Performance enhancement of GaN/GaAs based hybrid multi-quantum well LED structures

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In this paper, a numerical investigation of proposed hybrid QW layers in LED structures is carried out. The proposed light-emitting diode structures are obtained by combining the quantum well layers of two different direct bandgap semiconductor materials belonging to group III-V of the periodic table. The simulation results of the proposed light-emitting diode structures are compared with the conventional multi-quantum well GaN-based light-emitting diode design, and it is seen that the obtained values of the external efficiency of the proposed light-emitting diode hybrid multi-quantum well structure is higher than the efficiency of the existing multi-quantum well light-emitting diode structure. In one proposed structure, the maximum output power level increases to 17.96 mW compared to 7.7 mW in the conventional multi-quantum well GaN light-emitting diode structure. The increase in recombination rate achieved by hybrid multi-quantum well designs increases the device efficiency up to 127% from the traditional multi-quantum well light-emitting diodes.

(Received September 9, 2021; accepted August 10, 2022)

Keywords: Direct bandgap, External efficiency, Extraction efficiency, Hybrid multi quantum well, Internal quantum efficiency, Luminescence, Single quantum well, Structural design, Total internal reflection

1. Introduction

The light-emitting diodes (LEDs) are increasingly used as light sources and display devices in many fields, including physics, medical science, communications, sensors, etc. [1]. One of the applications of these devices is in the optical-fiber communication system for low and medium data rates (< 1Gb/S) over short and medium distances (< 10 km) [2][3]. The efficiency of the LEDs being used in these applications is an essential consideration for selecting a particular device. Now to enhance the device's performance since the beginning, its architecture is continuously transforming. It is well-known that if a heterojunction structure is utilized in the device design, the light emission efficiency of these devices can be improved [4]. This is due to an increase in excess carrier concentration, which reduces the radiative recombination lifetime leading to more efficient radiative recombination. The double heterojunction structures achieve higher efficiency than a single heterojunction structure and are more preferred for the device design [4].

If the central active layer width in the LEDs is reduced to or below 10 nm, a quantum well is formed [5]. In the quantum well (QW) based LED designs, the QW forms the active region where radiative recombination of the charge carrier (responsible for the emission of visible light) takes place [5]. Currently, the LEDs are designed using multi-quantum well (MQW) structures, as their performance and reliability are better than other LED structures reported so far in the literature [5]. Some of the literature's reported GaN-based MQW LED structures are as follows. In [6], an MQW structure is reported with a current spreading layer, and it exhibits a modulation bandwidth of 225.4 MHz and a light output power of 1.6 mW. A non-polar InGaN/GaN-based MQW structure is demonstrated in [7], and the device exhibits a large modulation bandwidth of 524 MHz. Similarly, in [8], a high-speed GaN-based green color LED is reported, which generates 1.6 mW output power at 50 mA, considered high output power concerning other high-speed LEDs.

All these GaN-based LEDs differ in terms of physical design, the number of layers in MQW structure, the composition of semiconductor compounds, etc. They emit light of different colors (different wavelengths), which fall in the range of green and blue light spectrum colors [9]. In this article, the staggered and alternating arrangement of GaN/GaAs layers is numerically investigated to improve its performance.

The proposal to use hybrid multi-quantum well (HMQW) layers are investigated in this paper using the base device design considered in [10]. The number of barrier and QW layers is increased from three to four. The base design is reproduced here for ease of reference in Fig. 6.a. The proposed HMQW structures are obtained using different combinations of layers and their material (combining two semiconductor compounds). Simulations of the proposed designs are carried out in TCAD software. It is observed that the proposed HMQW structures exhibit improved efficiency up to 127% and increased output power of 17.96 mW compared to 7.7 mW for the MQW LED designs considered in [10].

The rest of the paper is organized as follows. In section 2, a brief review of the QW structures is presented. The proposed designs are presented in section 3. The simulation results are shown in section 4, followed by conclusions.

