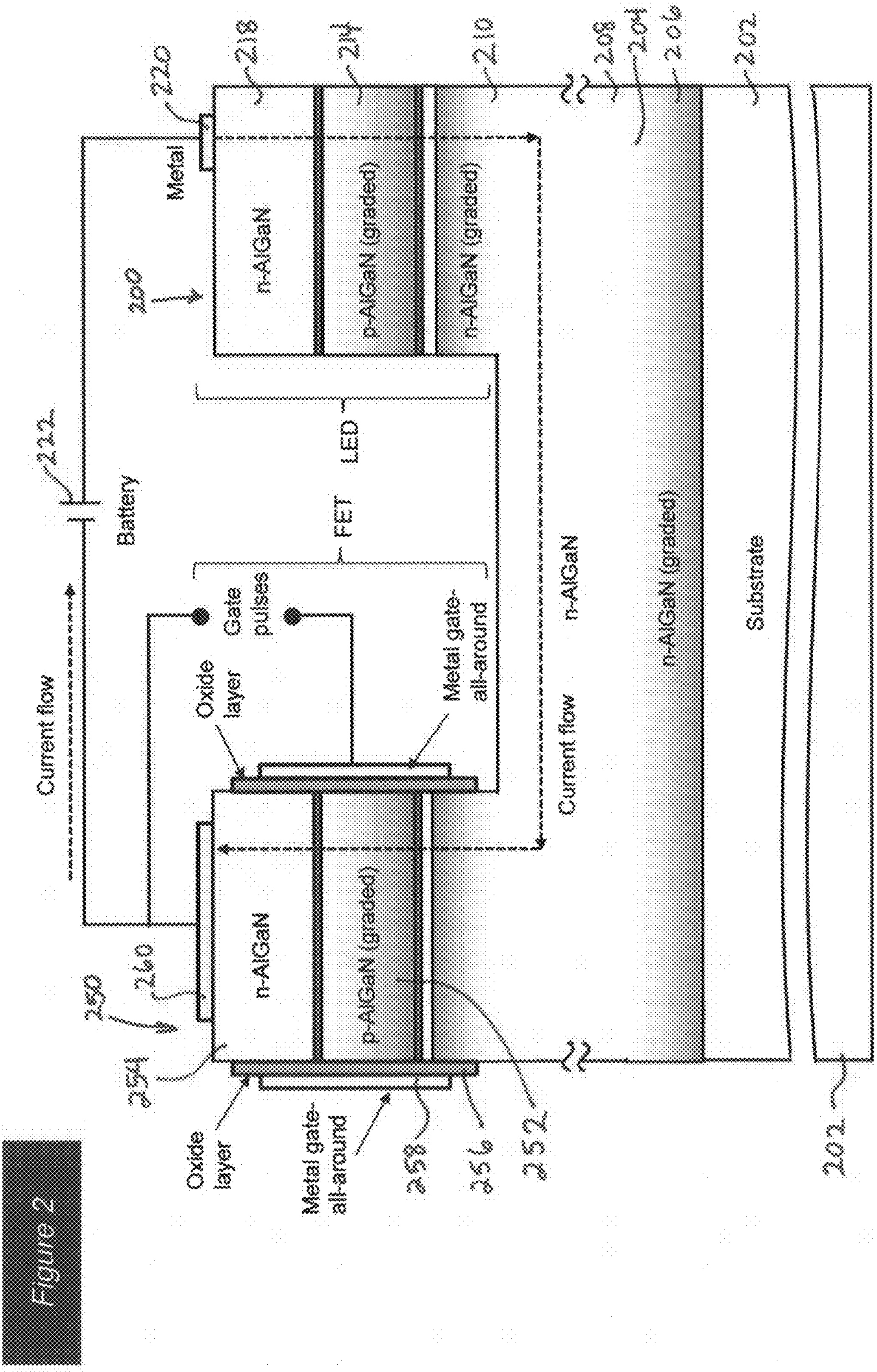


Figure 2
Current flow
Battery
222
220
Metal
218
214
210
208
204
206
202
200
n-AlGaN
p-AlGaN (graded)
n-AlGaN (graded)
LED
FET
Gate pulses
Oxide layer
Metal gate-all-around
n-AlGaN
n-AlGaN (graded)
Substrate
Current flow
250
260
254
n-AlGaN
p-AlGaN (graded)
Oxide layer
Metal gate-all-around
258
256
252
202

