The principle and simple design applications of blue LED

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Abstract. InGaN/GaN blue light-emitting diode (blue LED) is the most commonly investigated and applied LED for blue laser, optical memory, general luminescence, and the candidate for clean energy. However, limited by the efficiency droop, the luminous properties of InGaN/GaN blue LED still faces plenty of challenges. This paper aims to investigate the principle of strains on internal quantum efficiency of InGaN/GaN blue LED, as well as provide simple materials and structure design for high luminous efficiency and harmless blue LED based on the composite of InGaN/GaN. On this basis, the properties are simulated and testified based on the program TracePro Application. By tuning up the supper lattice on m-plane instead of c-plane, the polarization electric field will be eliminated and thus the efficiency droop will be improved. Besides, a backlight structure of the combination of cyan and hyacinthine LED chips is launched by grating ZnSeTe quantum dots and ZnSe quantum dots on the surface of p-GaN and this backlight structure design is proved to be high luminous and harmless to human eyes. These results shed light on possible ways to enhance the luminous properties and safety of InGaN/GaN blue LED both in materials aspect and in structure design.

Keywords: InGaN/GaN blue LED, internal quantum efficiency, blacklight structure, TracePro Application.

1. Introduction

Blue light-emitting dioxide (blue LED) known as "the second lighting revolution after Edison", is a kind of a diode that emits blue light, which is an indispensable part of RGB. The history of LED can be dated back to 1907, when Henry Joseph Round discovered the phenomenon of electroluminescence [1]. In 1962, the GaAsP alloy based red-light-emitting diode (red LED) was developed by Holonyak and Bevacqua [2]. In 1968, Logan et al. achieved the green-light-emitting diode (green LED) using the nitrogen-doped GaP p–n junction [3]. In addition, the invention of blue-light-emitting dioxide (LED) was in 1989-1993 [4]. In 2014, Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura were awarded the Nobel Prize for their creation of high-brightness GaN-based p-n junction blue LEDs [5]. The immense time gap is ascribed to the dilemma of improving the working efficiency of blue LED. Large driving current can bring high brightness, but the efficiency of LED will be weakened with the increase of current, which is called the efficiency droop [6]. In this way, promising materials and designs which can provide high luminance and wide color gamut for next-generation blue LED needs to be studied [7].

For years, researchers have spared no effort in improving the efficiency drop of blue LED, to lessen the efficiency droop, Lumileds, Maier, Li, et al. advocated extending the diameter of quantum wells or employing double heterojunction instead of multiple quantum wells as the active zone [8-10]. In Ref. [11], blue Cd-free QDs are fabricated with a basic top emitting structure, and achieved an optimized shell thickness of around 2.4 nm, which realizes outstanding electroluminescence properties of high-efficiency quantum dot blue LED. Jiang et al. invented the technologies of selective growth and maskless micro lateral extension [12]. In the scenario, only a single high-temperature AlN with a thickness of 100 nm was used as the buffer layer to prepare a device level GaN based LED film material with no crack and a thickness greater than 3 μm silicon based blue LED with high luminous efficiency and high reliability [12].

Despite the importance of the high luminescence of blue LED, long-term exposure to the blue light with a wavelength lower than 460nm will cause permanent damage to human eyes. Therefore, multi-wavelength LED is applied during the fabrication process [13]. With the combination of cyan LED chip (450-460nm), and hyacinthine LED chip (435nm-440nm), a new kind of harmless blue LED devices are launched. In this paper, factors that will make a droop on the internal quantum efficiency of InGaN/GaN blue LED is studied [14], and a simple design for high luminous efficiency and harmless blue LED based on the composite of InGaN/GaN is launched and the properties is simulated and testified by TracePro Application. In the final section, the limitations and prospects of modern LED is proposed. The rest part of the paper is organized as follows. The Sec. 2 will introduce the theoretical analysis. The Sec. 3 will demonstrate the setup of the simulation program. Afterwards, the Sec. 4 will present the results and explanation accordingly. Subsequently, the limitations and future outlooks are proposed in the Sec. 5 based on the analysis. Eventually, a brief summary is given in Sec. 6.