2. Proposed structures of HMQW LEDs

In this section, proposed designs of HMQW LED structures are presented. The motivation for these modified LED designs is to investigate the possibility of increasing the external efficiency of the LEDs by using different semiconductor materials in the active layers of the LED [11]. It is well known that LED's radiative and non-radiative recombination rates depend on several factors such as the material, doping levels, design construction, etc. [12]. The staggered arrangement of these materials also forms a lens-like structure due to the different dielectric constant of the semiconductor materials resulting in increased intensity and output optical power. The hybrid arrangement of different materials in the MQW layers changes the LED’s energy band diagram, creating some extra dips/well, which trap the charged particles in them, increasing the radiative recombination. This, in turn, increases the LED device's external efficiency and intensity and generates more output power than the conventional MQW LED. It may be mentioned here that GaN and GaAS belong to the III-V group of the periodic table, having nearly the same bandgap energy allowing this hybridization [13-14]. The hybridization of QW layers is achieved by combining alternating arrangements of the quantum well (QW) layers of two different direct bandgap semiconductor materials.

Two minor modifications are done to the existing structure of Fig. 1. The first modification is done in the active region of the LED, in which four structures are proposed as follows.

Structure 1: In this proposed LED design, the topmost QW layer is hybridized using two semiconductor materials, GaN and GaAs, whereas the remaining three QW layers are non-hybrid layers made up of GaN semiconductor material.

Structure 2: In the second design, layer the second and bottom-most layers are hybridized using the same materials, GaN and GaAS. The topmost and third layers from the top are GaN-based layers only.

Structure 3: All the layers are hybridized using GaN and GaAs except the topmost layer in this design.

Structure 4: In this design, hybridization of all the four layers in the LED structure is proposed.

In the upper confinement layer of all these four structures, GaN is replaced by GaAs semiconductor material.

The fraction of the length of two different materials in hybrid layers of the LED designs used in this paper is given in Table 1.

Table 1. Design details of HMQW LED structures

Design	Total no. of QW layer	No. of Hybrid QW Layer introduced	% Fraction of GaN in each Hybrid Layer	% Fraction GaAs in each Hybrid Layer
1	4	1	50%	50%
2	4	2	50%	50%
3	4	3	50%	50%
4	4	4	50%	50%

The hypothesis that this proposed change will increase radiative recombination over non-radiative recombination is verified in the next section through simulation experiments. In the following subsection, dimensional details of the LED structures are discussed.

2.1. Dimensional details of the structures

The structural details of all the proposed LED design structures shown in Fig. 2 are as follows. The width and height of the LED devices are of the order of 1 µm and 3.5 µm respectively. The height of the substrate layer is 3 µm with n-type doping concentration of $2\times10^{18}\,cm^{-3}$, followed by 0.1 µm thick layer of the uniformly doped *n*-type $Al_{0.2}Ga_{0.8}As$ layer with a doping concentration of $2\times10^{18}\,cm^{-3}$. Above these layers, the active region consists of four QW layers of height 3 nm and the height 7 nm barrier layer. Above the active region of the LED, the structure is capped with 0.1 µm thick layer of $Al_{0.2}Ga_{0.8}As$ uniformly doped with *p-type* with a doping concentration of $2\times10^{20}\,cm^{-3}$, followed by another 0.2 µm thick layer of $Al_{0.1}Ga_{0.9}As$, and it is highly doped with *p-type* of impurity with a doping concentration of $2\times10^{20}\,cm^{-3}$. Finally, the topmost layer of GaAs is kept 0.1 µm doped with *p-type* impurity with a doping concentration of $2\times10^{20}\,cm^{-3}$. The electrical contacts for the anode and cathode are placed at the device’s top and bottom, respectively.

