(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
09 January 2025 (09.01.2025)

WIPO | PCT

(10) International Publication Number
WO 2025/008748 A1

(51) International Patent Classification:
H01L 33/08 (2010.01) *H01L 33/06* (2010.01)
H01L 33/32 (2010.01) *H01L 33/38* (2010.01)
H01L 33/14 (2010.01)

(21) International Application Number: PCT/IB2024/056464

(22) International Filing Date: 02 July 2024 (02.07.2024)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
63/524,718 03 July 2023 (03.07.2023) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ,

(54) **Title:** MONOLITHIC INTEGRATION OF DEEP ULTRAVIOLET AND VISIBLE LIGHT-EMITTING DIODES FOR RADIATIVE STERILIZATION

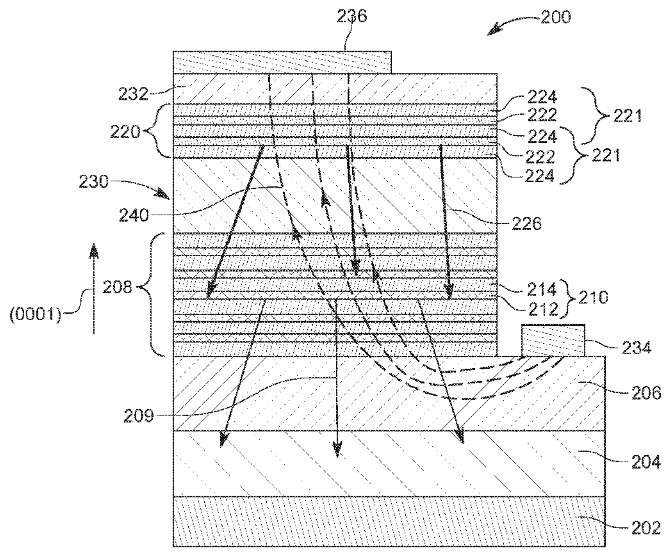

FIG. 2

(57) **Abstract:** A monolithic, vertically integrated, light emitting diode (LED) device (200) for radiative sterilization includes a substrate (202), a deep ultraviolet (DUV) active region (208) located on the substrate (202) and configured to generate DUV light (209), a visible (VIS) active region (220) located on top of the DUV active region (208) and configured to generate VIS light (226), and first and second electrodes (234, 236) configured to inject an electrical current that simultaneously excites the DUV active region (208) and the VIS active region (220) to simultaneously generate the DUV light (209) and the VIS light (226).

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RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*
— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

MONOLITHIC INTEGRATION OF DEEP ULTRAVIOLET AND VISIBLE LIGHT-EMITTING DIODES FOR RADIATIVE STERILIZATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 63/524,718, filed on July 3, 2023, entitled "MONOLITHIC INTEGRATION OF DEEP ULTRAVIOLET AND VIOLET LIGHT-EMITTING DIODES FOR RADIATIVE STERILIZATION," the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

TECHNICAL FIELD

[0002] Embodiments of the subject matter disclosed herein generally relate to a system and method for delivering deep ultraviolet (DUV) radiation for disinfection, and more particularly, to a monolithic single device that includes a structure for generating the DUV radiation and an additional structure for generating visible light so that both the DUV radiation and visible light are simultaneously emitted.

DISCUSSION OF THE BACKGROUND

[0003] The Covid-19 pandemic has generated substantial demand for sterilization and disinfection equipment that is efficient and cheap. This trend continues past the pandemic due to the threat of other viruses. High-energy DUV radiation has proven highly effective in disrupting the DNA double helix structure of viruses, making it a subject of significant interest in both civil and industrial applications. AlGaN-based DUV light emitting diodes (LEDs) offer several advantages, including compactness, portability, environmental friendliness, and longevity. As a result, they are poised to replace traditional mercury lamps in sterilization, disinfection, UV-curing processes, and biomedical detection.

[0004] However, human exposure to high-energy DUV radiation can pose risks to skin and eyes when using DUV disinfection products. Consequently, commercial DUV germicidal LED chips are commonly integrated with visible (VIS) LED chips during the packaging process [1-3]. As shown in FIG. 1, a commercial surface-mounted device (SMD) LED 100 used for sterilization generally contains discrete DUV and VIS chips (DUV chip 110 and VIS chip 120) mounted next to each other (in a plane) on a common substrate 102. The inclusion of the VIS chip 120 serves the dual purpose of providing an indicator for the operation of electronic products employing DUV light and serving as a warning signal to alert individuals to potential DUV radiation exposure. This is particularly relevant in compact and efficient devices like DUV LED sterilizers, air/water purifiers, and built-in UV disinfection lamps [4]. Another external Zener diode 130, parallel to the DUV LED 110, is employed for improving the electro-static discharge (ESD) capability of the DUV LED.

[0005] Nevertheless, the integration of an additional VIS LED chip, next to the DUV LED chip comes with notable drawbacks. The VIS LED chip necessitates an additional bias voltage of 3–4 V for proper operation, resulting in increased power supply consumption. Under the same 100 mA current, the additional VIS LED contributes by about 33.7% power consumption during the operation. This additional power consumption does not contribute to the sterilization process, leading to inefficiencies of the entire device. Additionally, integrating the visible chip next to the DUV chip, in a plane of the substrate, adds complexity and raises the cost during the chip fabrication, integration, and packaging process. Another concern is that the failure of either the visible chip or the DUV chip can lead to misjudgment by customers. This misjudgment has the potential of creating conflicts and pose safety risks when users rely on the visible light indicator for their safety.

[0006] Thus, there is a need for a new system that is capable of providing the same functionalities as the devices discussed above, but without the excessive power consumption of the VIS chip, and with a simplified manufacturing process.

SUMMARY OF THE INVENTION

[0007] According to an embodiment, there is a monolithic, vertically integrated, light emitting diode (LED) device for radiative sterilization, and the LED device includes a substrate, a deep ultraviolet (DUV) active region located on the substrate and configured to generate DUV light, a visible (VIS) active region located on top of the DUV active region and configured to generate VIS light, and first and second electrodes configured to inject an electrical current that simultaneously excites the DUV active region and the VIS active region to simultaneously generate the DUV light and the VIS light.

[0008] According to another embodiment, there is a light emitting diode (LED) device that includes a deep ultraviolet (DUV) active region including plural DUV quantum wells configured to generate DUV light, a visible (VIS) active region located on top of the DUV active region, including at least one VIS quantum well, and configured to generate VIS light, a first electrode located proximal to the DUV active region, and a second electrode located proximal to the VIS active region. The first and second electrodes are configured to inject an electrical current that simultaneously excites the DUV active region and the VIS active region to simultaneously generate the DUV light and the VIS light.

[0009] According to yet another embodiment, there is a light emitting diode (LED) device that includes plural deep ultraviolet (DUV) quantum wells configured to generate DUV light, a cascade region located on top of the plural DUV quantum wells, at least one VIS quantum well located on top of the cascade region, and configured to generate VIS light, a first electrode located proximal to the plural DUV quantum wells, and a second electrode located proximal to the at least one VIS quantum well. The first and second electrodes are configured to inject an electrical current that simultaneously excites the DUV quantum wells and the at least one VIS quantum well to simultaneously generate the DUV light and the VIS light.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0011] FIG. 1 is a schematic diagram of an existing DUV-VIS device that has the DUV chip horizontally separated from the VIS chip on a common substrate;

[0012] FIG. 2 is a schematic diagram of a monolithic, vertically integrated, DUV-VIS LED device according to an embodiment;

[0013] FIG. 3 schematically illustrates three variations of the DUV-VIS LED device of FIG. 2;

[0014] FIGs. 4A and 4B illustrate the energy bands for a reference DUV LED device and the DUV-VIS LED device of FIG. 2, respectively;

[0015] FIGs. 5A and 5B illustrate the spontaneous emission rates of the reference DUV LED device and the DUV-VIS LED device of FIG. 2, respectively;

[0016] FIG. 6 illustrates the electron concentration, hole concentration, and radiative recombination rate for the DUV-VIS LED device of FIG. 2;

[0017] FIG. 7 illustrates the electron current density distributions for the reference DUV LED device and the DUV-VIS LED device of FIG. 2, respectively;

[0018] FIG. 8A shows the current-dependent EL spectrum for the DUV-VIS LED device of FIG. 2;

[0019] FIG. 8B shows the current voltage curve for the DUV-VIS LED device of FIG. 2 and an image of the packaged DUV-VIS LED device under operation; and

[0020] FIG. 8C shows the DUV and VIS output power, and DUV/VIS power ratio for the DUV-VIS LED device of FIG. 2.

DETAILED DESCRIPTION OF THE INVENTION

[0021] The following description of the embodiments refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. The following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims. The following embodiments are discussed, for simplicity, with regard to a monolithic (single) DUV and VIS chip that uses five pairs of AlGaN quantum wells (QW) for the DUV generation and at least one pair of GaN/InGaN/GaN QW for the VIS generation, with a transition region having a grading Al content between the DUV region and the VIS region. However, the embodiments to be discussed next are not limited to a chip having a DUV structure made of five DUV QW and a VIS structure made of one VIS QW but may be applied to chips having different number of QW in the two structures/regions. Also, various other materials may be used for the QWs and/or the transition region instead of AlGaN. In one embodiment, the transition region has a first region with a constant Al content and a second region with a varying Al content.

[0022] Reference throughout the specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with an embodiment is included in at least one embodiment of the subject matter disclosed. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” in various places throughout the specification is not necessarily referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

[0023] According to an embodiment, a dual-wavelength LED device capable of (simultaneously) emitting both DUV and VIS light, referred in this document to as “the DUV-VIS LED device,” is introduced. This monolithic integration of DUV and VIS chips and corresponding emissions is designed for use in sterilization applications where simultaneous sterilization and indication of the on status of the sterilization process are desired. The compositional grading of an AlGaN transition region is employed in a cascade region to connect the DUV and VIS active regions and serve as three-dimensional hole gas (3DHG) reservoir for efficient hole injection. Both simulation and experimental investigations were conducted to validate the feasibility and effectiveness of this device.

[0024] When monolithically integrating the DUV and VIS LEDs as a single chip, several advantages may be reached while maintaining the dual-wavelength functionality. For example, the integrated device reduces power consumption since there is no need for an additional visible chip that consumes extra power. Moreover, the monolithic integration of DUV and VIS LEDs simplifies the fabrication process and reduces integration costs compared to the conventional approach of combining separate DUV and VIS LED chips on a substrate. In the event of chip failure, replacement becomes easier without concerns about misjudgment issues, as the entire integrated chip can be replaced as a unit. Except for the application of radiative sterilization, the device may be used in optical wireless communication (OWC) systems for VIS light and solar-blind DUV communication while each optical band features a distinct application. Combining both spectra from a single emitter could enhance versatility, support illumination, and secure optical communication in various environments, including low-light and non-line-of-sight conditions.