2. Theoretical analysis

Light is produced in LEDs when photons are emitted by the spontaneous combination of electrons in the conduction band and holes in the valence band [14]. When large current is injected into the blue LED, the luminescence properties will be improved, however, the efficiency of the blue LED will decrease with the increase of current, which is known as efficiency droop. The efficiency droop is caused by Auger recombination, Shockley Read Hall recombination, carrier delocalization, and electron leakage, which are all factors of temperature and carrier concentration. The optical extraction efficiency η_{OQE} (rate of creation of photons in quantum well to number of carriers injected in the LED) and internal quantum efficiency η_{IQE} (rate of photons emitted from the LED to photons produced in the quantum well) of an LED made up of the quantum efficiency of blue LED, i.e., $\eta = \eta_{OQE} \times \eta_{IQE}$.The drop of η_{IQE}, which follows the equation, is said to be the main cause of efficiency droop [15,16].

$$\eta_{IQE} = \frac{\eta_{inj} B n^2}{[(\alpha n + \beta n^2 + \gamma n^3) + k(n - n_0)^2]} \tag{1}$$

where α, β, γ, k are approximately equal to 1, n_0 is the intrinsic carrier concentration of a specific semiconductor, η_{inj} stands for the injection efficiency. It is acknowledged that η_{inj} is highly related to the carriers' recombination, and the polarization electric field (PE field) is the main cause of small recombination. In this article, the most commonly used InGaN/GaN blue LED is researched. Therefore, one of the most efficient ways of improving η_{IQE} is the elimination of the PE field by growing the supper lattice on m-plane instead of c-plane.

Quantum dots (QDs) are promise for next-generation displays because of their adjustable emission spectra, high quantum yields (QYs), and small emission line width [7]. With the proper semiconductor and proper size of its quantum dots, the thin film on the surface of p-type GaN will highly improve the luminous properties of InGaN/GaN blue LED. As reported in previous studies, ZnSeTe QDs with the wavelength of approximately 447nm is the candidate for cyan LED chip [17], and ZnSe QDs with the wavelength of 430nm is the candidate for hyacinthine LED chip [18]. Figure 1 presents the schematic layered structure of InGaN/GaN blue LED.

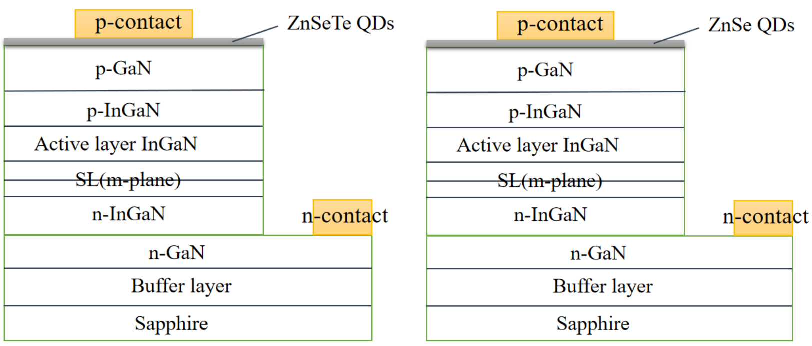

Figure 1. The schematic of InGaN/GaN.

As for the design of the blue LED devices, apart from the high luminance and quantum efficiency, the safety to human eyes must also be taken into consideration. It is known that short wavelength blue light could be harmful to human eyes and lens and the luminance of blue light LED is difficult to increase compared with other type of LED. Therefore, the initial idea of device design is using parallelogram structure as two types of different wavelength blue LED chips layout [13]. Each backlight unit comprises three cyan LED with average wavelength of 450nm and one hyacinthine LED chip with average wavelength of 430nm, and the connection between three cyan LED chips and hyacinthine LED chip is surrounded by a parallelogram. Figure 2 provides a new backlight structure sketch diagram of the new blue LED device design, the minimum distance between two adjacent backlight structure unit is equals to the distance between two same color adjacent LED chips. From another macro perspective, every six cyan become the hollow circle with hyacinthine in the center position. The rationality of this arrangement will be verified in the following simulation part.

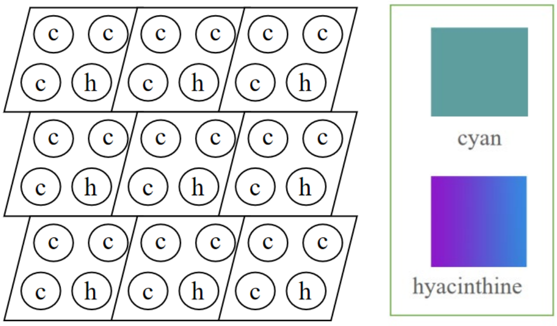

Figure 2. A new backlight structure sketch diagram.