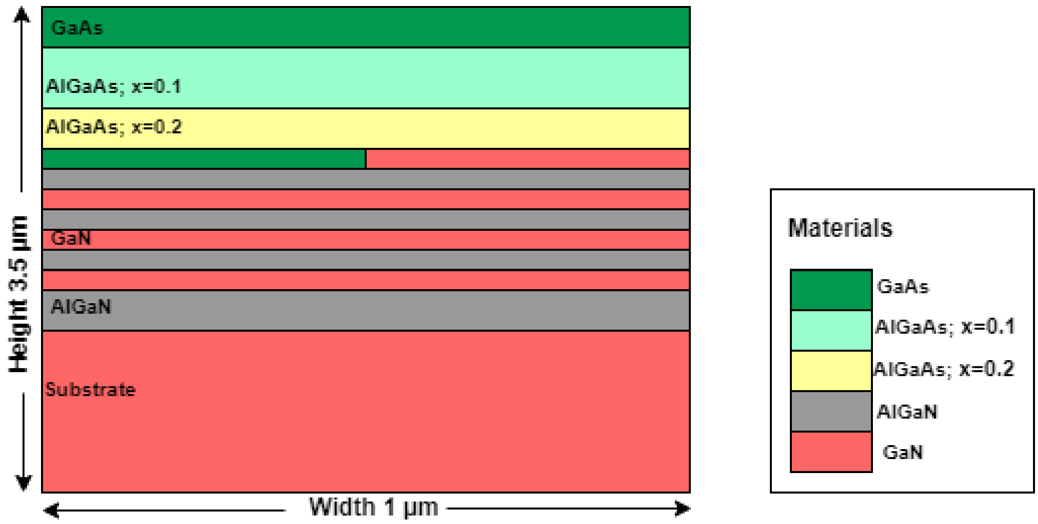

Fig. 1. Proposed hybrid multi-quantum well LED structure 1 (color online)

The proposed LED *structure 2* to *structure 4* differ only in the number of hybrid layers only. These LEDs are simulated in the next section and their details are not shown here separately similar to Fig. 1.

The following section presents the simulation results of all the proposed structures.

3. Results and discussions

The simulations of the proposed LED *structure 1* to *structure 4* are carried out in TCAD software, and the obtained results are presented in this section. Out of many other possible HMQW structures using a different fraction of GaN and GaAs, this article focuses on four hybrid structures (designs) that achieve better performance than the other structures. The dimensional detail of structure one discussed in section 2 is shown below in Fig. 2. The structure shown in Fig. 2 displays the replacement of GaN with GaAs in the confinement layers of the P region. Next is the simulated results of the proposed structures.

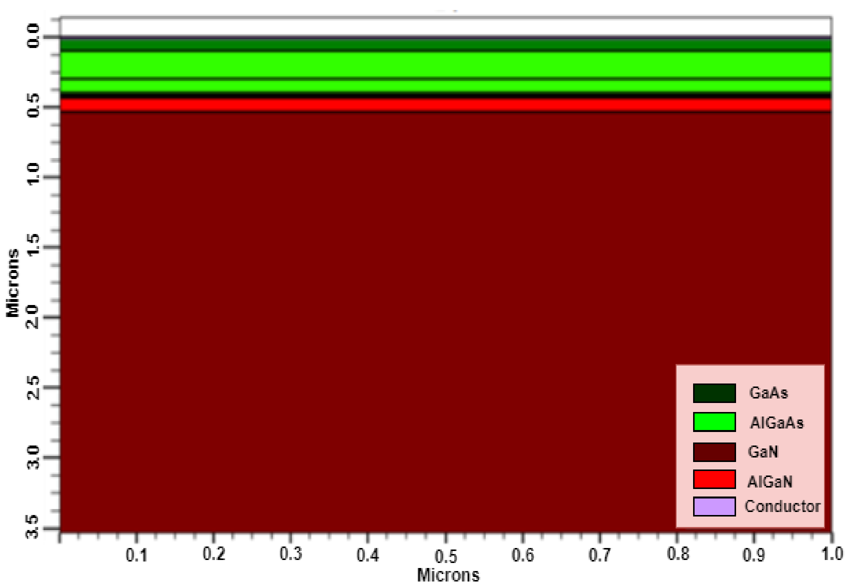

Fig. 2. GaN replaced to GaAS in P region of HMQW LED (color online)