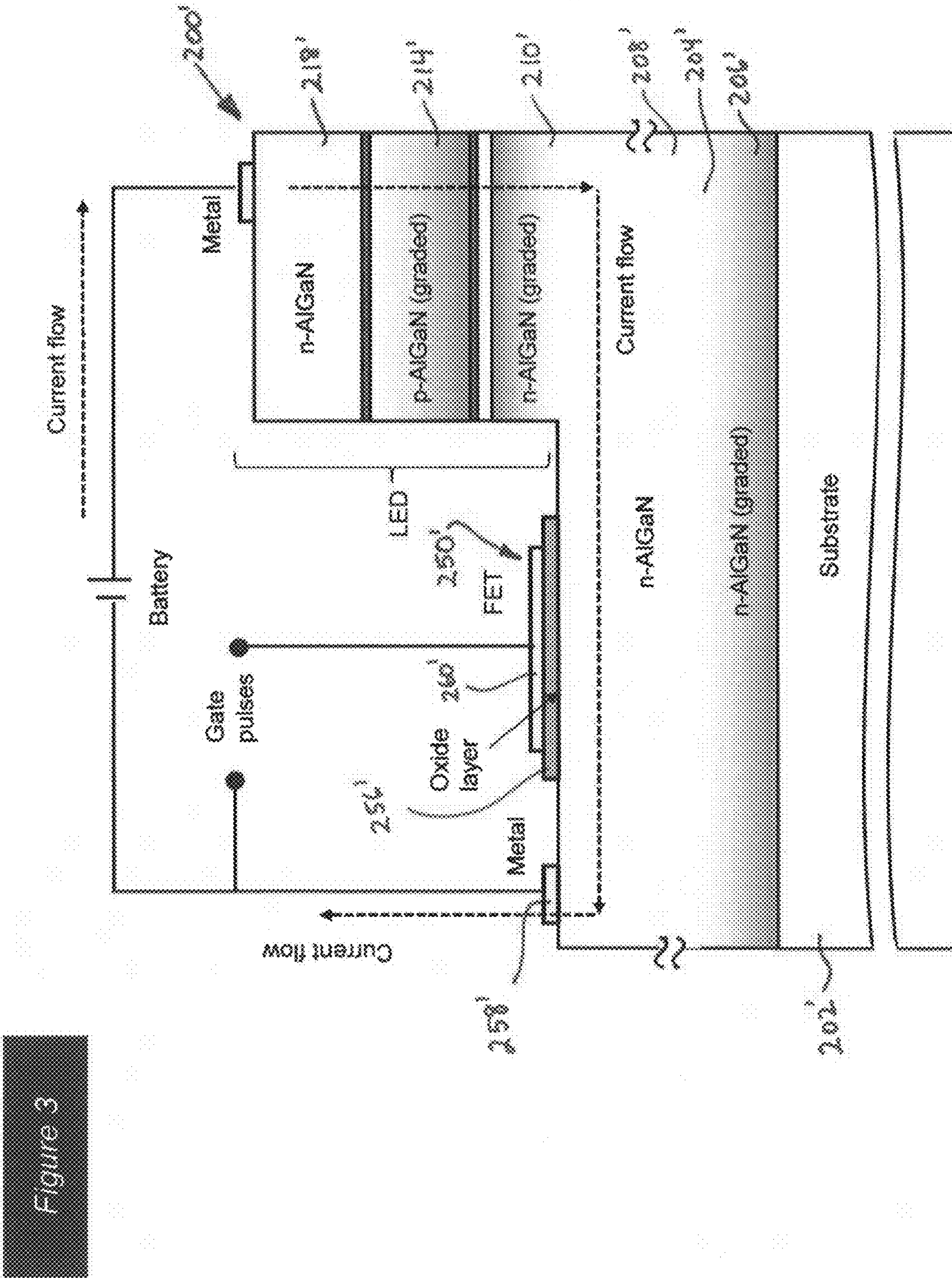


Figure 3
200'
218'
214'
210'
208'
204'
206'
Metal
n-AlGaN
p-AlGaN (graded)
n-AlGaN (graded)
Current flow
Current flow
LED
250'
FET
Battery
Gate
pulses
260'
Oxide
layer
252'
Metal
Current flow
258'
n-AlGaN
n-AlGaN (graded)
Substrate
202'