[0025] As illustrated in FIG. 2, the diode structure of a DUV-VIS device 200 on an AlN template begins with a substrate 202, made, for example, of sapphire. An AlN layer 204 is formed/located on the substrate 202, followed by an n-type Si-doped AlGaN layer 206 (for example, $Al_{0.6}Ga_{0.4}N$ with a Si doping concentration of about 5 x 10^{18} cm^{-3}). In this embodiment, an active region 208 (first active region for generating DUV radiation, also called “DUV active region”) includes five QWs 210, which are configured for generating the DUV radiation 209. Although the figure illustrates five QWs 210, more or less than five QWs 210 may be formed. Each QW 210 includes an active layer or well 212, for example, a 3-nm-thick $Al_{0.4}Ga_{0.6}N$ layer, sandwiched by two quantum barriers (QBs) 214, for example, a 12-nm thick $Al_{0.5}Ga_{0.5}N$ layer. A method for growing these layers is disclosed in [5] and thus, it is omitted herein. In one embodiment, the DUV active region 208 primarily emits light at about 275 nm, predominantly for applications in sterilization, sensing, and related fields. In one application, the DUV emitted light is in the 200 to 280 nm region.

[0026] Another active region 220 (also called “a second active region” or “a VIS active region”) is integrally made on the DUV active region 208. A transition region 230 vertically separates the DUV active region 208 from the VIS active region 220. The VIS active region 220 includes, in this embodiment, two QW 221, with the QW including a well layer 222 and two QBs 224 sandwiching the well layer 222. In this embodiment, the QBs 224 are made of GaN and the well layer 222 is made of

$In_{0.08}Ga_{0.92}N$. The VIS active region 220 serves as radiation indicator, emitting light 226 in the visible spectrum, for example, having a wavelength of about 425 nm. Other wavelengths may be used. The VIS active region 220 may include more than one QW 221 made of InGaN. The VIS active region is located above the DUV active region due to the lower growth temperature of InGaN compared to AlGaN.

[0027] FIG. 2 further shows the formation of a top p-type GaN contact layer 232 (for example, 50-nm thick) with an Mg doping concentration of about 1×10^{20} cm^{-3}. Two electrodes 234 and 236 are added to control the carrier distributions in the two active regions 208 and 220. A first electrode 234 is added (directly) on the n-type AlGaN layer 206 and the second electrode 236 is located (directly) on the GaN contact layer 232. Any metallic conductor may be used for the electrodes. An electrical current 240 generated between electrodes 234, 236 flows from one electrode to the other electrode, as illustrated in FIG. 2, and the same electrical current 240 simultaneously excites the DUV active region 208 and the VIS active region 220, to simultaneously generate the DUV light 209 and the VIS light 226.

[0028] To effectively control the carrier distributions (electron and hole distributions) in these two active regions, the carrier distributions are manipulated by enlarging the Al% (i.e., grading) the AlGaN layer in the transition region 230 or inserting an electron blocking layer (EBL) in the transition region 230. To maintain the DUV/VIS emission ratio, the Al% of the inserted EBL layer is optimized as now discussed.

[0029] The transition region 230, also called a cascade region, is incorporated to interconnect the DUV and VIS QWs. In one embodiment, transition region 230 contains a first region 230A (see FIG. 3) having a 10 nm $Al_{0.6}Ga_{0.4}N$ (60% of Al and 40% of Ga atoms out of the entire number of Al and Ga atoms in the first region) electron blocking layer (EBL) and a second region 230B (see also FIG. 3) having a 90 nm composition grading AlGaN layer with Al% from 0.6 to 0 (in terms of Al and Ga atom concentration of the entire second region 230B), so that a total thickness of the entire transition region 230 is about 100 nm. In one embodiment, a thickness of the transition region is between 20 and 500 nm. For any thickness of the transition region between 20 and 500 nm, a ratio of the thickness of the EBL and the thickness of the grading AlGaN can vary from 1:9 to 9:1. It is noted that the GaN/InGaN/GaN VIS QWs 221 may absorb the bottom DUV emission due to its narrower bandgap. However, this partial photon absorption generates electron–hole pairs within the VIS QW 220, thereby enhancing VIS emission.

[0030] The dual-wavelength LED device 200 may be epitaxially grown using a commercial MOCVD system. In one embodiment, device 200 is executed on a 2-in. (0001) AlN template which has been prepared on a (0001) Sapphire substrate with a low-temperature AlN buffer layer. TMA (trimethylaluminum), TMG (trimethylgallium), and NH3 (ammonia) were used as the source gases. A comprehensive description of the materials growth and device fabrication processes can be found in [6].

[0031] Variations of device 200 were investigated by changing the composition and/or concentration of the elements in transition region 230. The transition region 230 has different composition grading schemes within its thickness of about 100 nm in these embodiments. These different configurations are referred to as Samples A, B, and C in FIG. 3. The transition region 230 of Sample A has a decreased-Al-composition linear-grading profile from about 0.6% to 0% in the AlGaN layer forming the transition region 230, along the *c*-axis. For Sample B, the grading of transition region 230, made of the AlGaN layer, has a grading scheme from about 0.655 to 0. Sample C includes two different regions, a first region 230A having a 10-nm fixed-composition $Al_{0.6}Ga_{0.4}N$, followed by a second region 230B having a 90-nm composition grading AlGaN with Al% uniformly changing from 0.6 to 0. The 10-nm $Al_{0.6}Ga_{0.4}N$ region 230A could be viewed as an EBL. Although the grading of the AlGaN layer is assumed to be linear, i.e., the Al% changes in a linear way from one end of the transition region 230 to the other end (for samples A and B, and region 230B for sample C), it is possible to use a non-linear variation, for example, a parabola or other parametrized curve. Note that the end of the transition region 230 having the highest Al concentration is facing the DUV active region 208 and the end having the lowest Al concentration (0% in this embodiment) is facing the VIS active region 220. While the samples discussed above have a zero Al% at an interface with the VIS active region 220, in one embodiment, it is possible to have a small but non-zero Al% at the interface with the VIS active region. After performing various tests on these samples, the inventors found that Sample C achieves the highest spontaneous emission spectrum and the electron confinement Φ_e is remarkably improved due to the polarization-induced bending in $Al_{0.6}Ga_{0.4}N$ EBL, leading to simultaneously achieving better electron confinement in DUV active region and reduced electron overflow into the VIS active region. Thus, sample C is used in the remaining of this document for various tests.

[0032] The photoluminescence (PL) spectra (not shown) obtained for the device 200 (sample C), using a 325 nm laser as an excitation source, shows, in addition to a yellow luminescence, three distinct peaks. One peak originates from the GaN edge emitting at approximately 365 nm, and the second is attributed to the shallow donor–acceptor pair (DAP) and/or conduction-band-acceptor (e–A) transition. The spectra exhibit additional peaks centered at ~420 nm, indicating recombination in the InGaN QW. The emission peak in the visible region serves as evidence of the incorporation of the visible QWs. The PL intensity of this peak is limited, which may be attributed to the presence of a limited number of QW pairs and severe defect emissions. DUV emission is not observed due to the limitations imposed by the excitation laser wavelength.

[0033] The electroluminescence (EL) spectra (not shown) of the DUV-VIS LED 200 reveals a DUV emission peak at approximately 275 nm. Additionally, a broad visible emission peak, with a peak wavelength around 425 nm, is observed. Both the DUV and VIS emission intensities exhibit gradual enhancement as the injected current increases from 10 to 70 mA, while the emission wavelengths remain stable. This current-dependent emission property is evident in both the DUV and VIS regions, suggesting that the radiation intensity can be manually controlled by adjusting the current injection. When an indium electrode is probed and bias is applied, a noticeable violet-blue light emission emanates from the designed wafer.

[0034] A distinct disparity in the visible region was observed between a reference DUV LED device (device that includes only DUV chip 120) and the DUV-VIS LED device 200, emphasizing the presence of dual-wavelength emission in the latter case. Furthermore, the visible spectrum exhibits a broader range as opposed to a narrow visible emission. This broadening can be attributed to the existence of indium-rich clusters within the quantum well, which may result from strain effects.

[0035] For the device simulation, the Advanced Physical Models of Semiconductor Devices (APSYS) program was employed. The Shockley–Read–Hall (SRH) recombination lifetime, the Auger recombination coefficient, and the radiative recombination coefficient of AlGaN are set to be 15 ns, 2.88×10^{-30} cm^6/s, and 2.13×10^{-17} cm^3/s, respectively. For InGaN, they are 100 ns, 1×10^{-30} cm^6/s, and 2×10^{-17} cm^3/s, respectively. The band offset ratio of AlGaN and InGaN materials are set as 0.67/0.33. The built-in interface charges induced by spontaneous and piezoelectric polarization are assumed to be 50% of total charges considering the screening effect of defects. The charge densities screened by injected carriers under bias are taken into account self-consistently.

[0036] The energy band diagrams for a DUV LED reference device 400 (similar to device 100 but with no VIS chip 120 or VIS chip not monolithically integrated) and the DUV-VIS LED device 200 are presented in FIGs. 4A and 4B, respectively. The electrons are injected from the bottom *n*-type layer 206 to the DUV MQWs 208, and then in FIG. 4B, partial electrons flow into the VIS QW and recombine with holes. It should be noted that both samples contain 10 nm $Al_{0.6}Ga_{0.4}N$ EBL in the cascade region 230, resulting in a similar value of effective barrier heights for electron confinement (Φ_e) for both samples, i.e., 317–319 meV in FIGs. 4A and 4B. Therefore, the electrons in VIS QW 220 could be assumed as the overflown electrons from the DUV MQWs 208 in FIG. 4B, which are usually wasted in conventional DUV LED 400. The Al% in the EBL region 230A is deliberately designed to be slightly lower than the reported value of 65%, to maintain the desired DUV/VIS emitting ratio.