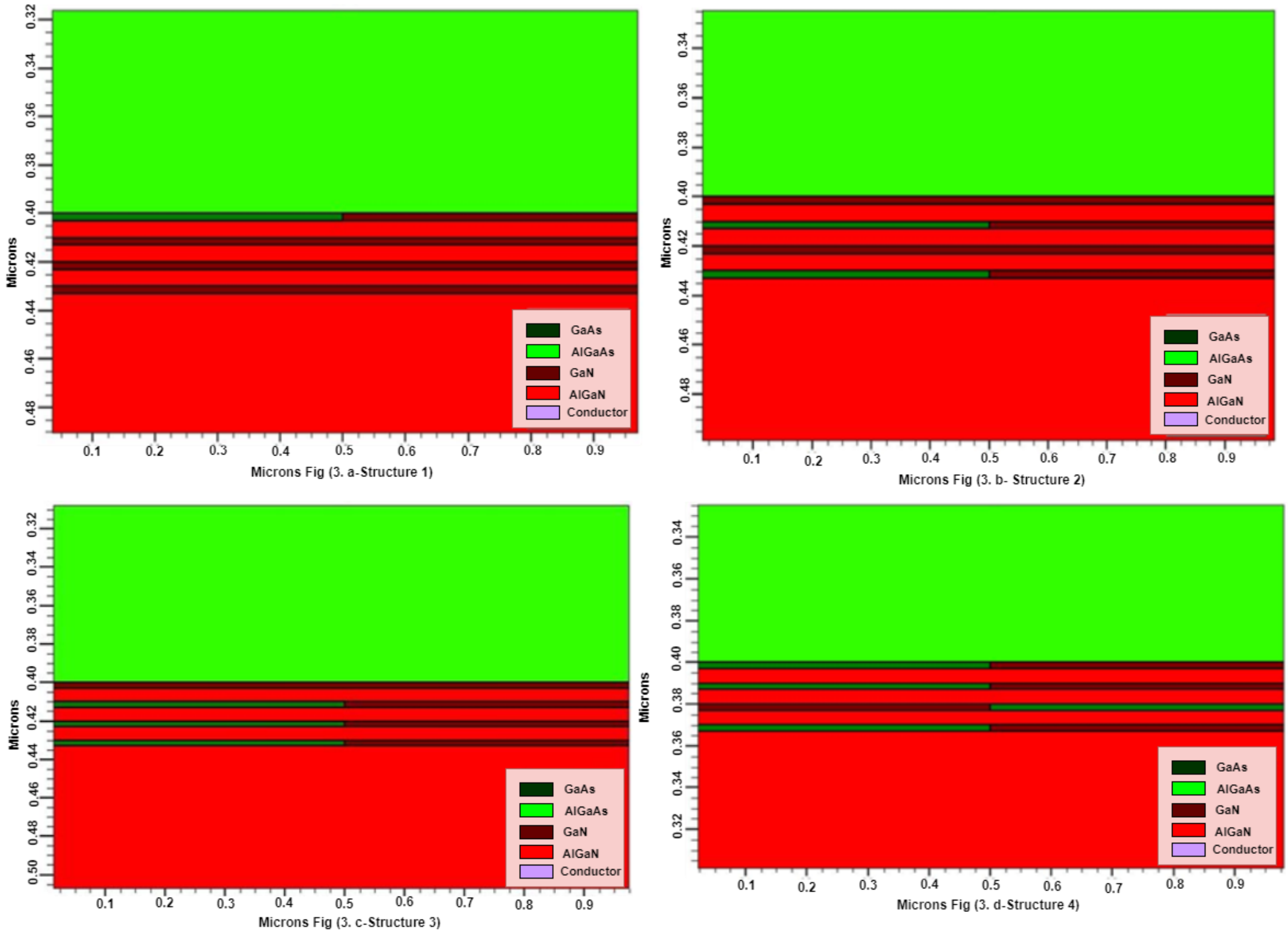

Fig. 3. Expanded view of proposed HMQW LED structures (color online)

For better clarity, the expanded view of the active region of structure 1 to structure 4 of the proposed LED structures are shown in Fig. 3.a-3.d. Fig. 3.a is the single hybrid layer MQW structure, followed by double hybrid layers MQW structure Fig. 3.b, three layers MQW shown in Fig. 3.c and lastly four hybrid layers MQW structure. The structural and semiconductor composition details of these structures are already discussed in section 2 and summarized in Table 1 as well.

The proposed structures are identical in all respects except the number of hybrid layers. The difference in the design of the active region changes the output performance of the device. The results in the upcoming section will clear and justify the motive and advantage of the proposed structures.