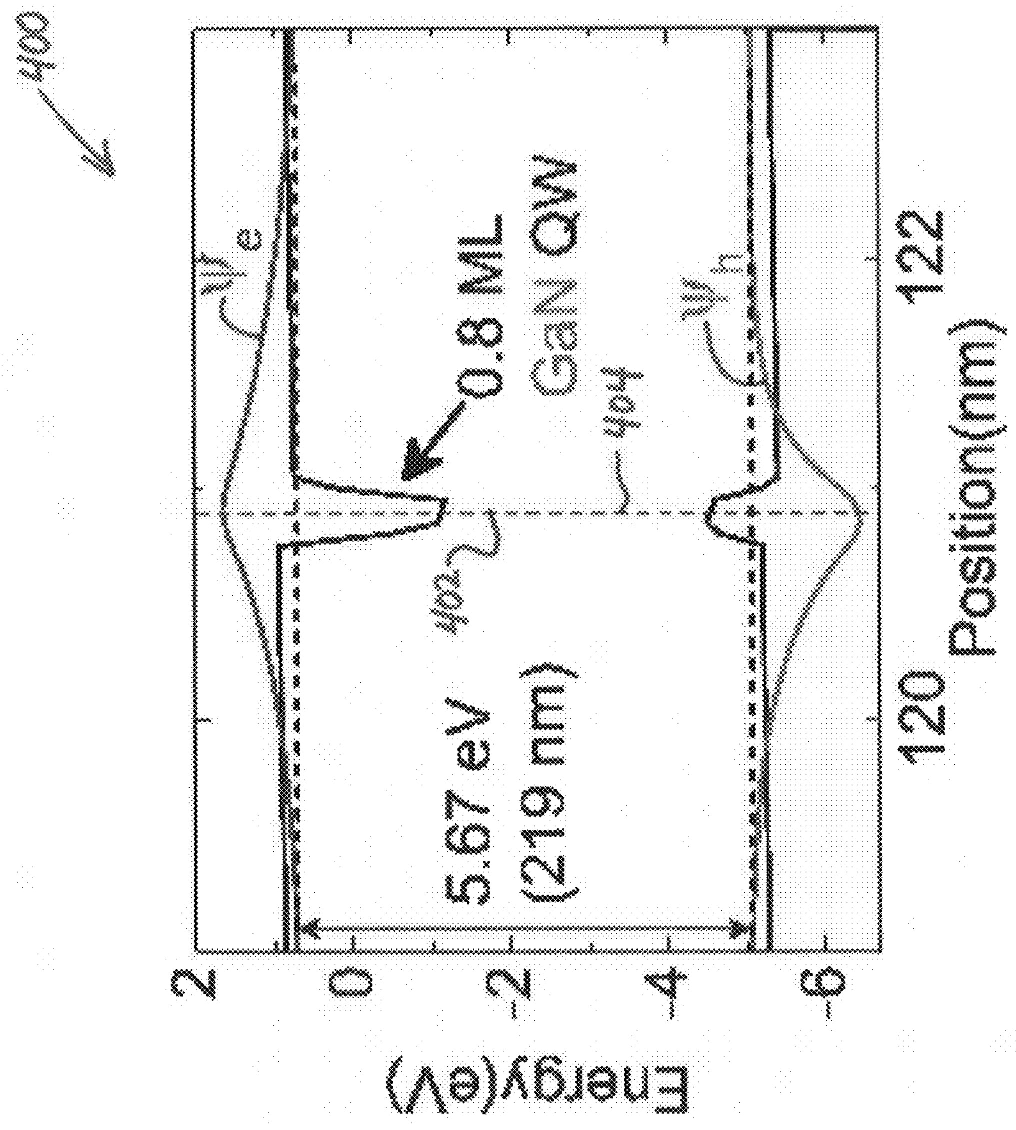


Figure 4

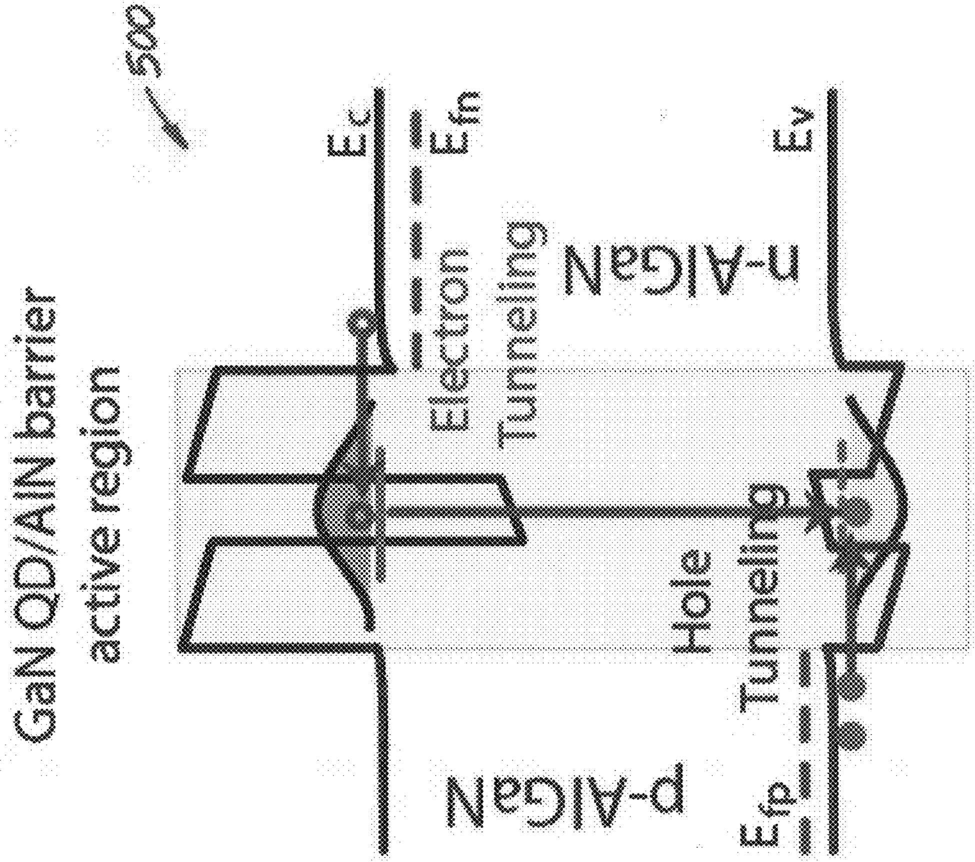


Figure 5

Figure 6

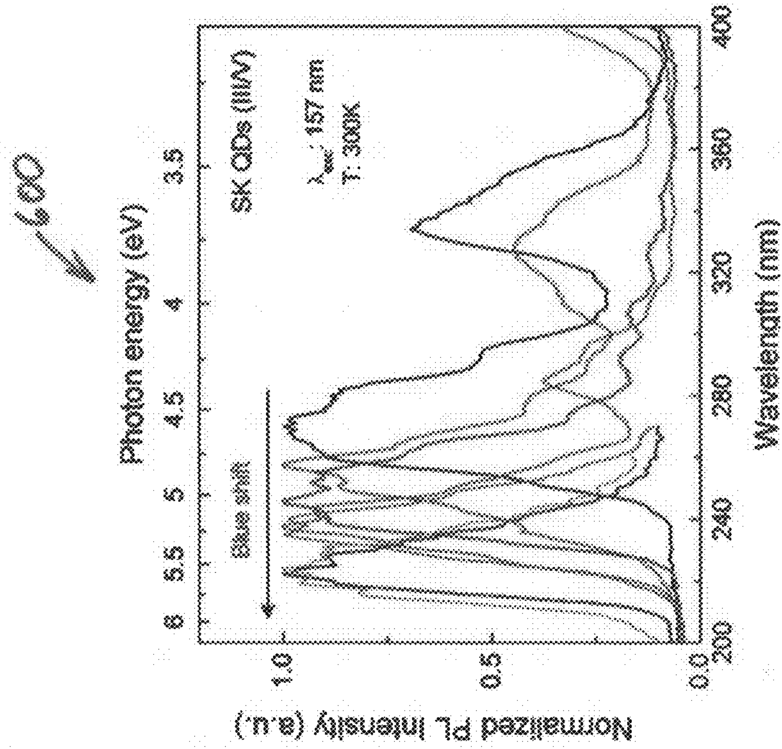
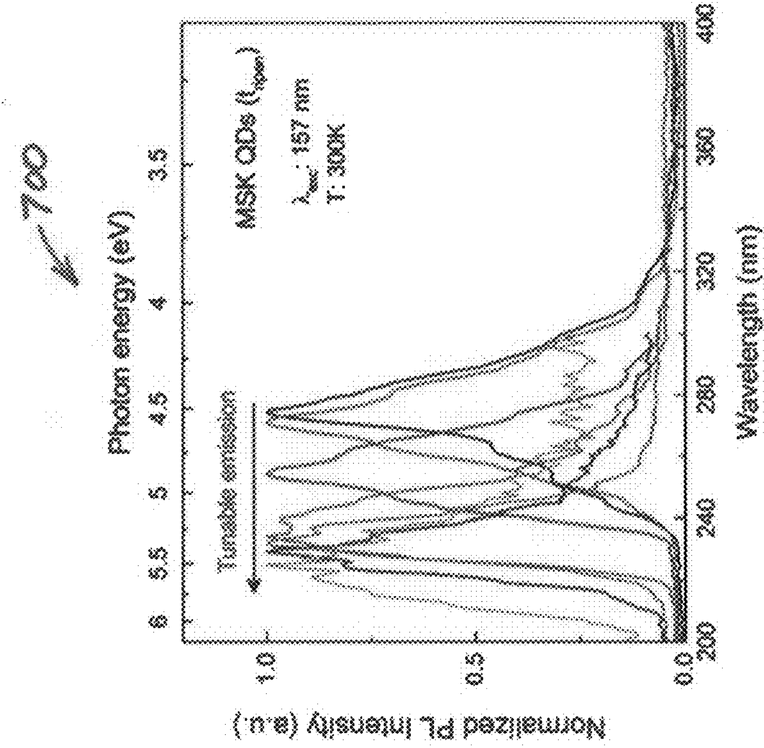