[0037] Regarding the holes, which are injected from the *p*-side (layer 232), the use of a compositional grading AlGaN layer 230B in the cascade region 230, with varying Al% along the c-axis, facilitates the creation of 3DHG, enhancing efficient hole injection. If removing this compositional grading AlGaN layer, a large barrier would be generated at the interface of EBL/GaN QB, which deteriorates the hole injection efficiency. If replacing the grading AlGaN layer using a bulk AlGaN layer, the large interfacial band offset would result in a large amount of hole accumulation on the EBL/AlGaN/GaN interface and hinder the hole injection into DUV MQWs. Moreover, the effective barrier heights for hole blocking (Φ_h) are also similar, i.e., 369–371 meV for both samples, indicating comparable hole injection efficiency. FIGs. 5A and 5B display the corresponding emission spectra under different injected currents for the reference DUV LED device 400 and the DUV-VIS LED device 200, respectively. The dominant emission peak at about 275 nm originates from the same active region in both cases, while the additional VIS emission peak in FIG. 5B aligning with the dual-wavelength emission spectrum observed in the grown DUV-VIS LED device.

[0038] FIG. 6 provides an overview of the distribution of electrons [N_{QW}], holes [P_{QW}], and radiative recombination rate [R_{rad}] in the DUV-VIS LED device 200. Electrons and holes are distributed within each quantum well (QW) 210, and it is notable that [R_{rad}] closely follows the carrier distribution. The spatial separation of electrons and holes is a consequence of the polarization effect observed in III-Nitride QWs. It is also apparent that the radiative recombination rates are predominantly influenced by the minority carriers, specifically holes in the DUV MQWs 208 and electrons in the VIS QW 220. [N_{QW}], [P_{QW}], and [R_{rad}] of DUV LED 400 are similar to those shown in FIG. 6. The similar values and distribution of both DUV LED device 400 and DUV-VIS LED device 200 could be attributed to the similar barrier height of Φ_e and Φ_h in FIGs. 4A and 4B.

[0039] Turning to the current density distribution in FIG. 7, electron injection originates from the bottom *n*-layer into the DUV QWs. Remarkably, some of these electrons overflow into the cascade region 230 despite the presence of the high-Al% AlGaN EBL 230A, owing to their high electron mobility. Therefore, a ~20 A/cm^2 electron current could be observed in the cascade region 230 for both samples. These overflown electrons have the opportunity to recombine with holes and emit visible light within the VIS QWs 220 in the DUV-VIS LED device 200. In contrast, in the DUV LED device 400, these electrons would simply flow into the *p*-layer 232 and are wasted. Consequently, the DUV-VIS LED device 200 effectively harnesses these overflow electrons for dual-wavelength emission, resulting in enhanced efficiency and performance.

[0040] FIGs. 8A to 8C present several characteristics of the fabricated and packaged LED device 200. In FIG. 8A, the LED device 200 exhibits dual-wavelength emission from 10 to 60 mA, consistent with the on-wafer test spectrum (not shown). This confirms the LED device's capability to emit both DUV and visible light as intended. The inset in FIG. 8A provides a visual representation of the visible color emitted by the fabricated LED device 200. The current-voltage (IV) curve 810 in FIG. 8B depicts the electrical behavior of the LED device 200. It indicates that the forward voltage of the LED device is approximately 5.93 V under a current of 40 mA (~95 A/cm^2, mesa size is 0.042 mm^2). FIG. 8C presents the output power components in both the DUV and VIS regions. For the DUV output power, it is integrating from 200 to 400 nm. For the VIS output power, it is integrating from 380 to 780 nm. The absolute output power in both regions increases with the applied current. At 40 mA, the DUV output power reaches approximately 3.66 mW, resulting in an external quantum efficiency (EQE) of around 2.03% and a wall-plug efficiency (WPE) of approximately 1.54%.

[0041] Furthermore, FIG. 8C also presents the DUV/VIS power ratio, which ranges from approximately 62 to 85 under various current injection conditions. This ratio reflects the relative contribution of DUV and VIS emission from the LED device 200. The high DUV/VIS ratio indicates a moderate electron blocking capability. The performance presented in FIGs. 8A to 8C underscores the fabrication and characterization results of the LED device 200, showcasing its dual-emission capability and providing essential performance metrics for further analysis and optimization.

[0042] In the realm of III-nitride emitters, the challenge of electron overflow, which can have detrimental effects on device performance, has been extensively explored through both experimental and theoretical investigations. However, addressing this issue typically requires intricate design and epitaxy processes. In this disclosure, an alternative approach is introduced to harness the overflow electrons from the DUV QWs 208 and inject them into the subsequent VIS QWs 220, thereby facilitating the generation of dual-wavelength emission. This innovation enables the DUV LED device 200 to simultaneously perform sterilization and indication functions in radiative sterilization applications.

[0043] An aspect of this approach involves the use of a compositional grading cascade region 230, which facilitates the seamless integration of DUV QWs 208 and VIS QWs 220 to achieve dual-wavelength emission. The experimental results obtained from the grown wafer and fabricated devices demonstrate both DUV and VIS emissions, affirming the implementation of monolithically integrated DUV and VIS LEDs. This advancement holds promise for various applications where the ability to emit both DUV and VIS light is advantageous.

[0044] The term “about” is used in this application to mean a variation of up to 20% of the parameter characterized by this term.

[0045] It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first object or step could be termed a second object or step, and, similarly, a second object or step could be termed a first object or step, without departing from the scope of the present disclosure. The first object or step, and the second object or step, are both, objects or steps, respectively, but they are not to be considered the same object or step.

[0046] The terminology used in the description herein is for the purpose of describing particular embodiments and is not intended to be limiting. As used in this description and the appended claims, the singular forms "a," "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any possible combinations of one or more of the associated listed items. It will be further understood that the terms "includes," "including," "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. Further, as used herein, the term "if" may be construed to mean "when" or "upon" or "in response to determining" or "in response to detecting," depending on the context.

[0047] The disclosed embodiments provide a monolithic integration of two different wavelength emitting structures. It should be understood that this description is not intended to limit the invention. On the contrary, the embodiments are intended to cover alternatives, modifications and equivalents, which are included in the spirit and scope of the invention as defined by the appended claims. Further, in the detailed description of the embodiments, numerous specific details are set forth in order to provide a comprehensive understanding of the claimed invention. However, one skilled in the art would understand that various embodiments may be practiced without such specific details.

[0048] Although the features and elements of the present embodiments are described in the embodiments in particular combinations, each feature or element can be used alone without the other features and elements of the embodiments or in various combinations with or without other features and elements disclosed herein.

[0049] This written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the subject matter is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

References

The entire content of all the publications listed herein is incorporated by reference in this patent application.

[1] See aolittel-china.com/disinfect-deep-ultraviolet-0-5w-3535-uv-surface-mount-uvc-led-alt35uva-uvc02-002.html for "Disinfect deep ultraviolet 0.5W 3535 UV surface mount UVC LED ALT35UVA+UVC02-002."

[2] See ykgdled.com/en/products_112.html for "UVC + UVA dual-wavelength deep ultraviolet germicidal SMD LED 3535 ceramic plexiglass package 275 + 395 nm 3–5 mW."

[3] See ledcobchip.com/sale-13340122-3535-uvc-uva-265-280 nm-sterilization-disinfection-uv-led-chip.html for "3535 UVC UVA 265 280 nm sterilization disinfection UV LED chip."

[4] M. Guettari, I. Gharbi, and S. Hamza, " UVC disinfection robot," Environ. Sci. Pollut. Res. 28(30), 40394–40399 (2021). //doi.org/10.1007/s11356-020-11184-2.

[5] H. Chang, Z. Chen, B. Liu, S. Yang, D. Liang, Z. Dou, Y. Zhang, J. Yan, Z. Liu, and Z. Zhang, “Quasi-2D growth of aluminum nitride film on graphene for boosting deep ultraviolet light-emitting diodes,” Adv. Sci. 7(15), 2001272 (2020). doi.org/10.1002/advs.202001272.

[6] P. Dong, J. Yan, J. Wang, Y. Zhang, C. Geng, T. Wei, P. Cong, Y. Zhang, J. Zeng, and Y. Tian, “282-nm AlGaN-based deep ultraviolet light-emitting diodes with improved performance on nano-patterned sapphire substrates,” Appl. Phys. Lett. 102(24), 241113 (2013). doi.org/10.1063/1.4812237.

WHAT IS CLAIMED IS:

1. A monolithic, vertically integrated, light emitting diode (LED) device (200) for radiative sterilization, the LED device (200) comprising:

a substrate (202);

a deep ultraviolet (DUV) active region (208) located on the substrate (202) and configured to generate DUV light (209);

a visible (VIS) active region (220) located on top of the DUV active region (208) and configured to generate VIS light (226); and

first and second electrodes (234, 236) configured to inject an electrical current that simultaneously excites the DUV active region (208) and the VIS active region (220) to simultaneously generate the DUV light (209) and the VIS light (226).

2. The LED device of Claim 1, further comprising:

a cascade region (230) sandwiched between the DUV active region and the VIS active region, along a flow direction of the electrical current.

3. The LED device of Claim 2, wherein the cascade region includes a first region having a constant concentration of Al atoms, and a second region having a varying concentration of Al atoms.

4. The LED device of Claim 3, wherein both the first region and the second region include AlGaN.

5. The LED device of Claim 3, wherein the constant Al concentration of the first region is about 60% of a total number of Al and Ga atoms in the first region and the varying Al concentration of the second region varies from 60 to 0 % of a total number of Al and Ga atoms in the second region.

6. The LED device of Claim 5, wherein the 60% Al concentration of the second region is directly facing the constant Al concentration of the first region.

7. The LED device of Claim 3, wherein the first region has a thickness of about 10 nm and the second region has a thickness of about 90 nm.

8. The LED device of Claim 1, wherein the DUV active region includes multiple quantum wells, each quantum well including a well layer sandwiched between two quantum barrier layers.

9. The LED device of Claim 8, wherein the VIS light active region includes at least one quantum well.

10. The LED device of Claim 8, wherein each of the well layer and the two quantum barrier layers is made of AlGaN.

11. The LED device of Claim 8, wherein the well layer is made of $Al_{0.4}Ga_{0.6}N$ and the two quantum barrier layers are made of $Al_{0.5}Ga_{0.5}N$.

12. The LED device of Claim 1, wherein the DUV light has a wavelength of about 275 nm and the VIS light has a wavelength of about 425 nm.

13. A light emitting diode (LED) device (200) comprising:

a deep ultraviolet (DUV) active region (208) including plural DUV quantum wells (210) configured to generate DUV light (209);

a visible (VIS) active region (220) located on top of the DUV active region (208), including at least one VIS quantum well (221), and configured to generate VIS light (226);

a first electrode (234) located proximal to the DUV active region (208); and

a second electrode (236) located proximal to the VIS active region (220),

wherein the first and second electrodes (234, 236) are configured to inject an electrical current that simultaneously excites the DUV active region (208) and the VIS active region (220) to simultaneously generate the DUV light (209) and the VIS light (226).