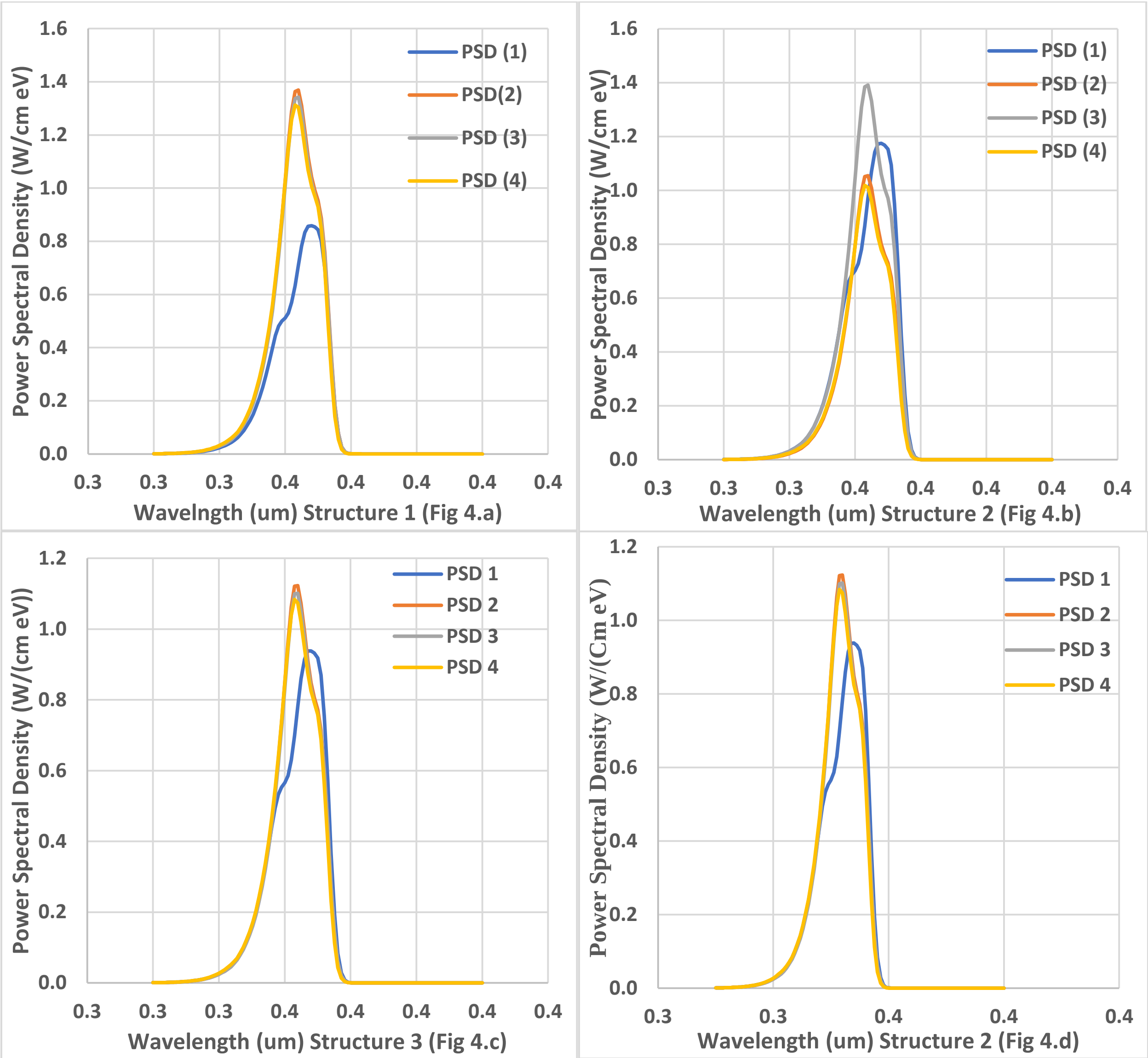

Fig. 4. Power spectral density versus wavelength curves of HMQW structures (color online)

From Fig. 4.a-4.d, the characteristic curves show the variation of power spectral density versus wavelength. In Fig. 4.a (structure 1) the maximum intensity of light recorded is 13.2 (W/cm eV), followed by structure 2 in that it is 12.4 (W/cm eV), for structure 3, the recorded intensity is 12.2 (W/cm eV) and the least value of intensity recorded for the structure 4 and it is 11.8 (W/cm eV). As the number of hybrid layers increases from one to four, the intensity of light emitted from each layer varies, and the peak wavelength at which the maximum power of light is achieved is 351 nm. All the proposed HMQW structures are simulated to obtain the light output versus anode current, obtained results of all the devices are shown in Fig. 5.