3. Simulation setups

TracePro Application, which is a powerful optical simulation software for ray-tracing, stray light, polarization effects, bulk scatter and fluorescence is chosen as the execution software [19]. It is used to make profound research in illumination effect under different simulation circumstances. Considering the possible practicability, the searchlight shape might be the best option, whose necessary components including LED (emitter, surface and coating), front lens, PC board, base, lamp housing, target and receiver. Control group will also be added in the whole experiment, i.e., linear arrangement contrast parallelogram arrangement. As analyzed in the former part, in order to fit the output energy range of backlight into controllable mode, the emission ratio electromagnetic power to output is 5:1. As for the internal component of chips, two distinguishing features will be applied in this LED chips. To be specific, the ZnSeTe QDs and ZnSe QDs thin films lies on the top of p-GaN layer and the p-n junction (m-plane super lattice structure) that could increase IQE significantly places in the middle.

- In modulate parameter part, for target receiver property, the surface is modulated to “perfect absorber” with description of 100% absorbing, no reflectance or transmittance”. For LED emitter property, the surface source is modulated to “CorePro Blue LED capsuleLV 1.8-20W G4 830” and the scale of device is modulated into 1. As for front lens property, the surface is modulated to “perfect transparent surface”.
- In ray tracing, 90651 rays were traced in total, only 56771 incident rays were received by the target receiver for experiment group. Besides, in the control group 70489 rays were traced in total only 49507 incident rays were received by the target receiver.

4. Results and discussions

The irradiance map for absorbed flux is shown in the upper panel in Figure 3 and the simulated light is shown in the lower panel in Figure 3. Flux I is the arrangement of squares, and Flux II is our proposal, the arrangement of parallelogram. For Flux I, the flux for single LED chips is 0.503244W, the incident ray for single LED chips is 6307.9, the flux/emitted flux is 0.50324, and the peak intensity is 10.239W. For Flux II, the flux for single LED chips is 0.610786W, the incident ray for single LED chips is 7072.4, the flux/emitted flux is 0.61079, and the peak intensity is 13.115W. According to the results, the arrangement of parallelogram will make the blue light more concentrated and the luminous brighter.

The advantages for our backlight structure blue LED include:

- Improving the display effect;
- Better luminous surface and uniformity;
- Changeable working mode.

By setting two chips with different emission wavelengths in the backlight unit, the blue light output of the backlight structure can be adjusted, so as to maintain the brightness and chroma of the backlight and improve the display effect. For better luminous surface and uniformity, the center position of the cyan and hyacinthine LED chips is arranged in the way of regular triangle or regular hexagon to obtain luminous surface and uniformity. Except bringing better luminous surface and uniformity by its distinctive regular triangle or regular hexagon layout. This arrangement may have two other potential natural advantages which could lead to a foothold in luminous market currently. Firstly, by setting two chips with different emission wavelengths in the backlight unit, the blue light output of the backlight structure can be adjusted, so as to maintain the brightness and chroma of the backlight and improve the display effect. On this basis, it also adds certain flexibility to use it as the secondary converter. Secondly, it may make the systems become adaptive in changeable working mode. Additionally, there are two changeable working modes, daylight mode and night mode. For daylight mode, the backlight unit makes the structure between the four LED chips more compact and the spacing smaller, and the brightness of the light emitted by the four LED chips can reach the maximum. Regarding to night mode, since the electromagnetic radiation power output energy of the hyacinthine LED chip is lower than cyan, i.e., the hyacinthine LED chip is suitable for output in night mode.