14. The LED device of Claim 13, further comprising:

a cascade region (230) sandwiched between the DUV active region and the VIS active region, so that the cascade region (230) is in direct contact with a quantum blocking layer of the plural DUV quantum wells (210) and in direct contact with a quantum blocking layer of the at least one VIS quantum well.

15. The LED device of Claim 14, wherein the cascade region includes a first region having a constant concentration of Al atoms, and a second region having a varying concentration of Al atoms.

16. The LED device of Claim 15, wherein both the first region and the second region include AlGaN, the constant Al concentration of the first region is about 60% Al out of a total number of Al and Ga atoms in the first region, and the varying Al concentration of the second region varies from 60 to 0 % of a total number of atoms of Al and Ga in the second region.

17. The LED device of Claim 15, wherein the first region has a thickness of about 10 nm and the second region has a thickness of about 90 nm.

18. The LED device of Claim 13, wherein each quantum well of the multiple quantum wells includes a well layer made of $Al_{0.4}Ga_{0.6}N$ and two quantum barrier layers made of $Al_{0.5}Ga_{0.5}N$.

19. The LED device of Claim 13, wherein the DUV light has a wavelength of about 275 nm and the VIS light has a wavelength of about 425 nm.

20. A light emitting diode (LED) device (200) comprising:

plural deep ultraviolet (DUV) quantum wells (210) configured to generate DUV light (209);

a cascade region (230) located on top of the plural DUV quantum wells (210);

at least one VIS quantum well (221) located on top of the cascade region (230), and configured to generate VIS light (226);

a first electrode (234) located proximal to the plural DUV quantum wells (210); and

a second electrode (236) located proximal to the at least one VIS quantum well (221),

wherein the first and second electrodes (234, 236) are configured to inject an electrical current that simultaneously excites the DUV quantum wells (210) and the at least one VIS quantum well (221) to simultaneously generate the DUV light (209) and the VIS light (226).

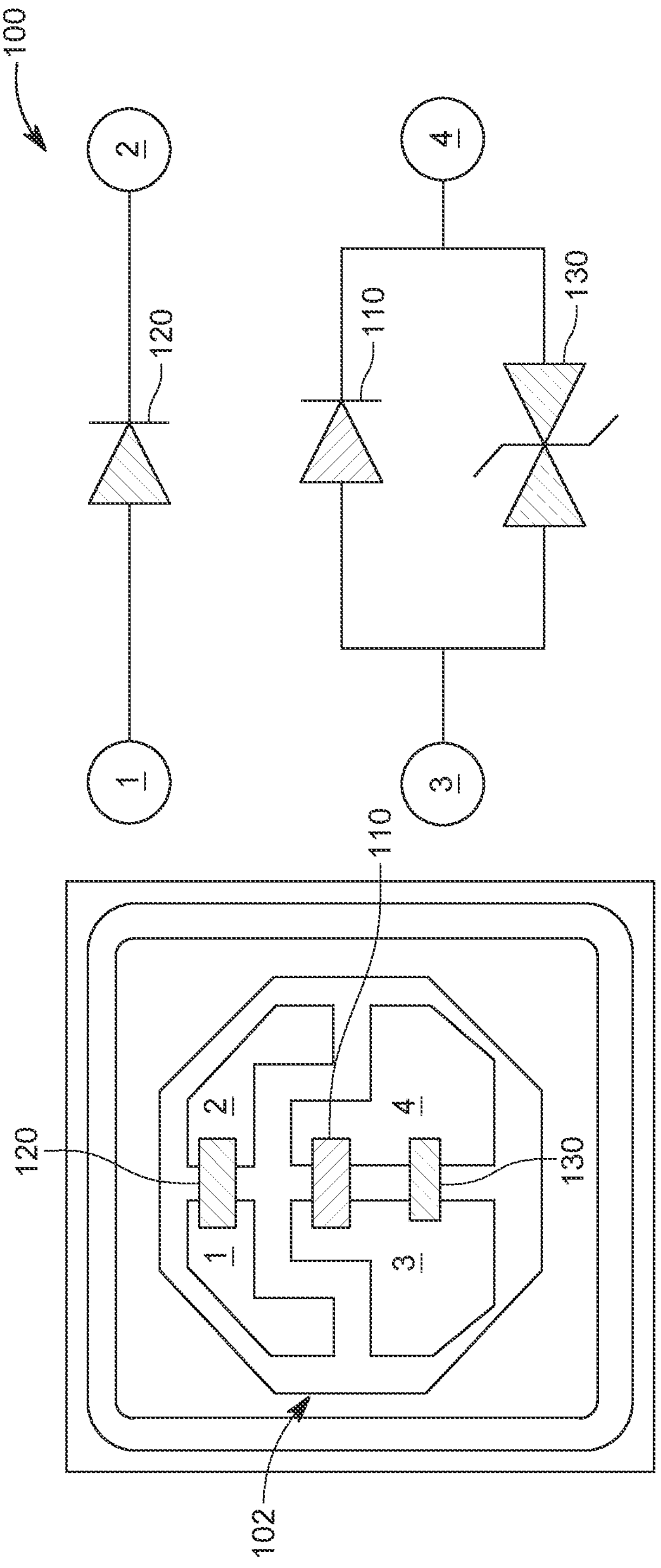

FIG. 1

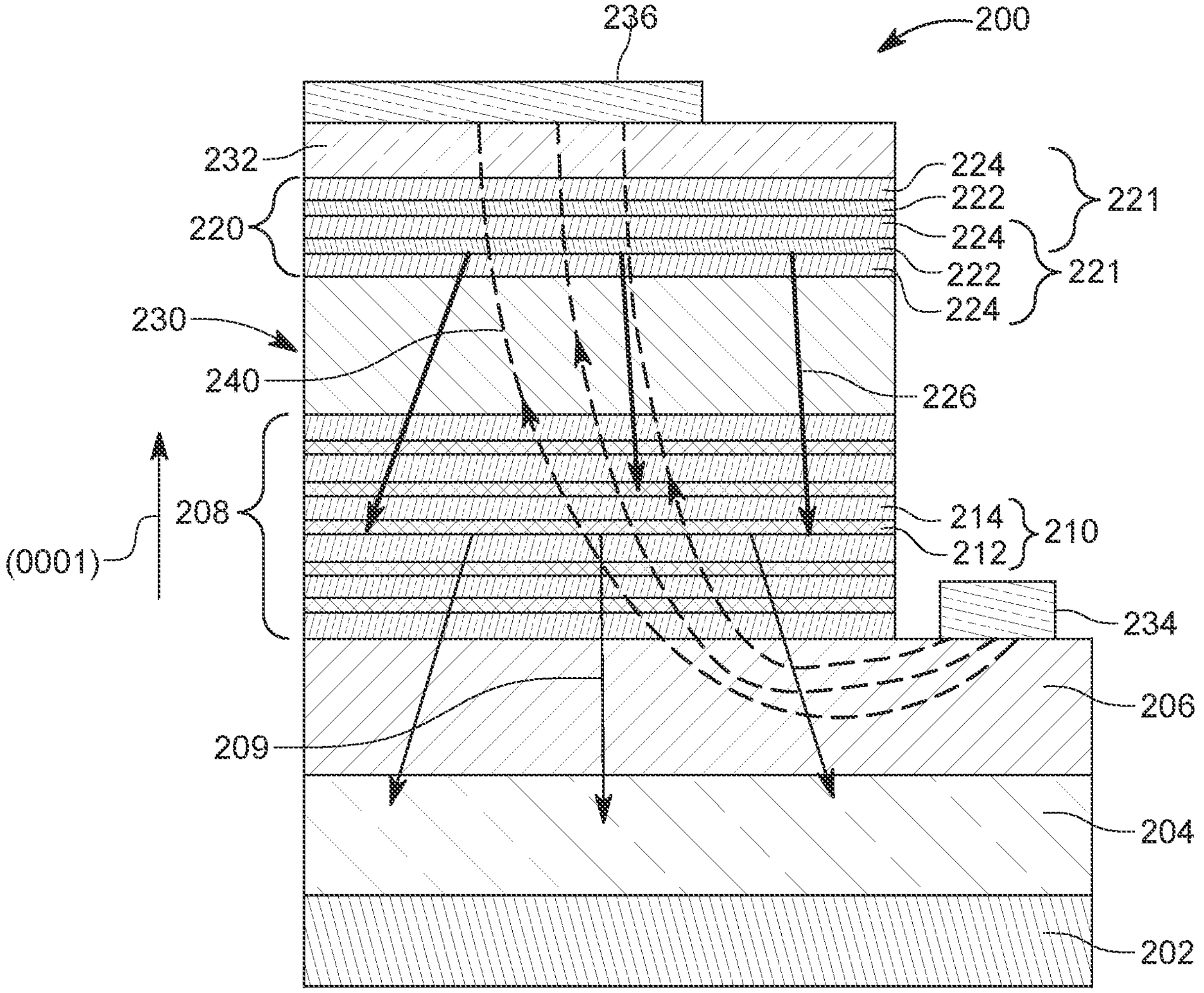
236
200
232
224
222
221
220
224
222
221
224
230
240
226
208
214
210
212
(0001)
234
206
209
204
202

