Effect of current spreading on the efficiency droop of InGaN light-emitting diodes

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Abstract: We investigate the effects of current spreading on the efficiency droop of InGaN blue light-emitting diodes with lateral injection geometry based on numerical simulation. Current crowding near the mesa edge and the decrease in the current spreading length with current density are shown to cause significant efficiency droop. It is found that the efficiency droop can be reduced considerably as the uniformity of current spreading is improved by increasing the resistivity of the p-type current spreading layer or decreasing the sheet resistance of the n-GaN layer. The droop reduction is well interpreted by the uniformity of carrier distribution in the plane of quantum wells.

OCIS codes: (230.3670) Light-emitting diodes; (230.0250) Optoelectronics.

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1. Introduction

Recently, white light sources based on semiconductor light-emitting diodes (LEDs) have attracted great interest as high energy-efficiency and environment-friendly lighting technologies [1–6]. Although the performance of GaN-based LEDs has been improved considerably over the last decade, the application of LEDs toward general lighting requires even higher brightness and efficiency. The ‘efficiency droop’ phenomenon in InGaN quantum wells (QWs) has been a large obstacle that has hindered high-efficiency operation at high current density [5–14]. The maximum efficiency of InGaN LEDs occurs at relatively low current density, a few to tens of A/cm^2, and the efficiency decreases gradually. Recently, extensive research has been conducted on the origin of efficiency droop phenomena in InGaN LEDs. Several carrier-loss mechanisms such as Auger recombination [8], carrier leakage [9], carrier delocalization [10,11], and poor hole injection [12] have been considered causes of the efficiency droop. Although the origin of the efficiency droop remains under debate, it is clear that it becomes large as the carrier density in QWs increases.

It has been reported that carrier distribution between InGaN QWs can be quite inhomogeneous, mainly due to inefficient hole transport through QWs caused by low hole mobility [15–18]. As a result of this inhomogeneous carrier distribution, carrier density at specific QWs close to p-side layers can be very high, which results in a significant droop in internal quantum efficiency (IQE) at high current density. Therefore, in order to reduce the efficiency droop, the carrier density should be uniformly distributed between QWs. Reduction in the efficiency droop has been demonstrated in InGaN MQW structures with improved hole carrier transport [12,19]. The concept of a uniform carrier distribution to reduce efficiency droop effects can also applied to the carrier distribution in the horizontal direction of a QW. The carrier distribution in the plane of a QW can actually be inhomogeneous due to the nonuniform current spreading of LEDs. The region of high carrier density where current is locally crowded is expected to undergo significant efficiency droop. Therefore, uniform current distribution can be helpful in reducing the efficiency droop problem.

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Poor current spreading in LEDs is known to deteriorate electrical and thermal properties in both lateral and vertical injection chip configurations [5,20–22]. However, the relationship of the nonuniform current spreading and the efficiency droop has rarely been studied. In this paper, we investigate the effect of current spreading on the efficiency droop of InGaN blue LED structures by numerical simulation. Advanced device simulation software, APSYS has been employed, which self-consistently solves QW band structures, radiative and nonradiative carrier recombination, and the drift and diffusion model of carriers [23,24]. Here, a conventional planar LED structure with lateral current injection geometry is considered. First, based on the current spreading model, we discuss important structural parameters that affect current spreading characteristics in the LED. Then, on the bases of simulation results, it is demonstrated that the current spreading is closely related to the IQE droop. Methods for improving the current spreading, and hence reducing the efficiency droop, are also presented.

2. Simulation structure

A vertical cross section of the simulated structure is schematically depicted in Fig. 1. We assume that LED layer structures are grown on a sapphire substrate. Multiple-quantum-well (MQW) active layers consist of five 25-Å-thick $In_{0.18}Ga_{0.82}N$ QWs separated by 100-Å-thick GaN barriers. The thickness and In composition at the QWs corresponds to the peak emission wavelength of ~0.46 μm. Below the MQW layers is an n-type GaN layer, which acts as an n-type current spreading layer. Above the MQW layers, a p-type 20-nm-thick $Al_{0.1}Ga_{0.9}N$ electron blocking layer (EBL) and a 200-nm-thick p-type GaN layer are subsequently grown. The electron concentration at the n-GaN layer and the hole concentration at the EBL and p-GaN layers are set at 5×10^{18} cm^{-3} and 5×10^{17} cm^{-3}, respectively. Above the p-GaN layer is a transparent contact oxide (TCO) that acts as a p-type current spreading layer. Indium tin oxide (ITO) is employed as the TCO material. The thickness of ITO is 200 nm. A mesa structure is formed to expose the n-GaN layer to deposit an n-electrode. The n-GaN contact layer below the n-electrode is positioned 0.5-μm below the MQW layers. The width of p-type layers, MQWs, and ITO is 300 μm, as depicted in Fig. 1, and the area of these layers is 0.1 mm^2. The p- and the n-electrode are formed from the edge of the LED chip and are 100 μm and 80 μm long, respectively.