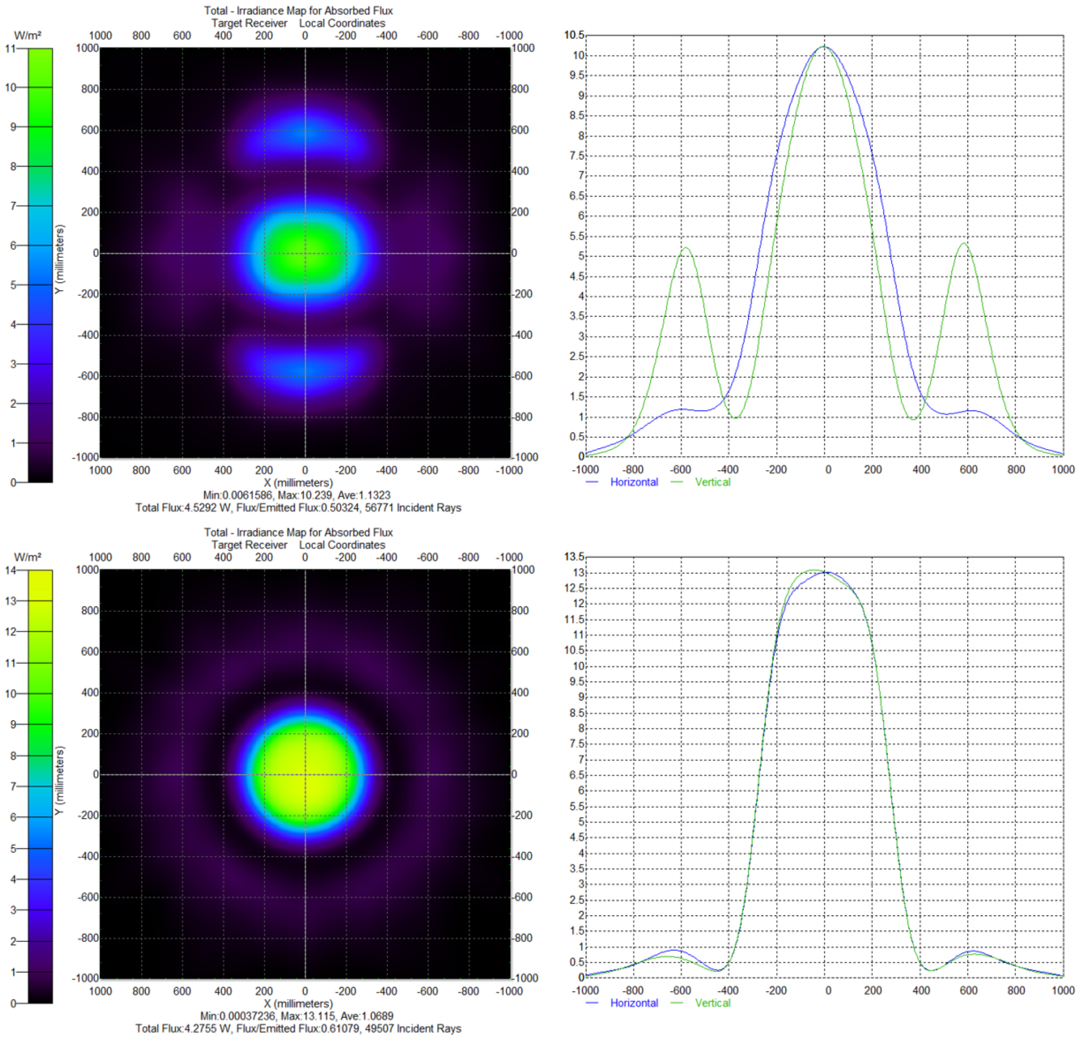

Figure 3. The 2D version for simulation Results of Irradiation Map Absorbed Flux I (upper panel) and Flux II (lower panel).

5. Limitations and future prospects

By arranging LED chips in the way of regular triangle or regular hexagon, it can get better durability. The structure between the four LED chips is more compact and the spacing is smaller, hence the brightness of the light emitted by the LED chips is higher. Nevertheless, some potential problems exist in the proposed blacklight structure of the blue LED as well. For example, if one faces with the requirements of very dense LED layout for certain backlight product with high intensity light, two different types of LED may have difficulties in growing in the same plane because of the lattice constant especially in the relatively small scale. Such problem could be solved by adjusting the depth of the quantum dots to make the two different wavelength chips coexist in the same plane. Besides, the study aims at the plane structure and arrangement of the blue LED instead of a 3D structure, which will limit its use as photoelectronic devices.

The structural form and materials of 3D structure need to be further optimized [20]. The processing technology of adapting a more suitable film of quantum dots on top of the p-GaN surface, which is able to monitor the emissive wavelength in a more precise way, also needs to be further studied to meet the demand of high-end lighting market characterized by point light source, high current density and optical density. Plasmonic grating of the quantum dots may also be introduced during the process of fabrication in order to provide sufficient accuracy for the purposes of depth measuring. In the future, this technology has very broad prospects, and there is room for development in artificial lighting, screen display, or national defense if the coexistence of different chips in small scale can be solved appropriately.

6. Conclusion

In summary, this paper investigates the efficiency droop impacting factors for InGaN/GaN blue LED, possible surface materials on the top of the p-GaN layer, and the luminous properties of a new backlight structured LED based on TracePro Application. One of the most efficient ways of improving η_{IQE} is growing the supper lattice on m-plane instead of c-plane in order to eliminate the PE field. Besides, on the premise of harmless to human eyes, a backlight structure of the combination of cyan and hyacinthine LED chips is launched by grating ZnSeTe QDs and ZnSe QDs on the surface of p-GaN. By arranging LED chips in the configuration of regular triangle or regular hexagon, it can improve the durability. The structure between the four LED chips is more compact and the spacing is smaller, thus the brightness of the light emitted by the LED chips is higher. The problems of growing in the same plane could be solved by adjusting the depth of the quantum dots to make the two different wavelength chips coexist in the same plane. In this case, the structural form and materials of 3D structure will be further optimized. Overall, these results offer a guideline for new materials and arrangement design for high luminous and harmless InGaN/GaN blue LED.

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