FIG. 2

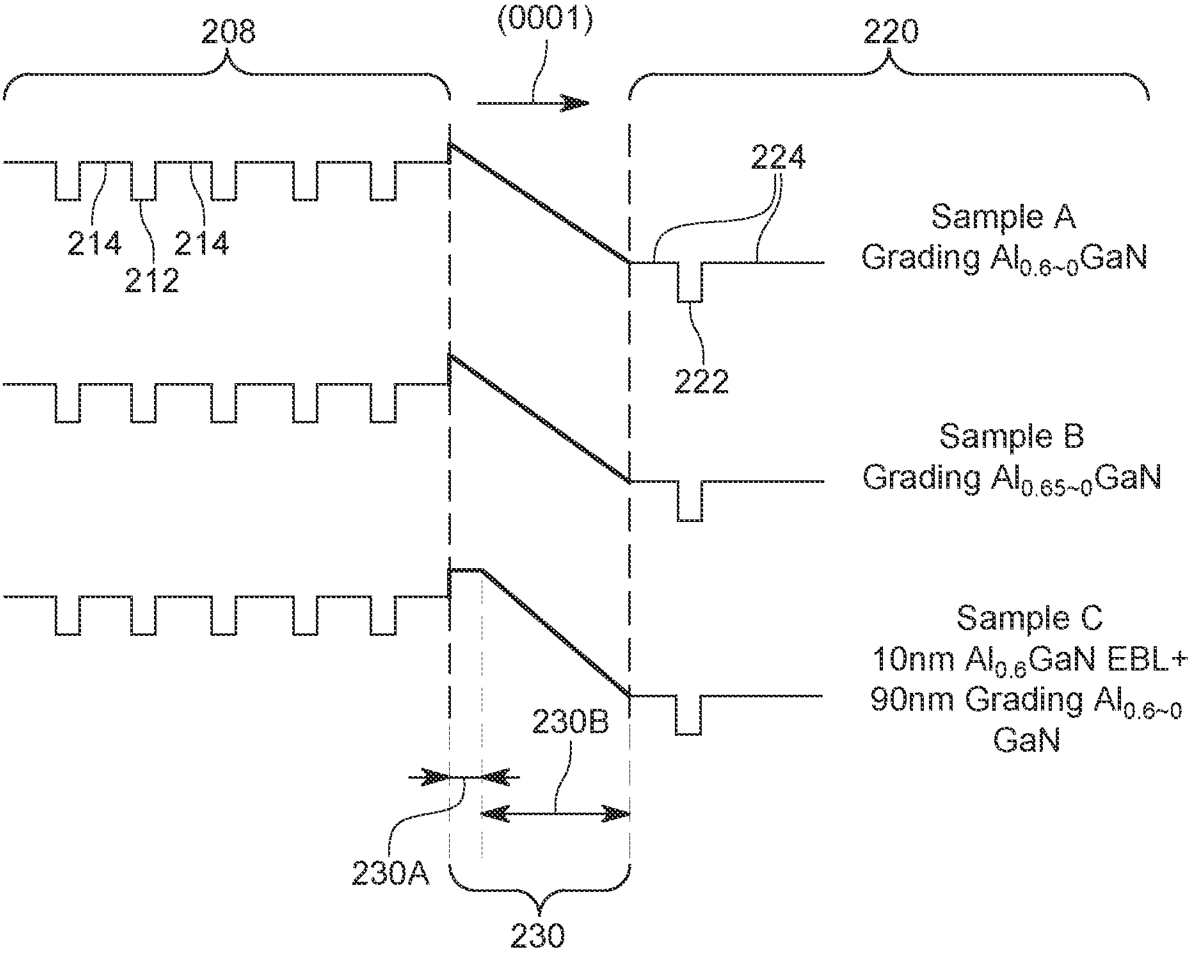
208
(0001)
220
224
214
212
214
Sample A
Grading Al0.6~0GaN
222
Sample B
Grading Al0.65~0GaN
Sample C
10nm Al0.6GaN EBL+
90nm Grading Al0.6~0
GaN
230B
230A
230

FIG. 3

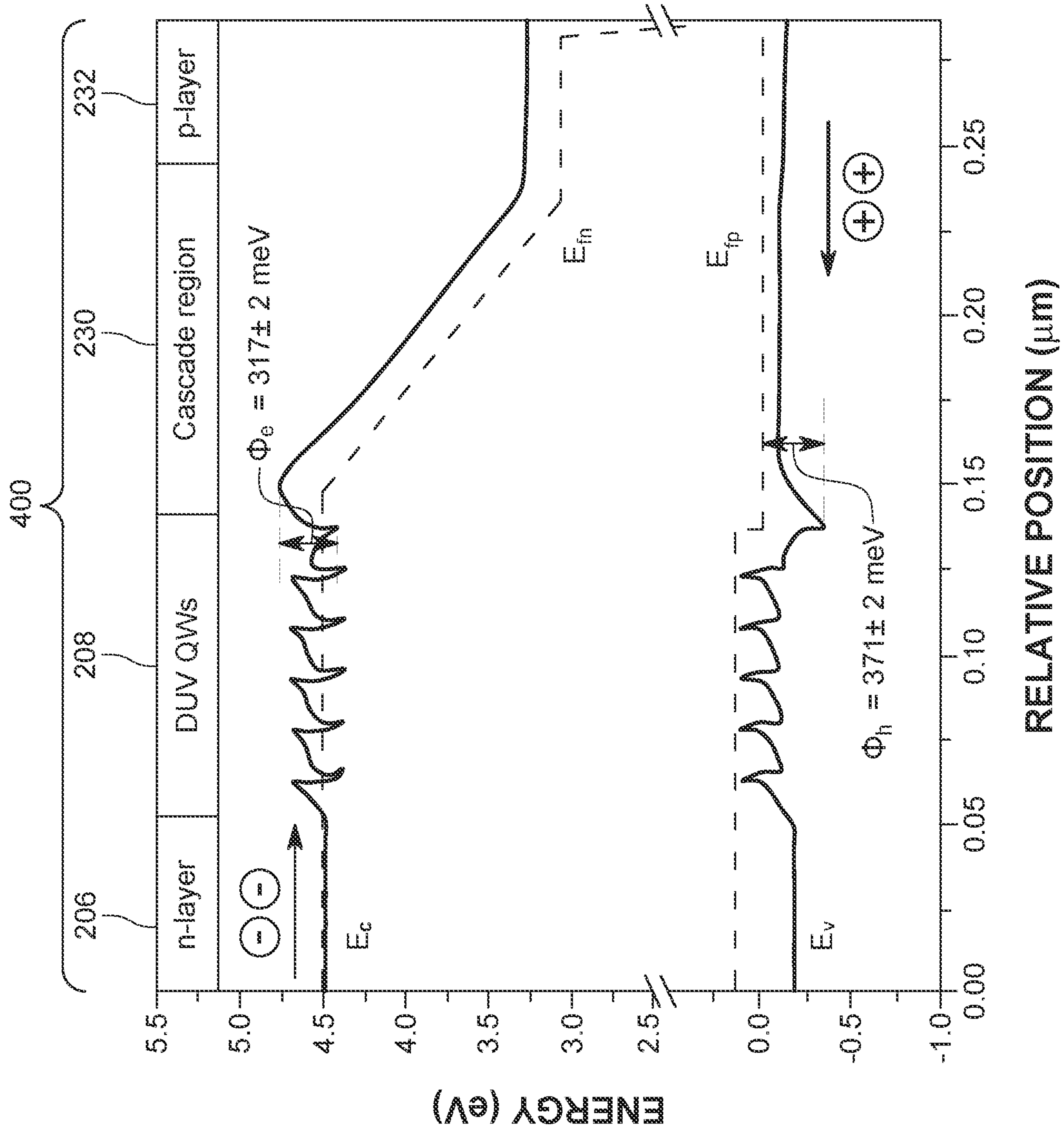
400
206
n-layer
208
DUV QWs
230
Cascade region
232
p-layer
E_c
E_v
E_{fn}
E_{fp}
Φ_e = 317± 2 meV
Φ_h = 371± 2 meV
ENERGY (eV)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
0.0
-0.5
-1.0
RELATIVE POSITION (μm)
0.00
0.05
0.10
0.15
0.20
0.25

FIG. 4A

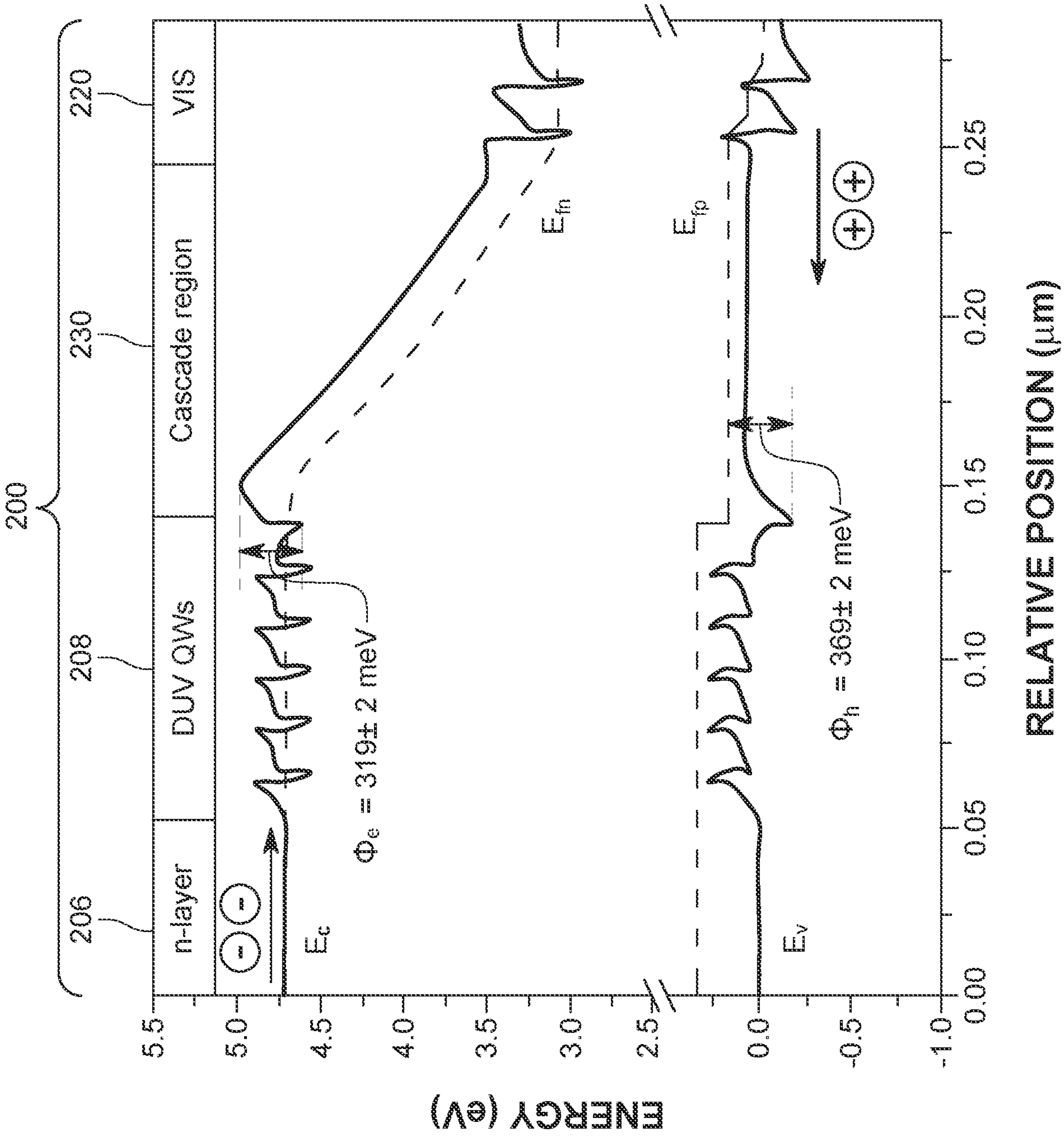
200
206
208
230
220
n-layer
DUV QWs
Cascade region
VIS
E_c
E_v
E_{fn}
E_{fp}
Φ_e = 319± 2 meV
Φ_h = 369± 2 meV
ENERGY (eV)
RELATIVE POSITION (μm)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
0.0
-0.5
-1.0
0.00
0.05
0.10
0.15
0.20
0.25