In the carrier recombination model, the Schockley-Read-Hall (SRH) recombination lifetime (τ_{SRH}) is set at 50 ns, which is a similar value to that reported in recent work [8,25–28]. The radiative recombination rate is calculated by integrating the spontaneous emission spectrum with a Lorentzian line-shape function. The Auger recombination in InGaN QWs has been one of the central issues in the debate related to efficiency droop, and no consensus has been reached regarding the Auger recombination coefficient (*C* coefficient). Nevertheless, the efficiency droop phenomena can be conveniently modeled using the *C* coefficient in the *ABC* carrier recombination model [13,24]. Here, the *C* coefficient is set to be 5×10^{-31} cm^6/s to account for the efficiency droop. The IQE is defined as the ratio of radiative recombination

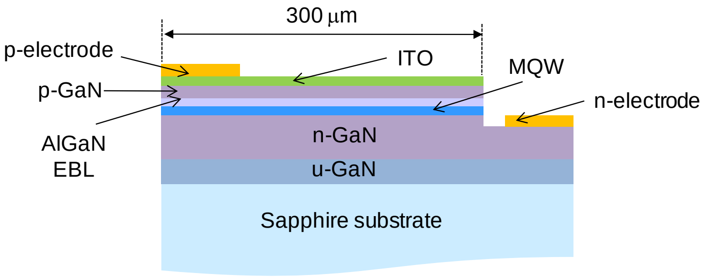

Fig. 1. Vertical cross section of the simulated light-emitting diode (LED) structure with lateral injection geometry.

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current to total injection current. Here, built-in electric fields induced by spontaneous and piezo-electric polarizations at the hetero-interfaces of InGaN/GaN and AlGaN/GaN are also included. The strength of the built-in field at the interfaces of the InGaN QW and the GaN barrier is set at approximately 1 MeV/cm.

In the GaN-based LEDs, the resistivity of the p-GaN layer is higher than that of the n-GaN layer and the TCO layer by more than two orders of magnitude as a result of the relatively low hole mobility and low carrier concentration. Therefore, in the LED structure depicted in Fig. 1, hole current is mainly spread laterally in the ITO layer above the p-GaN layer, and current tends to crowd at the edge of the mesa contact adjoining the n-contact layer. The current density extending away from the n-electrode is expressed as [22]

$$J(x) = J_0 \exp(-x / L_S), \tag{1}$$

where J_0 is current density at the electrode edge and x is the distance from the edge. L_S in Eq. (1) is the current spreading length given by

$$L_S = \sqrt{\frac{2nkT}{eJ_0(\rho_n / t_n)}}, \tag{2}$$

where n is the diode ideality factor and T is absolute temperature. ρ_n/t_n is the sheet resistance of the n-GaN current spreading layer, where ρ_n and t_n are the resistivity and the thickness of the n-GaN, respectively. Equation (2) implies that the current spreading length decreases as the sheet resistance or current density increases. That is, current becomes increasingly crowded near the mesa edge as injection current increases, especially when the sheet resistance of the n-GaN layer is high.

Because hole current flows a long distance through the ITO layer, the resistance at the ITO layer has a significant influence on the current-voltage (*I*-*V*) relation of the LED. This means that the current density, J_0 is inversely proportional to the resistivity of the ITO layer. Therefore, the current spreading length in Eq. (2) has the following dependence;

$$L_S \propto \sqrt{t_n \rho / \rho_n}, \tag{3}$$

where ρ is the resistivity of the ITO. In Eq. (3), it is notable that the current spreading length can be increased as the resistivity of the ITO increases. Although high resistivity in the ITO