Figure 7



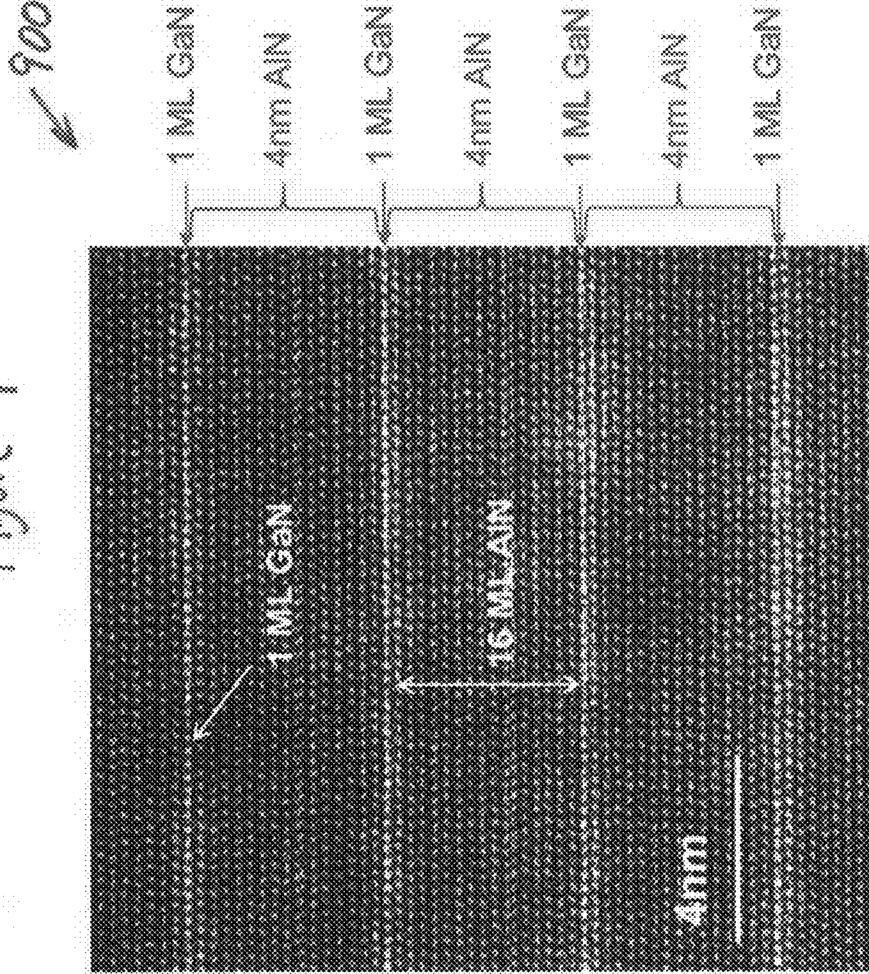


Figure 9

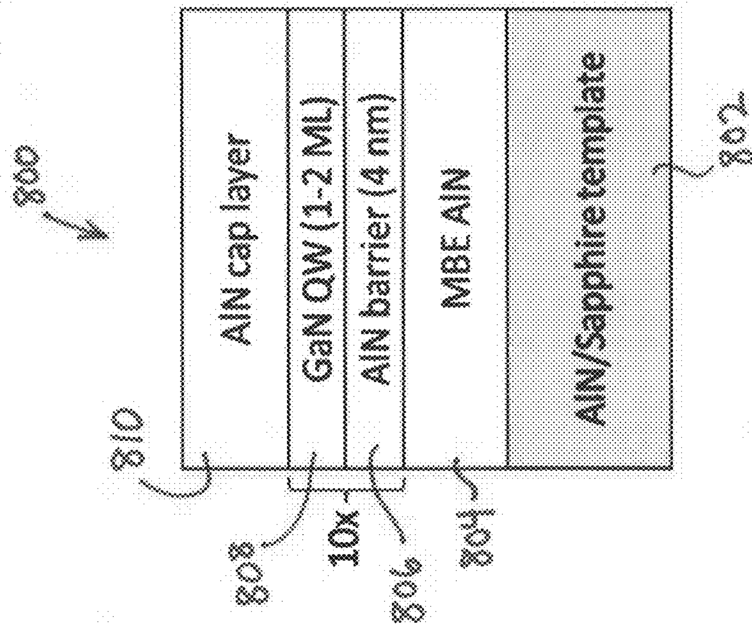


Figure 8

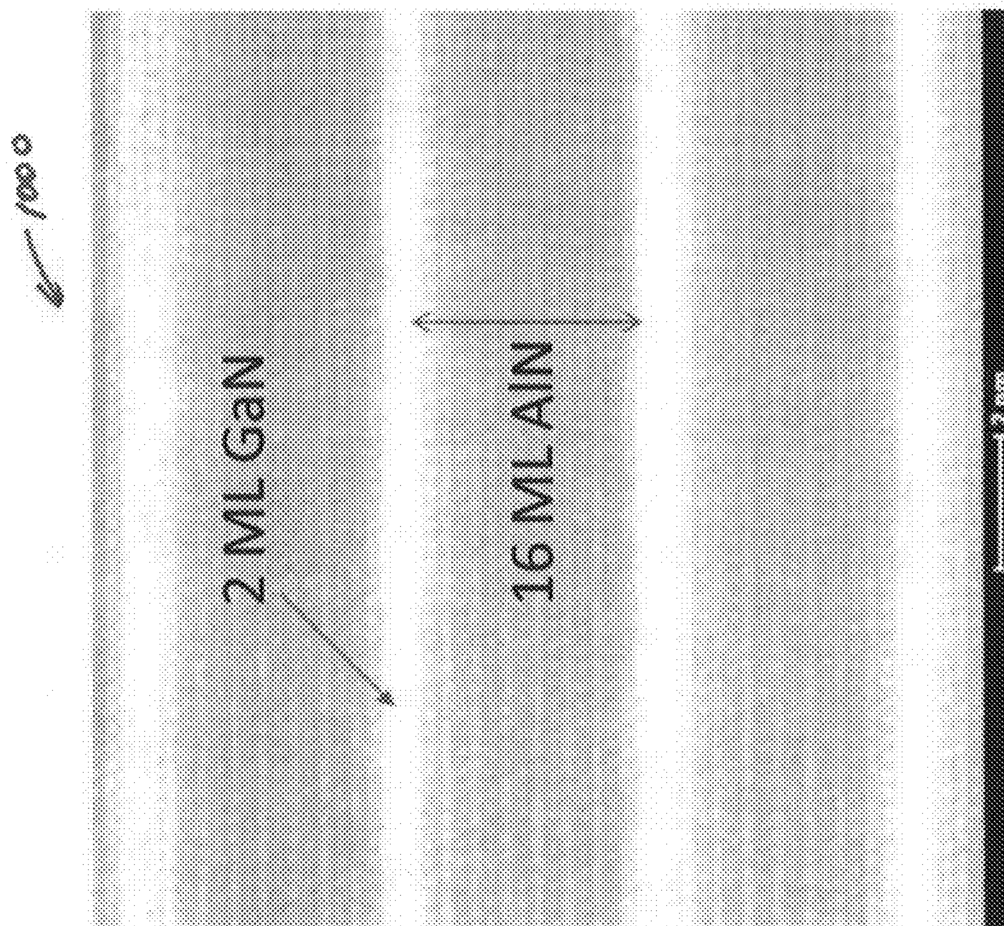


Figure 10

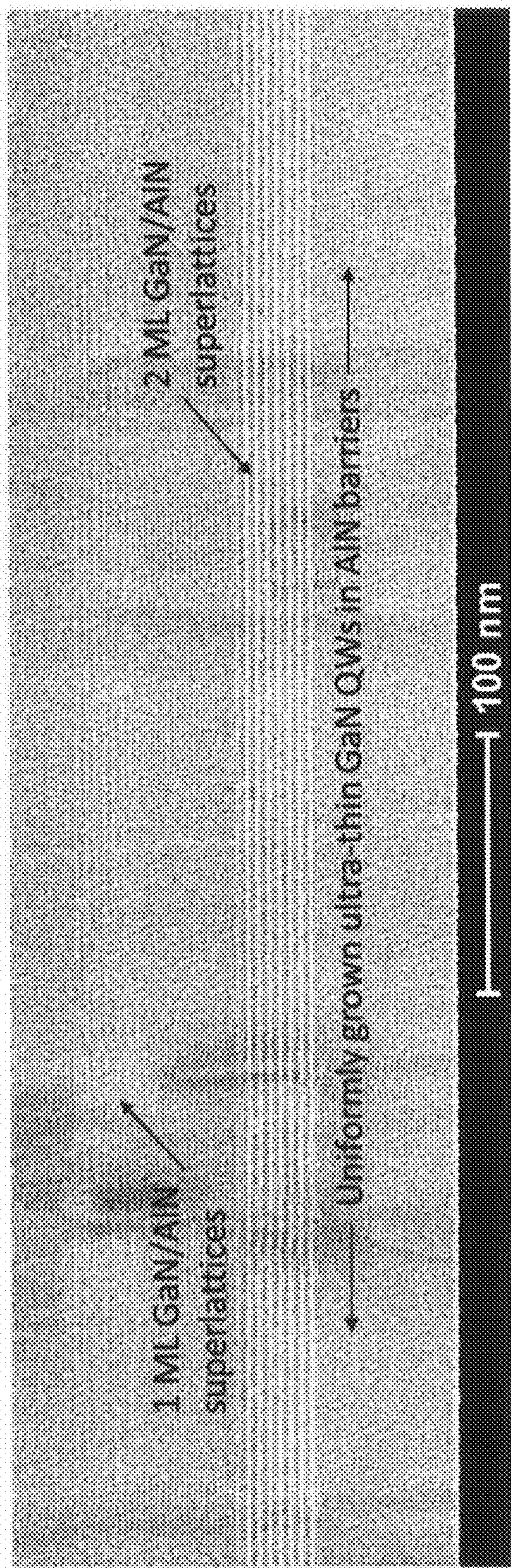


Figure 11

LIGHT EMITTING DIODES USING ULTRA-THIN QUANTUM HETEROSTRUCTURES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/586,466, filed Nov. 15, 2017, and U.S. Provisional Patent Application No. 62/586,488, filed Nov. 15, 2017, each of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0002] The subject disclosure relates to light-emitting diodes (LEDs), and more particularly to improved LEDs having ultra-thin quantum heterostructures configured to control the photon emission wavelength.

2. Background of the Related Art

[0003] Replacing mercury-based DUV lamps with semiconductor LEDs is environmentally friendly, enables miniaturization, and enhances portability. DUV emission from LEDs using AlGaN multi-quantum well light-emitting active regions has been demonstrated but typically suffers from low external quantum efficiency (EQE), which drops particularly for wavelengths shorter than 240 nm. Several factors contribute to the low EQE such as: non-native substrates create large lattice mismatch, leading to dislocation densities; poor doping efficiency; limited light extraction efficiency because of total internal reflection due to refractive index mismatch; and polarization properties of the emitted light that makes light extraction efficiency difficult.

[0004] Low internal quantum efficiency (IQE) is also a barrier to product development. IQE decreases due to high densities of threading dislocations and due to the quantum-confined stark effect (QCSE).

[0005] Further, deep ultra-violet light emitting diodes (DUV-LEDs), say less than 280 nm emission wavelength, are currently realized using ternary $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ quantum well/barrier heterostructures where the light is generated in the AlGaN material. The polarization property of the emitted light is strongly dependent on the Al content of AlGaN active region (value of x).

SUMMARY OF THE INVENTION

[0006] In view of the above, a need exists for technology to fabricate DUV-LEDs with improved EQE and/or IQE. Further, it is desirable for a DUV-LED to have a tunable wavelength for optimal use in various applications.

[0007] One embodiment of the subject technology is a method for producing the DUV light for an LED comprising the step of using ultra-thin GaN/AlN quantum heterostructures, which results high internal quantum efficiency for enhanced wavefunction overlap and TE polarized light emission from GaN to enhances light extraction.