FIG. 4B

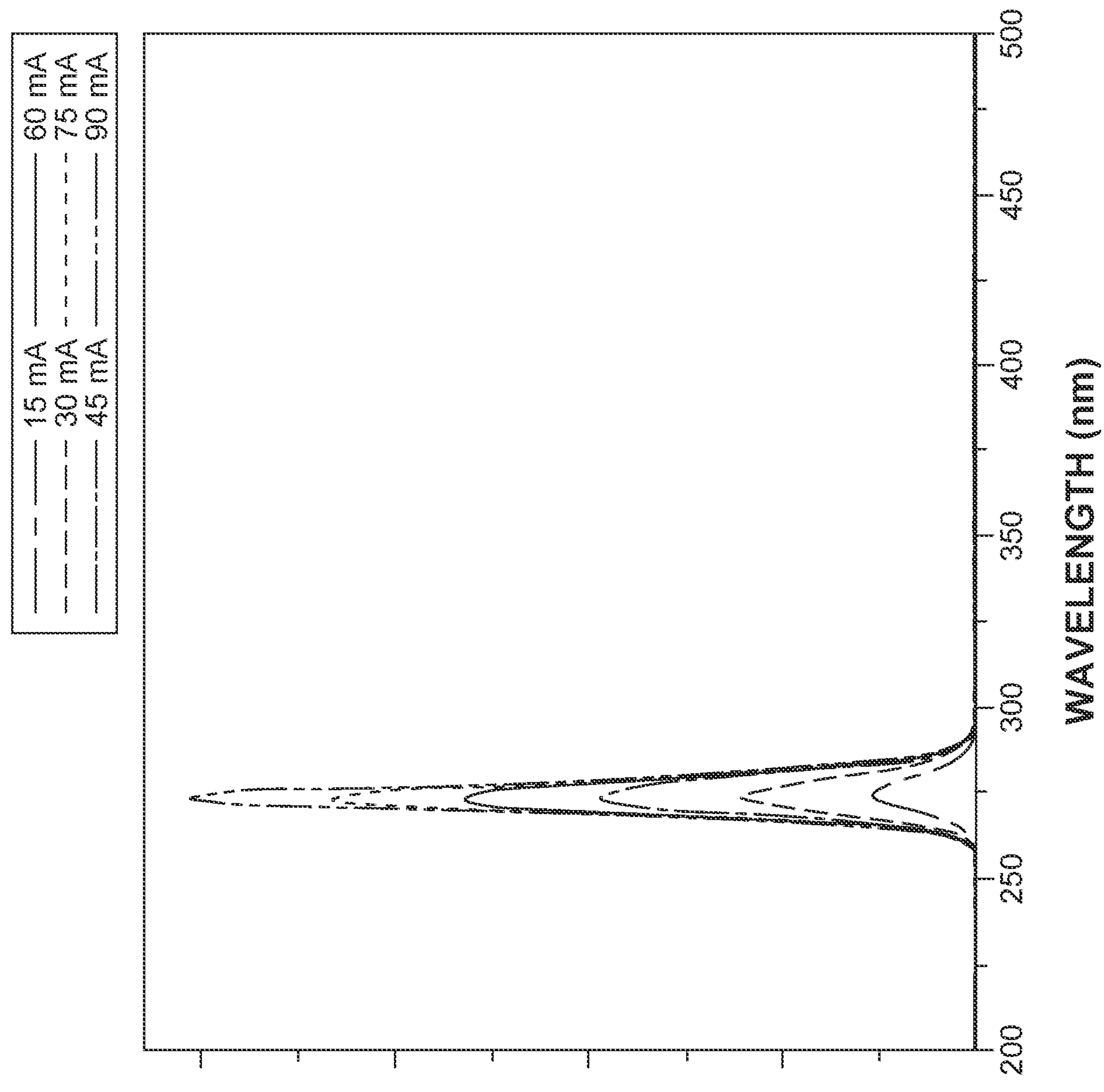
15 mA
30 mA
45 mA
60 mA
75 mA
90 mA
RSP (a.u.)
200
250
300
350
400
450
500
WAVELENGTH (nm)

FIG. 5A

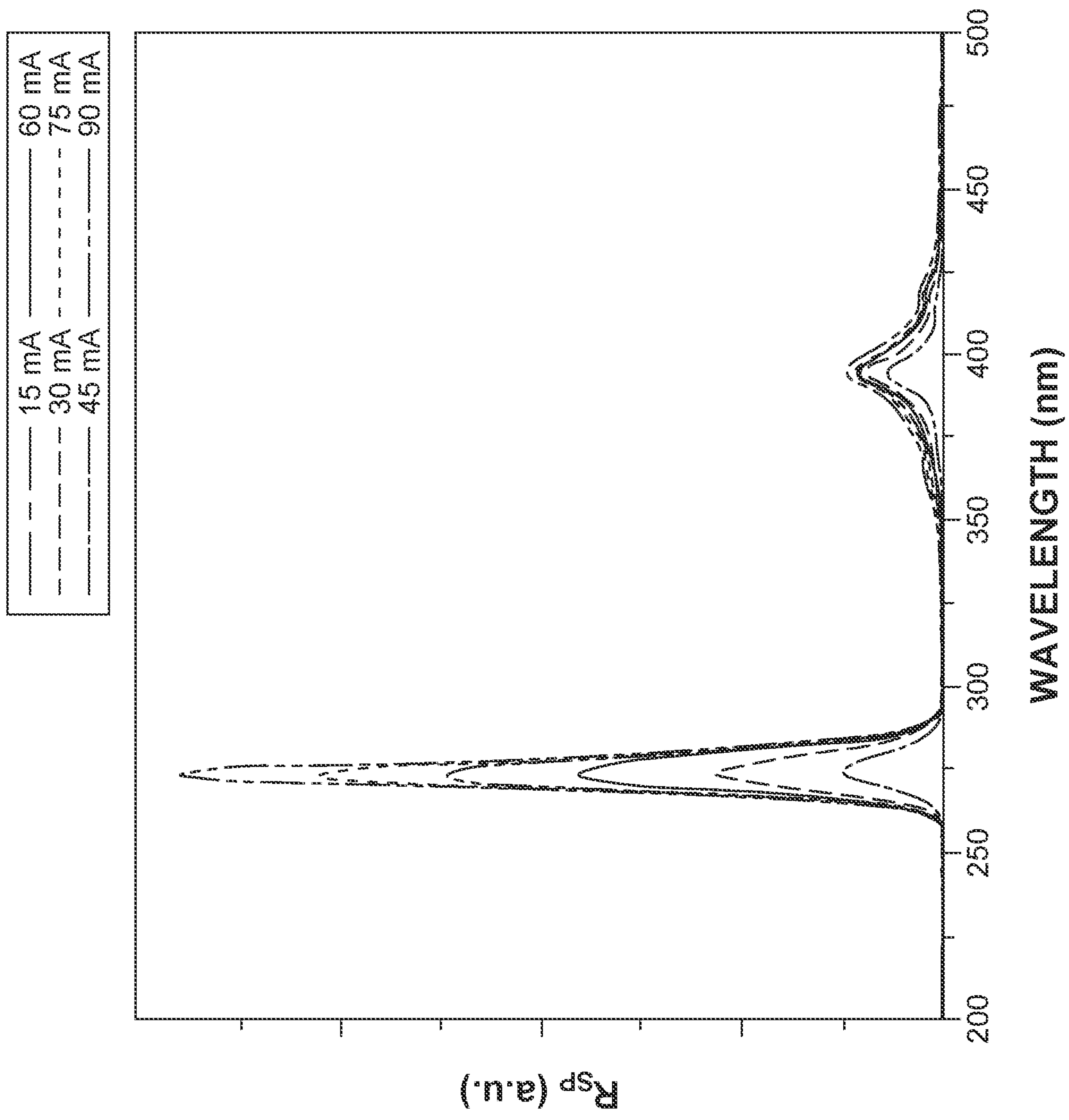
15 mA
30 mA
45 mA
60 mA
75 mA
90 mA
200
250
300
350
400
450
500
WAVELENGTH (nm)
R_{SP} (a.u.)

FIG. 5B

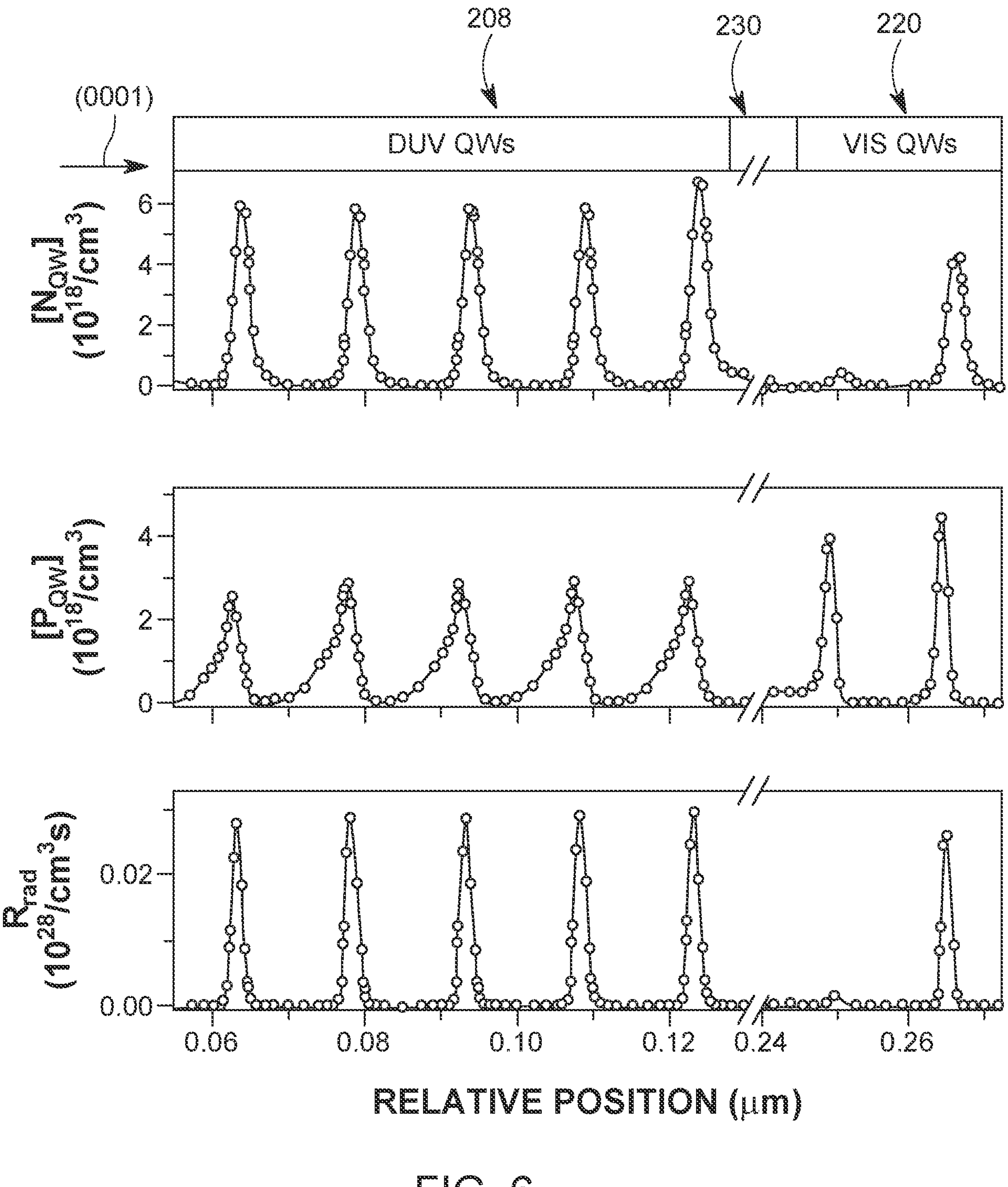
208
230
220
(0001)
DUV QWs
VIS QWs
[N_QW] (10^18/cm^3)
6
4
2
0
[P_QW] (10^18/cm^3)
4
2
0
R_rad (10^28/cm^3s)
0.02
0.00
0.06
0.08
0.10
0.12
0.24
0.26
RELATIVE POSITION (μm)