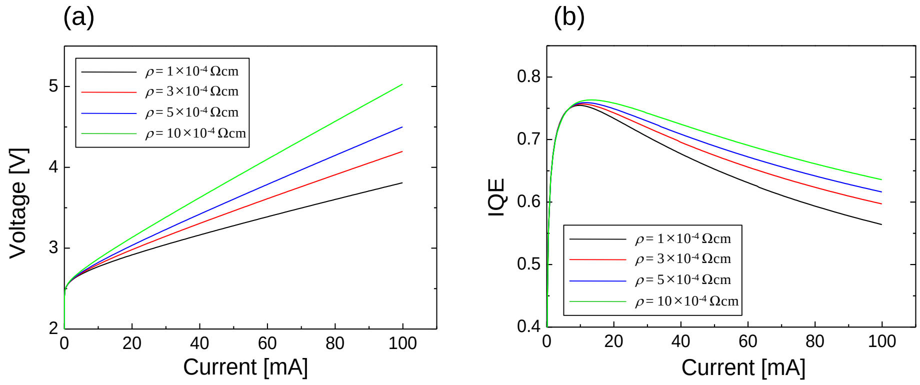

Fig. 2. Effect of the resistivity of ITO (ρ) from 1 × 10^{-4} to 1 × 10^{-3} Ωcm. (a) Current–voltage relation (*I*–*V* curve), and (b) internal quantum efficiency (IQE) as a function of injection current.

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layer results in an increase in forward voltage, it would be effective for uniform current spreading. Equation (3) implies that the degree of current spreading can be controlled by ρ, ρ_n, and t_n. Therefore, we vary the resistivity of the ITO layer (ρ) and the n-GaN layer (ρ_n), and the thickness of the n-GaN layer (t_n) to investigate the relationship between current spreading and efficiency droop. All interfaces between electrodes, ITO, and semiconductor layers are assumed to be Ohmic contacts.

3. Simulation result

First, the effects of the ITO resistivity are investigated. In Fig. 2, the forward voltage and IQE are shown as a function of injection current when ρ varies from 1×10^{-4} to 1×10^{-3} Ωcm. As expected, the forward voltage increases with ρ as a result of the increase in the resistance at the ITO layer. At 50 mA, the forward voltage increases from 3.28 to 3.88 V when ρ increases from 1×10^{-4} to 1×10^{-3} Ωcm. The IQE curve in Fig. 2(b) exhibits typical efficiency droop behavior, where the peak IQE of 76 - 77% appears at low current near 10 mA, IQE then decreases rapidly as current increases. The peak IQE value is similar to that reported in high-performance InGaN blue LEDs [2,29,30]. It is interesting to note that IQE droop is reduced as ρ increases. Although the peak IQE is of a similar level, the IQE droops differently for each ρ value, and the IQE difference becomes large as current increases. At 50 mA, the IQE increases from 65 to 71% when ρ increases from 1×10^{-4} to 1×10^{-3} Ωcm.

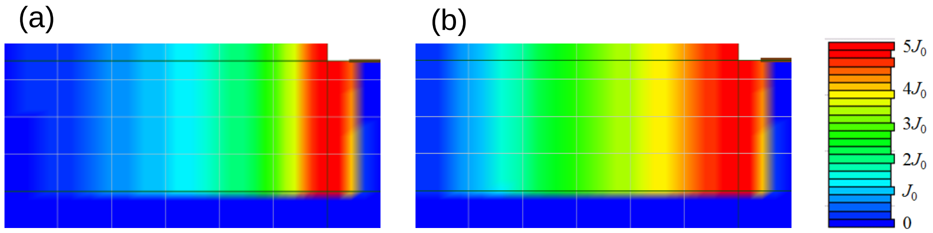

Fig. 3. Two-dimensional distribution of current density below multiple-quantum-well (MQW) layers when injection current is 20 mA. (a) $\rho = 1 \times 10^{-4}$, and (b) $\rho = 1 \times 10^{-3}$ Ωcm. J_0 in the color scale bar corresponds to the current density, I/A where I is injection current and A is the light-emitting area.