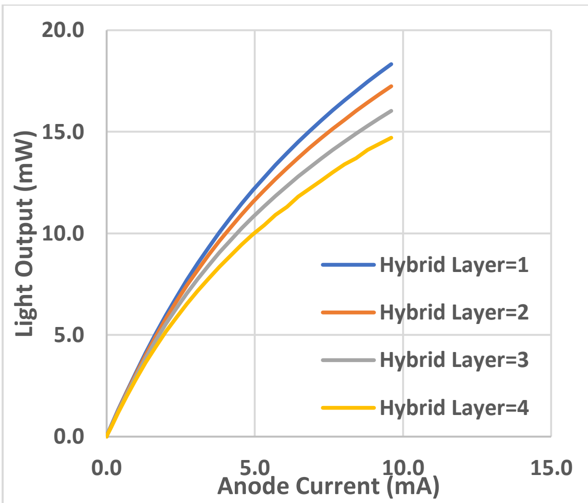

Fig. 5. Light output versus current curve of HMQW structures (color online)

It is evident from the results shown in Fig. 5 that the maximum output power is obtained for *structure 1* at the value of 9 mA at an applied voltage of 6V. The obtained optical power for *structure 1* is of the order of 17.96 mW. The optical power of the double hybrid layer *structure 2* is approximately 16.80 mW followed by a three-layer hybrid *structure 3* that emits the light of optical power of 15.58 mW. *Structure 4* consisting of four hybrid layers gives the optical power of the order of 13.09 mW.

To compare the results of the proposed structures with the GaN-based LED having identical dimensions, the LED design shown in Fig. 6.a is also simulated and the simulation result is shown in Fig. 6.b.

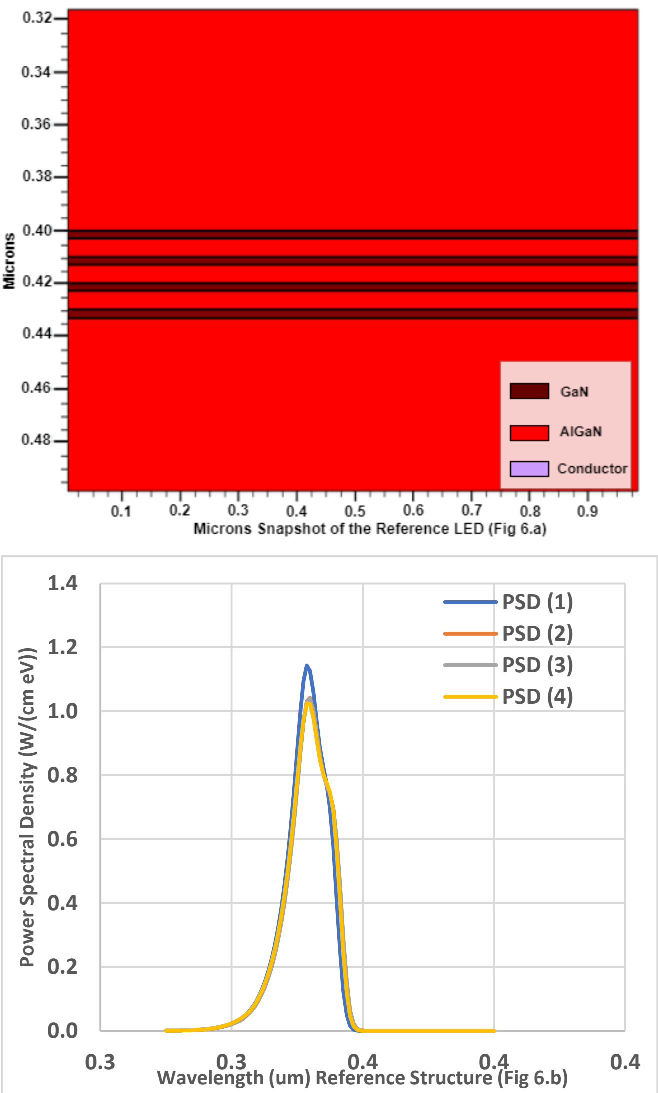

Fig. 6. Reference LED structure and its characteristic curve (color online)