FIG. 6

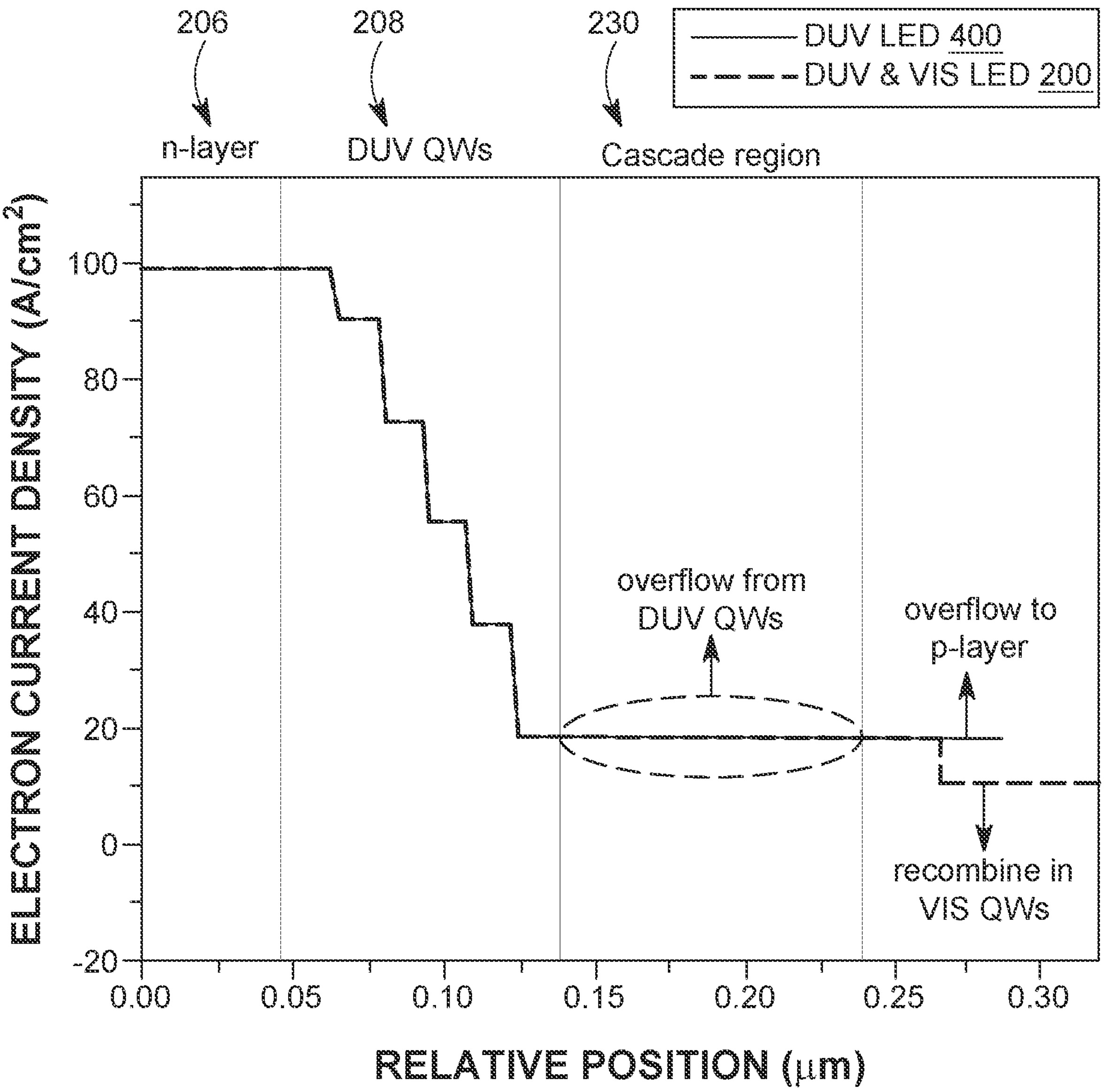
206
208
230
n-layer
DUV QWs
Cascade region
DUV LED 400
DUV & VIS LED 200
ELECTRON CURRENT DENSITY (A/cm2)
100
80
60
40
20
0
-20
overflow from
DUV QWs
overflow to
p-layer
recombine in
VIS QWs
0.00
0.05
0.10
0.15
0.20
0.25
0.30
RELATIVE POSITION (μm)

FIG. 7

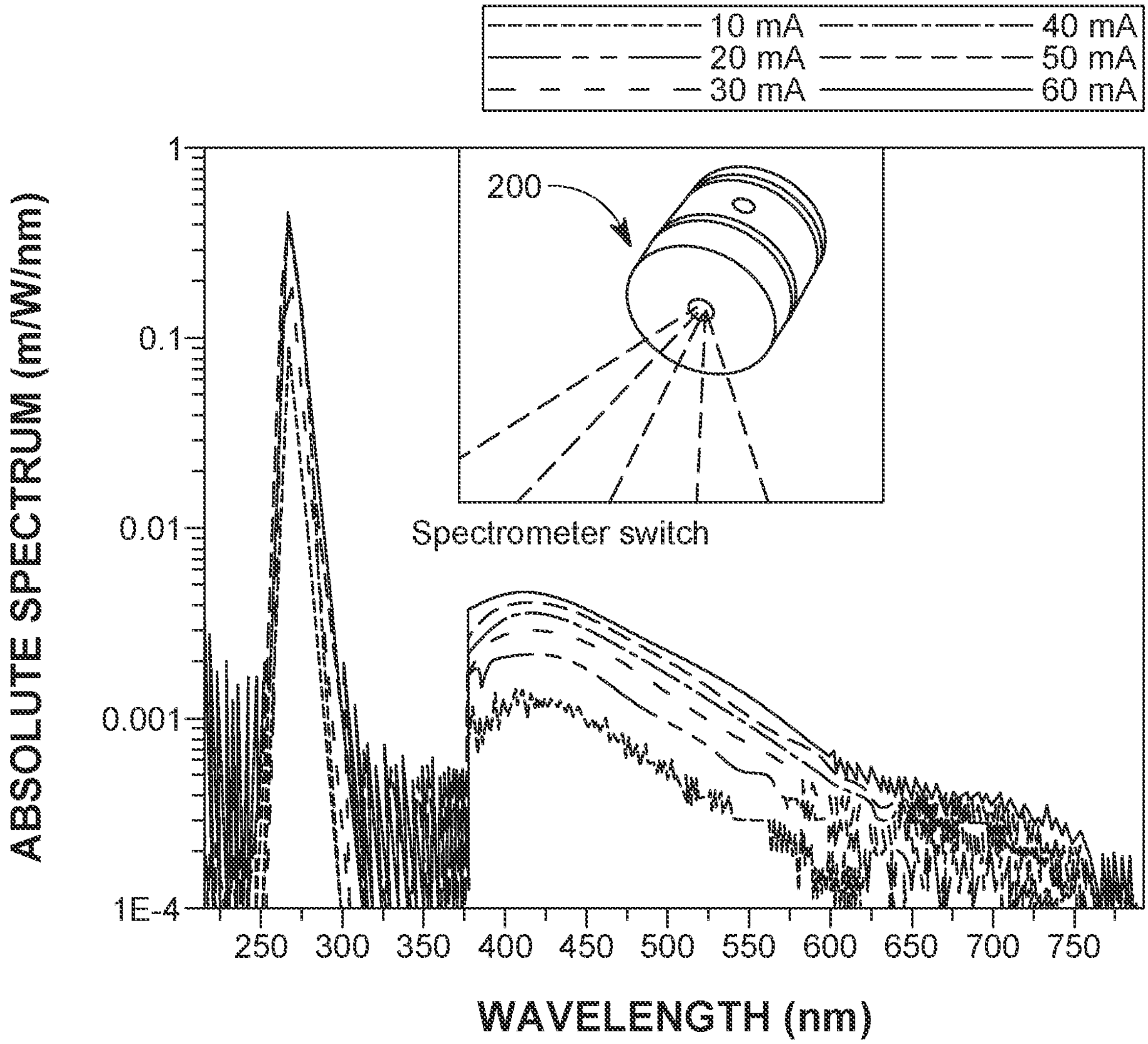
10 mA
40 mA
20 mA
50 mA
30 mA
60 mA
200
Spectrometer switch
ABSOLUTE SPECTRUM (m/W/nm)
1
0.1
0.01
0.001
1E-4
250 300 350 400 450 500 550 600 650 700 750
WAVELENGTH (nm)