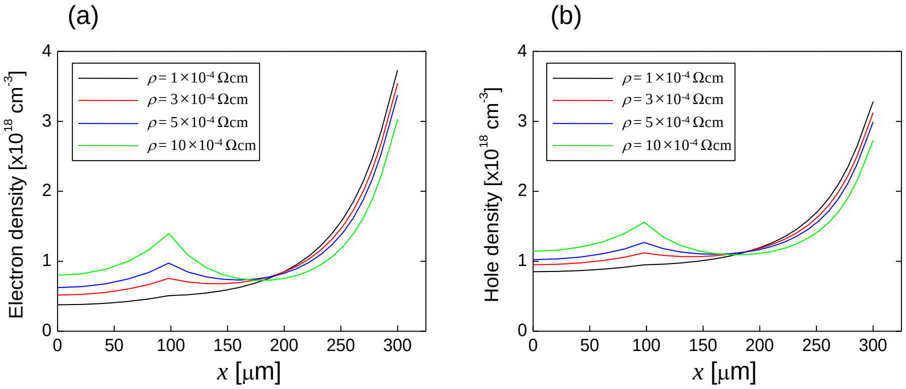

Fig. 4. Distributions of carrier density along the horizontal direction of a quantum well (QW) for several ρ values from 1×10^{-4} to 1×10^{-3} Ωcm. Here, the QW is positioned nearest to the p-GaN layer. (a) Electron density, and (b) hole density distribution.

The reduction in the efficiency droop for high ρ can be understood by the current spreading effect. Figure 3 presents a two-dimensional (2-D) distribution of current density

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below MQW layers for ρ of 1×10^{-4} and 1×10^{-3} Ωcm when injection current is 20 mA. As discussed previously, the current is mainly crowded at the mesa edge for both cases. However, the degree of current crowding differs for these two cases. The current spreads more uniformly when ρ increases from 1×10^{-4} to 1×10^{-3} Ωcm. This improvement in current spreading for the higher resistivity in the ITO layer agrees well with Eq. (3). Uniform current spreading should result in more homogeneous carrier distribution in the QW plane. In Fig. 4, the distributions of electron and hole density are depicted along the horizontal direction of the QW that is positioned nearest to the p-GaN layer. Both electron and hole carriers are mainly crowded at the mesa edge in all ρ values. High carrier density near the mesa edge causes large carrier loss in that region, which results in significant IQE droop at high current. However, as ρ increases, the difference between the highest and the lowest carrier density is reduced. That is, the carrier distribution for both electrons and holes becomes homogeneous in the QW plane as ρ increases, which leads to the reduction in the efficiency droop.

In Eq. (2), the current spreading length is inversely proportional to the square root of current density, implying that current crowding effects become more significant at high current. Figure 5 depicts the variation of 2-D current density distribution below MQWs as current increases from 10 to 50 mA when ρ is 1×10^{-4} Ωcm. As current increases, it becomes significantly crowded near the mesa edge and the current spreading length decreases. With increasing injection current, carrier distribution becomes increasingly inhomogeneous in the plane of QWs and carrier concentration near the mesa edge increases rapidly. This decrease in the current spreading length with increasing current should intensify the efficiency droop at high current. Even though the current appears uniformly spread at low current, it can be strongly crowded at the mesa edge at high current where the efficiency droop is important. This increasing current crowding effect causes the efficiency droop problem to grow even worse.

By combining the results of Fig. 2(a) and 2(b), the power-conversion efficiency or wall-plug efficiency (WPE) can be compared relatively for different ρ values. The WPE, η_{WPE}, of an LED can be simply written as

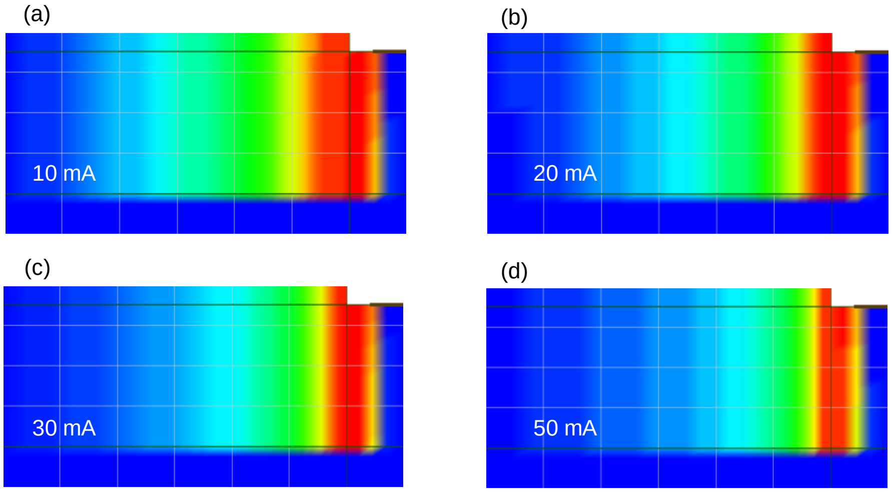

Fig. 5. Variation of two-dimensional current density distribution when injection current is (a) 10 mA, (b) 20 mA, (c) 30 mA, and (d) 50 mA. Here, ρ is 1×10^{-4} Ωcm.