[0008] Another method producing DUV light for an LED comprising the step of tuning a wavelength over a 219-280 nm DUV range by only changing a geometry of a GaN layer. A size of the GaN layer can be controlled during fabrication by controlling an epitaxial deposition time. A shape of the GaN layer can be determined by changing a Ga/N ratio. The shape of the GaN layer can also determined by thermal anneal of the deposited GaN layer in high vacuum during the epitaxy. The subject technology also includes a light emitting diode (LED) comprising an emitting region with at least one ultra-thin GaN heterostructure. A number of layers of heterostructures is from 2 to 10, wherein the ultra-thin quantum heterostructure has a thickness ranging approximately from 0.25 nm to 0.75 and is a quantum dot/disk.

[0009] Another embodiment of the subject technology is directed to a DUV-LED having a bottom substrate, a n-contact/injection layer formed on the bottom substrate, a p-contact region, and an emitting active region between the n-contact/injection layer and the p-contact region, the emitting active region including at least one GaN quantum heterostructure. The at least one GaN quantum heterostructure may be selected from the group consisting of: a quantum well; a quantum dot/disk; and combinations thereof. The n-contact/injection layer can include: a first region for accommodating strain relaxation; a second region for lateral access with a low sheet resistance and higher conductivity compared to the first region to minimize resistive losses and heat generation; and a third region of a graded vertical injection layer with low vertical resistance to minimize heat loss due to vertical resistance. The at least one GaN quantum heterostructure is preferably three ultra-thin monolayers of quantum wells and quantum dots/discs within AlN barriers of approximately 2-3 nm. The at least one GaN quantum heterostructures is sized and shaped to determine a certain emission wavelength. The certain emission wavelength can be in a range of approximately 219-280 nm. The size may be controlled by precisely controlling parameters selected from the group consisting of: an epitaxial deposition time; a Ga/N ratio; a thermal annealing time; a temperature during deposition; and combinations thereof. The at least one GaN quantum heterostructure may be three ultra-thin monolayers of quantum wells and quantum dots/discs within AlN barriers of approximately 2-3 nm. In one embodiment, operation of the emitting active region is pulsed such as by being connected in series with a MOSFET.