The maximum optical power for the all GaN based LED shown in Fig. 6.a is only 7.7 mW at 9 mA at an applied voltage of 6V. It is also seen from the power spectral density versus wavelength curves that the peak wavelength of light with maximum intensity doesn't deviate much but the intensity of light increases in three out of four proposed HMQW structures compared to GaN-based LED.

A comparison of the simulation results of the HMQW structures and base structure are summarized in Table 2.

Table 2. Primitive characteristic of designed hybrid and existing LED

Structure No.	No. of Total & Hybrid QW Layers	I_{max} (m**A**)	Vmax (**V**)	P_{out} (m**W**)	λ_p (nm)
1	4 & 1	9.231	6	17.96	351
2	4 & 2	9.210	6	16.80	351
3	4 & 3	9.208	6	15.58	351
4	4 & 4	9.207	6	13.09	351
Reference	4 & 0	9.088	6	7.783	351

It can be seen from Table 2 that the generated output power decreases with the increase in the number of hybrid layers. However, each hybrid structure's least generated optical power is still higher than the conventional MQW structure (Fig. 6.a).

It suggests that the hybridization increases the optical power without much change in existing infrastructure. To justify the proposed idea, the external efficiencies of all the structures are also calculated to support the statement. The output optical power P_{out} of an LED is equal to the fraction of input electrical power emitted after accounting for all kinds of losses and is given by the formula [15-17]

$$P_{out} = \eta_{ext} \frac{hc}{e} \frac{i}{\lambda}, \qquad (1)$$

where the circuit current i is in ampere (A), λ denotes the emitted peak wavelength in nm, and the η_{ext} stands for the external quantum efficiency.

Table 3. External efficiency of designed hybrid and existing GaN LED

Structure No.	No. of Total & Hybrid QW layer	External efficiency (η_{ext})	% change in η_{ext} w.r.t. to Reference
1	4 & 1	55.07	127
2	4 & 2	51.63	112
3	4 & 3	47.89	97.56
4	4 & 4	40.24	66
Reference	4 & 0	24.24	-

Table 3 displays the theoretical calculated external efficiency and percentage change in efficiency compared to the conventional MQW design shown in Fig. 6.a. From Table 2 and Table 3, it can be quickly concluded that the single-layer hybrid structure generates the maximum output power and is the most efficient structure among all the four HMQW designs reported in this article. The simulation and calculated results of single-layer HMQW LED are highlighted in Tables 2 and 3.

It is observed from the simulation results that the proposed HMQW structures in this paper generate more output power for the exact value of circuit current than the single material conventional MQW LED. Hence, it can be concluded that the hybridization of the active region and confinement layers could increase efficiency and generate more output power for the LEDs.

4. Conclusion

This paper proposes novel GaN/GaAs LED structures based on hybrid layers in multi-quantum well structures. The proposed modified structures are based on the device's upper confinement layer (P region) and active region (MQW region). Simulation results validate the increased efficiency of the proposed HMQW LED structures than the GaN-based MQW LEDs. The output power level of one of the proposed LED structures increases from 7.7 mW to 17.96 mW. Among all the proposed hybrid MQW structures, the structure with a single hybrid QW layer generates the maximum optical power for the given value of circuit current and applied external voltage. Hence it is concluded that the HMQW structure turns out to be better as it improves the efficiency of the existing GaN-based MQW structures and generates more output power. Single-layer hybridized structure is more efficient among all the four structures discussed in this paper. The increment in the value of efficiency achieved is up to 127% concerning the conventional GaN MQW LED design. The designed UV LED can be helpful in medical science applications.

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