$$\eta_{\text{WPE}} = \eta_{\text{voltage}}\eta_{\text{int}}\eta_{\text{extract}}, \tag{4}$$

where η_{voltage}, η_{int}, and η_{extract} are voltage efficiency, IQE, and light extraction efficiency (LEE), respectively. η_{voltage} is the ratio of photon energy to electron energy, i. e.:

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$$\eta_{\text{voltage}} = h\bar{\nu}/(eV), \tag{5}$$

where $\bar{\nu}$ is the average frequency of emitted photons and V is the forward voltage. By substituting Eq. (5) in Eq. (4) and using the results of Fig. 2, the ratio of WPE to LEE can be obtained. Figure 6 depicts $\eta_{\text{WPE}}/\eta_{\text{extract}}$ for several ρ values from 1 × 10^{-4} to 1 × 10^{-3} Ωcm. Assuming that LEE is the same for all ρ values, the result of Fig. 6 can be used to compare WPE for different ρ values. As a result of the combined effects of efficiency droop and series resistance, $\eta_{\text{WPE}}/\eta_{\text{extract}}$ decreases rapidly as current increases. It also decreases as ρ increases at the same current. However, the change in $\eta_{\text{WPE}}/\eta_{\text{extract}}$ with ρ is not very large. At 50 mA, $\eta_{\text{WPE}}/\eta_{\text{extract}}$ decreases from 54 to 50% as ρ increases from 1 × 10^{-4} to 1 × 10^{-3} Ωcm, which is much smaller compared with the 0.6 V increase in the forward voltage at this current. The increasing behavior of the IQE droop with ρ results in this relatively small decrease in $\eta_{\text{WPE}}/\eta_{\text{extract}}$ despite the large increase in the forward voltage as ρ increases. This result implies that decreasing the resistivity of ITO would not be much more effective than expected for improving the power conversion efficiency of LEDs. For example, when ρ is decreased from 3 × 10^{-4} to 1 × 10^{-4} Ωcm, $\eta_{\text{WPE}}/\eta_{\text{extract}}$ increases by only ~1%. The result of Fig. 6 indicates the important role of the ITO resistivity in the IQE droop, which results from the significant influence of the ITO resistivity on the current spreading.

From the previous results, it is evident that the high resistivity in the ITO layer may be advantageous for reducing the efficiency droop through the improvement of current spreading. However, it is not a desirable solution in general because the forward voltage can be increased significantly as ρ increases. Equations (2) and (3) imply that the current spreading length increases as the sheet resistance in the n-GaN layer decreases. Because the efficiency droop is reduced by increasing the current spreading length, decreasing the sheet resistance can be regarded as an effective method for improving the efficiency droop problem. In addition, it also results in the decrease of the forward voltage. The sheet resistance can be decreased by either increasing the thickness or the doping concentration of the n-GaN layer.

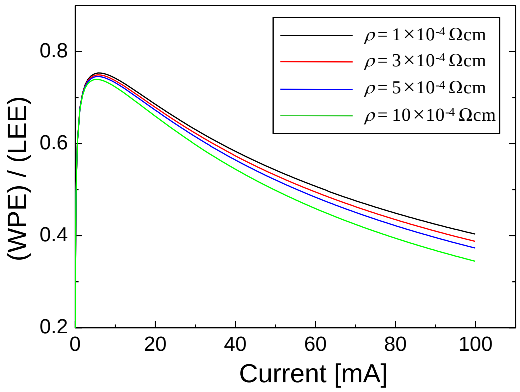

Fig. 6. Ratio of the wall-plug efficiency (WPE) to the light extraction efficiency (LEE) for several ρ values from 1 × 10^{-4} to 1 × 10^{-3} Ωcm.