[0010] It should be appreciated that the subject technology can be implemented and utilized in numerous ways, including without limitation as a process, an apparatus, a system, a device, a method for applications now known and later developed. These and other unique features of the system disclosed herein will become more readily apparent from the following description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] So that those having ordinary skill in the art to which the disclosed technology appertains will more readily understand how to make and use the same, reference may be had to the following drawings.

[0012] FIG. **1** is a schematic diagram of a DUV-LED in accordance with the subject disclosure.

[0013] FIGS. **2** and **3** are schematic diagrams of DUV-LEDs with an integrated FET switch connected in series in accordance with the subject disclosure.

[0014] FIG. **4** is a graph of electron and hole wavefunctions for a DUV-LED with ultra-thin quantum structures in accordance with the subject technology.

[0015] FIG. **5** is a graphic depiction of the carrier injection mechanism through the barrier into the light emitting active

region using tunneling injection for ultra-thin GaN/AlN quantum heterostructures in accordance with the subject technology.

[0016] FIG. **6** is a graph of intensity versus wavelength to illustrate tunable deep-UV emission from the ultra-thin quantum heterostructure by controlling the Ga/N ratio for the GaN layer-SK mode in accordance with the subject technology.

[0017] FIG. **7** is a graph of intensity versus wavelength to illustrate tunable deep-UV emission from the ultra-thin quantum heterostructure by controlling the thermal anneal duration of the GaN layer-MSK mode in accordance with the subject technology.

[0018] FIG. **8** is a schematic depiction of an ultra-thin quantum heterostructure in accordance with the subject technology.

[0019] FIGS. **9-11** are depictions of ultra-thin quantum heterostructure in accordance with the subject technology.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0020] The subject technology overcomes many of the prior art problems associated with DUV LEDs. The advantages, and other features of the technology disclosed herein, will become more readily apparent to those having ordinary skill in the art from the following detailed description of certain preferred embodiments taken in conjunction with the drawings which set forth representative embodiments of the present technology and wherein like reference numerals identify similar structural elements. Directional indications such as upward, downward, right, left, bottom, top and the like are used with respect to the figures and not meant in a limiting manner.

[0021] In brief overview, the subject technology realizes deep UV LEDs (DUV-LEDs) with design and crystal growth methods using molecular beam epitaxy (MBE). For example, the DUV-LED consists of a n-doped injection region, a p-doped injection region with polarization field-assisted doping of ternary AlGaN (Aluminum-Gallium-Nitride) wide bandgap material and a light emitting active region consisting of quantum hetero-structures to create enhanced wall-plug-efficiency for DUV LEDs by reducing carrier injection losses.

[0022] Referring now to the FIG. **1**, there is shown schematically a polarization field assisted DUV-LED **100** in accordance with the subject technology. The DUV-LED **100** is a layered structure having a bottom substrate **102**. The bottom substrate **102** can be single crystal Aluminum-Nitride (AlN) or a AlN template on a foreign substrate. A n-contact/injection layer **104** is formed directly on top of the bottom substrate **102**. The n-contact/injection layer **104** includes three distinct AlGaN regions **106**, **108**, **110**.

[0023] The first region **106** is preferably a n-AlGaN region fabricated of a compositionally graded buffer region doped with n-type chemical impurity to accommodate strain relaxation. The thickness of the first region **106** is preferably 100-500 nanometer (nm). For a metal polar AlGaN surface, the Aluminum content is linearly graded down from a start value of 100% to an end value of 70% near the light emitting active region for a 260 nm LED. The terminal composition of the Aluminum is decided based on the emission wavelength of the DUV-LED to ensure transparency.

[0024] The second region **108** is preferably a n-AlGaN region fabricated of a constant composition heavily impurity doped thick AlGaN lateral access region. Preferably, the impurity doping is a Silicon concentration of approximately 5×10^{18} cm^{-3}. The thickness of the second region **108** is preferably greater than 1 micron. The second region **108** is a lateral access region that ensures the lateral electronic charge carriers access the third region **110**, which is a light emitting active region. The heavy impurity doping of the second region **108** provides a low sheet resistance and higher conductivity to minimize resistive losses and heat generation.

[0025] The third region **110** is a graded vertical injection layer. The third region **110** is preferably a compositionally graded polarization doped AlGaN layer with n-type impurity. For a metal polar AlGaN surface, the Aluminum content is linearly graded up to 100% near the light emitting active region **112**. The thickness of the third region **110** is preferably between about 100-200 nm. The third region **110** provides low vertical resistance to minimize the heat loss due to vertical resistance.

[0026] Preferably, the emitting active region **112** includes ultra-thin GaN/AlN quantum structures for high internal quantum efficiency due to better electron-hole overlap compared to conventional thick AlGaN quantum wells as well as high light extraction efficiency due to TE dominated surface emission from GaN compared to TM dominated edge emission from the conventional AlGaN. Such ultra-thin quantum heterostructures are described below with respect to FIGS. **4-7**.

[0027] Still referring to FIG. **1**, the DUV-LED **100** includes contact region **116**. The contact region **116** includes a graded p-type vertical injection layer **114** above the light-emitting active region **112**. To form the graded p-type vertical injection layer **114**, MBE p-AlGaN layers are grown at a temperature of 650° C. or less to account for p-dopant (i.e., Magnesium) out-diffusion. By using the compositionally graded p-AlGaN for the graded p-type vertical injection layer **114**, the MBE crystal growth temperature is increased compared to conventional constant Al-containing p-AlGaN without compromising the conductivity. The elevated growth temperature enhances the crystal quality and, in turn, improves the vertical carrier transport property.

[0028] The contact region **116** also includes a vertical tunnel injection layer **118** on top of the graded p-type vertical injection layer **114**. Accordingly, the growth temperature for one or more layers of the contact region **116** can be increased, for example to 730° C. The elevated growth temperature enhances the crystal quality and thus the carrier transport property. The growth temperature can be the same temperature used for growing AlGaN layers such as the first layer **104**. The DUV-LED **100** includes two metal contacts **120** attached to the first layer **104** and contact region **116**, respectively, with a battery **122** connected between the metal contacts **120**.