FIG. 8A

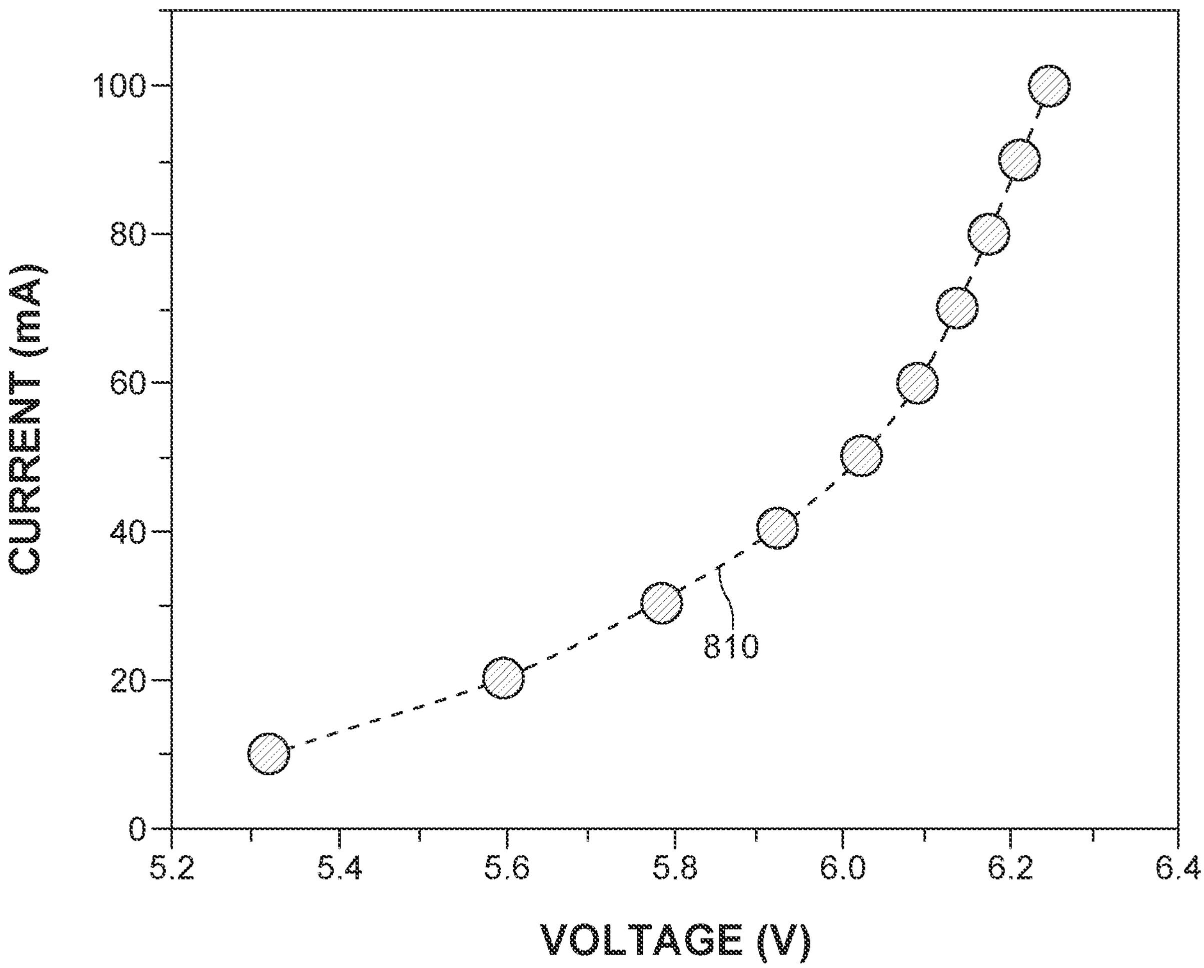

FIG. 8B

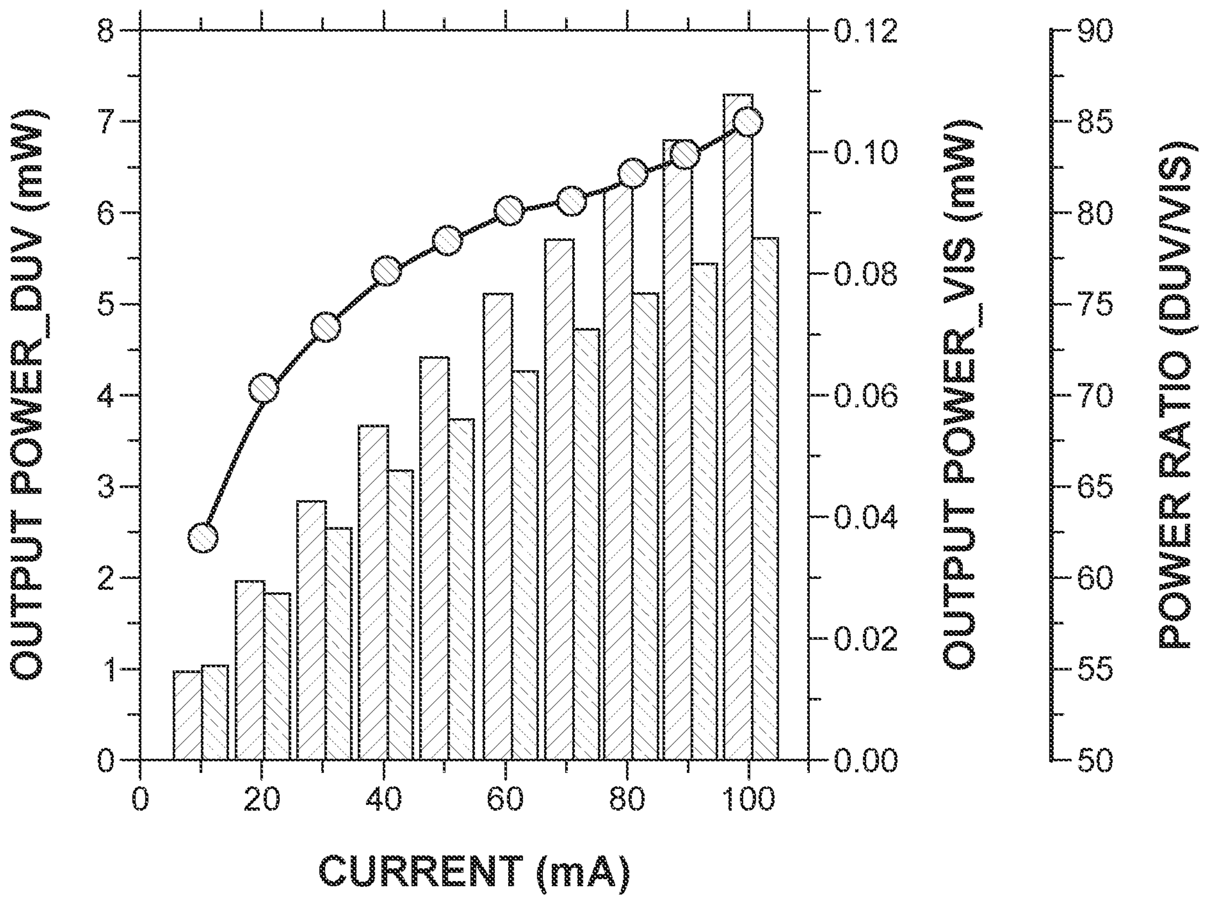
OUTPUT POWER_DUV (mW)
OUTPUT POWER_VIS (mW)
POWER RATIO (DUV/VIS)
CURRENT (mA)
0
1
2
3
4
5
6
7
8
20
40
60
80
100
0.00
0.02
0.04
0.06
0.08
0.10
0.12
50
55
60
65
70
75
80
85
90

FIG. 8C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2024/056464

A. CLASSIFICATION OF SUBJECT MATTER

H01L 33/08(2010.01)i; **H01L 33/32**(2010.01)i; **H01L 33/14**(2010.01)i; **H01L 33/06**(2010.01)i; **H01L 33/38**(2010.01)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 33/08(2010.01); G01N 33/18(2006.01); H01L 25/075(2006.01); H01L 33/14(2010.01); H01L 33/32(2010.01); H01L 33/38(2010.01); H01L 33/40(2010.01)

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

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: light emitting diode (LED), deep ultraviolet (DUV), visible, monolithic, electrode

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2020-0209208 A1 (NANJING UNIVERSITY) 02 July 2020 (2020-07-02) See paragraphs 72-80, claims 1-18 and figures 6-9.	1-20
A	US 2019-0148593 A1 (CORNELL UNIVERSITY) 16 May 2019 (2019-05-16) See paragraphs 25-29, claims 1-18 and figures 2-3.	1-20
A	JP 2019-176016 A (NICHIA CHEM IND. LTD.) 10 October 2019 (2019-10-10) See paragraphs 10-18 and figure 1.	1-20
A	US 2022-0367755 A1 (NANJING LIANGXIN INFORMATION TECHNOLOGY CO., LTD.) 17 November 2022 (2022-11-17) See paragraphs 27-44 and figure 1.	1-20
A	US 2019-0067520 A1 (NIKKISO CO., LTD.) 28 February 2019 (2019-02-28) See paragraphs 27-52 and figure 1.	1-20

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"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	Date of mailing of the international search report
14 October 2024	**15 October 2024**

Name and mailing address of the ISA/KR	Authorized officer
Korean Intellectual Property Office **189 Cheongsa-ro, Seo-gu, Daejeon** **35208, Republic of Korea**	**LEE, Kang Ha**
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IB2024/056464

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
US 2020-0209208 A1	02 July 2020	CN 109655110 A	19 April 2019
		US 11092584 B2	17 August 2021
US 2019-0148593 A1	16 May 2019	US 10957817 B2	23 March 2021
		US 11043612 B2	22 June 2021
		US 2019-0148584 A1	16 May 2019
JP 2019-176016 A	10 October 2019	CN 110323314 A	11 October 2019
		JP 2022-019963 A	27 January 2022
		JP 7068577 B2	17 May 2022
		KR 10-2019-0113647 A	08 October 2019
		US 10804434 B2	13 October 2020
		US 11302847 B2	12 April 2022
		US 11777062 B2	03 October 2023
		US 11824140 B2	21 November 2023
		US 2019-0305187 A1	03 October 2019
		US 2020-0411723 A1	31 December 2020
		US 2022-0181523 A1	09 June 2022
US 2022-0367755 A1	17 November 2022	CN 111106212 A	05 May 2020
		WO 2021-129214 A1	01 July 2021
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		KR 10-2075286 B1	07 February 2020
		TW 201806184 A	16 February 2018
		TW I730079 B	11 June 2021
		US 11355670 B2	07 June 2022
		WO 2017-195507 A1	16 November 2017