[0029] It can be seen that the DUV-LED **100** has built-in polarization charge of polar III-N crystals to circumvent the fundamental material related doping challenges that cause limited EQE. The compositionally graded AlGaN contact layers are further doped with chemical impurities for carrier injection from the p and n regions to enhance doping efficiency and thus improve the injection efficiency. Such field ionization makes operation of the DUV-LED **100** temperature independent as well. According, the DUV-LED **100** can function well at cryogenic temperatures.

[0030] In operation, battery **122** supplies voltage between metal contact **120** on top of layer **118** (positive terminal) and metal contact **120** on top of layer **108** (negative terminal). Under such conditions, the tunneling junction **116** will be under reverse bias and LED comprised of p-layer **116**, active area **116**, and n-layer **108** and region **110** under forward bias. The reverse bias allows injection of holes from layer **118** into p-AlGaN **114** and electrons into layers **108** and region **110**. Due to low resistivity of the layers **108**, **110**, **114**, the electrons and holes drift to active area **112**. In the active area **112**, electrons and holes localize in GaN quantum well (dots, discs) and either radiatively or non-radiatively recombine. Preferably, all recombination proceeds radiatively and photons are generated. Upon the event of photon generation, photons can exit the device **100** in all directions. For light generated in ultra-thin GaN layers, light propagation in a vertical direction (toward layers **118** or **106**) is preferable, as it is indicated by arrow a.

[0031] Referring now to FIG. **2**, there is shown a schematic diagram of a DUV-LED assembly with an integrated FET switch **250** connected in series with a DUV-LED **200** in accordance with the subject disclosure. Similar elements to those described in connection with the DUV-LED **100** described above are indicated with the like reference numbers in the **200** series. Many elements are essentially the same as those of the foregoing embodiments and, thus, are not further described herein. Due to low electrical efficiency for DUV-LEDs, typically less than 10%, heat management is a challenge. The monolithic FET switch **250** is integrated in series to the DUV-LED **200** to run in a pulsed-mode. The pulsed operation allows for proper thermal management of the DUV-LED **200**, which leads to enhanced lifetime and operation hours for the DUV-LED **200**.

[0032] The FET switch **250** includes a graded p-AlGaN layer **252** similarly formed to layer **214**. The graded p-AlGaN layer **252** is also formed on the region **210**. A n-AlGaN layer **254** is formed on the graded p-AlGaN layer **252** in a similar manner to layer **218**. To form the FET switch **250**, an oxide layer **256** then a metal gate-all-around **258** are formed on the layers **210**, **252**, **254**. A metal contact **260** is also formed on the n-AlGaN layer **254** for connection to the battery **222**. Gate pulses are injected into the metal gate-all-around **258** to accomplish the pulsed operation. This is one way to incorporate the FET switch with the LED but other ways are also possible to achieved the pulsed operation.

[0033] In operation, vertical metal oxide semiconductor field effect transistor (VMOSFET) **250** comprised of items **252**, **254**, **256**, **258**, **260** is connected to LED structure (items **210**, **214**, **218**, **220**) by an n-type channel (e.g., layers **204**, **206**, and **208**). The VMOSFET **250** operates in enhancement mode (E-mode). Under positive gate-source voltage Vgs, a conductive channel for electrons is formed under the gate **258** and resistivity between n-AlGaN layers **254** and layers **204**, **206**, **208**, **210** becomes small. It is equivalent to shortening layer **210** to negative terminal battery **222** and the LED is in the ON state. Under negative voltage on the gate **258**, the channel under the gate is depleted (electrons pushed away by negative potential on the gate) and channel resistivity is high. Since the VMOSFET **250** is in series with the LED structure, only small current can flow through the LED and the LED is in the OFF state. By switching gate voltage between positive and negative potentials, the LED switches between the ON and OFF states. By varying duration of the ON state, the amount of heat generated by LED can be controlled. FIG. **3** is also a schematic diagram of a DUV-LED assembly with an integrated FET switch **250'** connected in series with a DUV-LED **200'** in accordance with the subject disclosure. The elements are similar to those described in connection with FIG. **2** above and indicated with the like reference numbers. Many elements are essentially the same as those of the foregoing embodiments and, thus, are not further described herein.

[0034] Referring now to FIG. **4**, a graph **400** of wavefunction for a DUV-LED with ultra-thin quantum structures in the active emitting region in accordance with the subject technology is shown. The DUV-LED has light emitters with high wavefunction overlap between the electron wave function **402** and the hole wave function **404**. As a result, the DUV-LED has enhanced IQE. Further, the DUV-LED includes binary GaN/AlN quantum structures instead of AlGaN/AlGaN heterostructure to generate the DUV light. Ultra-thin GaN produces TE polarized light which propagates in a direction normal to the GaN layer of the DUV-LED for enhanced extraction. As shown in FIG. **1**, the light is emitted vertically as represented by arrow a, which is a preferred direction for extraction.

[0035] Referring now to FIG. **5**, a graphic depiction **500** of the carrier injection mechanism for the light emitting active region using tunneling injection for ultra-thin GaN/AlN quantum heterostructures in accordance with the subject technology is shown. In one embodiment, the DUV-LED includes thin AlN barriers (e.g., less 2 nm) in the active region which enable tunneling injection of the charge carriers into the GaN light emitting material compared to the over-the barrier or hot-carrier injection as commonly used for prior art AlGaN—AlGaN heterostructures. Such tunneling-injection mechanism enhances the injection efficiency of the DUV-LED.

[0036] In FIG. **6**, a graph **600** of intensity versus wavelength to illustrate tunable deep-UV emission from the ultra-thin quantum heterostructure by controlling the Ga/N ratio for the GaN layer-SK (Stranski-Krastanov) mode in accordance with the subject technology is shown. Referring additionally to FIG. **7**, a graph **700** of intensity versus wavelength to illustrate tunable deep-UV emission from the ultra-thin quantum heterostructure by controlling the thermal anneal duration of the GaN layer-MSK (Modified Stranski-Krastanov) mode in accordance with the subject technology is shown. Preferably, ultra-thin GaN heterostructures have a thickness ranging approximately from 0.25 nm to 0.75 nm to achieve <280 nm emission.

[0037] DUV-LEDs in accordance with the subject technology have been tunable to control the photon emission wavelength over a range of 219-280 nm using binary GaN (Gallium Nitride) and AlN (Aluminum Nitride) quantum hetero-structures. GaN and AlN are considered as III-V wide bandgap semiconductor materials, with a bulk bandgap of 3.4 eV for GaN and 6.2 eV for AlN. In one embodiment, the DUV-LED included ultra-thin 1-3 monolayers of GaN quantum heterostructures, such as quantum wells and quantum dots/discs, within AlN barriers of 2-3 nm. The effective bandgap of GaN increases up to 5.66 eV using the concept of quantum confinement as defined in quantum mechanics. The increase in the effective bandgap translates into shortening of photon emission wavelength because of the following:

$$\lambda = \frac{hc}{E}$$

photon wavelength = Plank's constant × speed of light/(Bandgap energy).

[0038] A wavelength range of 200-280 nm is considered as UV-C or deep-UV (DUV). DUV-LEDs are tunable in a range of 219-280 nm by changing the geometry of the GaN layer only while keeping the AlN barrier thickness the same. The size and/or shape of the GaN layer may be modified to make the GaN layer bigger or smaller.

[0039] In one method, the ultra-thin GaN and AlN films are deposited using MBE but other techniques like metal-organic chemical vapor deposition and the like can be used. The size of the GaN layer can be controlled by precisely controlling the epitaxial deposition time, the Ga/N ratio, and/or by the thermal annealing time and temperature of the deposited film.

[0040] In one method, wavelength tuning is accomplished by: i) deposition time of GaN; ii) controlling the Ga/N ratio (Stranski-Krastanov or SK-mode); and iii) controlling thermal anneal of the deposited GaN layer in high vacuum during the epitaxy (Modified SK or MSK mode). If only the deposition time of GaN is changed to form 1, 2 or 3 monolayers of GaN within an AlN barrier of 2-3 nm, the emission wavelength is tuned to 224 nm, 260 nm and 290 nm respectively.

[0041] For the SK-mode, where the emission wavelength tuning is achieved by controlling the Ga/N ratio, the wavelength tuning can be achieved from 219-280 nm depending on the film thickness and Ga/N ratio. The shortening of wavelength is achieved due to formation of quantum dot/disc with a Ga/N ratio of smaller than one, an N-rich growth condition as known in MBE epitaxy. For example, with three monolayers of GaN, a 240 to 280 nm range of emission can be achieved by changing the Ga/N ratio from 0.6 to 0.95. With 2 monolayers of GaN, a 219 to 260 nm range of emission can be achieved by changing the Ga/N ratio from 0.6 to 0.95.

[0042] Similar wavelength tuning over a range of 222-280 nm can be achieved by thermal anneal of the deposited GaN layers in ultra-high vacuum. The high vacuum anneal also can cause GaN quantum dot/disc formation in a 2-3 nm AlN matrix. For example, three monolayers of GaN deposited by MBE technology and then annealed for 5 to 30 seconds can provide a tuning from a 280 to 250 nm range. Two monolayers of GaN deposited by MBE and then annealed for 5 to 30 seconds can provide a tuning from a 222 to 250 nm range.

[0043] Referring now to FIG. **8**, a schematic depiction **800** of an ultra-thin quantum heterostructure in accordance with the subject technology is shown. Preferably, this heterostructure is grown using MBE to have an AlN layer **804** on a 1 micron thick AlN template on sapphire as the substrate. The thickness of the AlN barrier layer **806** is about 4 nm for both one and two monolayer GaN quantum wells, which were repeated ten times. After which, an AlN cap layer **810** was formed. FIGS. **9-11** are images **900**, **1000**, **1100** indicating that the desired thicknesses for the GaN quantum wells and AlN barriers were achieved. In particular, FIG. **10** illustrates continuous and uniform GaN quantum wells over the entire plane of the portion shown.

[0044] While the subject technology has been described with respect to preferred embodiments, those skilled in the art will readily appreciate that various changes and/or modifications can be made to the subject technology without departing from the spirit or scope thereof as defined by the claims.

What is claimed is:

1. A method for producing the DUV light for an LED comprising the step of:

using ultra-thin GaN/AlN quantum heterostructures, which results high internal quantum efficiency for enhanced wavefunction overlap and TE polarized light emission from GaN to enhances light extraction.

2. A method for producing DUV light for an LED comprising the step of:

tuning a wavelength over a 219-280 nm DUV range by only changing a geometry of a GaN layer.

3. A method as recited in claim **2**, wherein a size of the GaN layer is controlled during fabrication by controlling an epitaxial deposition time.

4. A method as recited in claim **2**, wherein a shape of the GaN layer is determined by changing a Ga/N ratio.

5. A method as recited in claim **2**, wherein a shape of the GaN layer is determined by thermal anneal of the deposited GaN layer in high vacuum during the epitaxy.

6. A light emitting diode (LED) comprising:

an emitting region with at least one ultra-thin GaN heterostructure.

7. A LED as recited in claim **6**, wherein a number of layers of heterostructures is from 2 to 10.

8. A LED as recited in claim **6**, wherein the ultra-thin quantum heterostructure has a thickness ranging approximately from 0.25 nm to 0.75 and is a quantum dot/disk.

9. A DUV-LED comprising:

a bottom substrate;

a n-contact/injection layer formed on the bottom substrate;

a p-contact region; and

an emitting active region between the n-contact/injection layer and the p-contact region, the emitting active region including at least one GaN quantum heterostructure.

10. A DUV-LED as recited in claim **9**, wherein the at least one GaN quantum heterostructure is selected from the group consisting of: a quantum well; a quantum dot/disk; and combinations thereof.

11. A DUV-LED as recited in claim **9**, wherein the n-contact/injection layer includes: a first region for accommodating strain relaxation; a second region for lateral access with a low sheet resistance and higher conductivity compared to the first region to minimize resistive losses and heat generation; and a third region of a graded vertical injection layer with low vertical resistance to minimize heat loss due to vertical resistance.

12. A DUV-LED as recited in claim **9**, wherein the at least one GaN quantum heterostructure is three ultra-thin monolayers of quantum wells and quantum dots/discs within AlN barriers of approximately 2-3 nm.

13. A DUV-LED as recited in claim **9**, wherein the at least one GaN quantum heterostructures is sized and shaped to determine a certain emission wavelength.

14. A DUV-LED as recited in claim **13**, wherein the certain emission wavelength is in a range of approximately 219-280 nm.

15. A DUV-LED as recited in claim **13**, wherein the size is controlled by precisely controlling parameters selected from the group consisting of: an epitaxial deposition time; a Ga/N ratio; a thermal annealing time; a temperature during deposition; and combinations thereof.

16. A DUV-LED as recited in claim **9**, wherein the at least one GaN quantum heterostructure is three ultra-thin monolayers of quantum wells and quantum dots/discs within AlN barriers of approximately 2-3 nm.

17. A DUV-LED as recited in claim **9**, wherein operation of the emitting active region is pulsed.

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