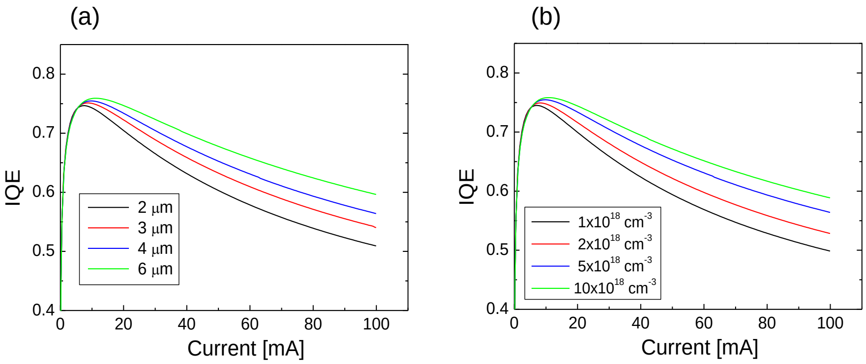

Fig. 7. IQE as a function of injection current when ρ is 1×10^{-4} Ωcm. (a) Thickness of the n-GaN is varied from 2 to 6 μm when doping concentration is 5×10^{18} cm^{-3}. (b) Doping concentration is increased from 1×10^{18} cm^{-3} to 1×10^{19} cm^{-3} when the n-GaN thickness is 4 μm.

Figure 7 shows the effects of the thickness and the doping concentration on the IQE droop when the resistivity of the ITO is 1×10^{-4} Ωcm. In Fig. 7(a), the thickness of the n-GaN is varied from 2 to 6 μm when doping concentration is fixed at 5×10^{18} cm^{-3}. In Fig. 7(b), doping concentration is increased from 1×10^{18} cm^{-3} to 1×10^{19} cm^{-3} when the n-GaN thickness is 4 μm. As expected, the IQE droop is reduced as the thickness or doping concentration of the n-GaN increases. At 50 mA, IQE is improved by ~8% as the n-GaN thickness increases from 2 to 6 μm or the doping concentration increases from 1×10^{18} cm^{-3} to 1×10^{19} cm^{-3}.

This reduction in the IQE droop results from the increase in the current spread length or the improvement in the uniformity of carrier distribution in the plane of QWs. Figure 8 depicts the distribution of electron density along the QW plane as the thickness or doping concentration of the n-GaN layer varies. The electron distribution becomes more homogeneous and the difference between the highest and the lowest electron density decreases as the n-GaN thickness increases or the doping concentration increases. This tendency is in good agreement with the behaviors of the IQE droop shown in Fig. 7. However, in some situations, a large increase in the n-GaN thickness or doping concentration can exhibit only marginal improvement in the IQE. For example, when doping concentration is increased

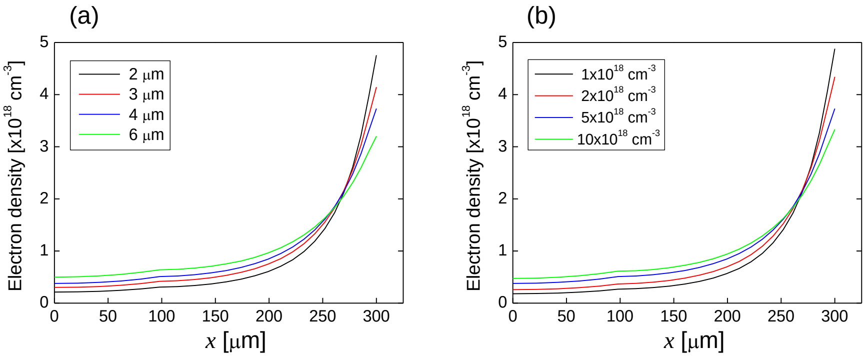

Fig. 8. The distribution of electron density along the QW plane when ρ is 1×10^{-4} Ωcm. (a) Thickness of the n-GaN is varied from 2 to 6 μm when doping concentration is 5×10^{18} cm^{-3}. (b) Doping concentration is increased from 1×10^{18} cm^{-3} to 1×10^{19} cm^{-3} when the n-GaN thickness is 4 μm.

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from 5×10^{18} to 1×10^{19} cm^{-3}, only 2% increase in the IQE is obtained at 50 mA. An excessive doping concentration or thickness of a doped layer may cause substantial optical losses associated with free-carrier absorption, which degrades the LEE considerably. That is, although increasing the sheet resistance of the n-GaN layer can improve the IQE at high current, there is a possibility that it could decrease the LEE and hence not be effective for increasing the WPE. Therefore, the sheet resistance in the n-GaN layer and the ITO layer should be carefully optimized with full consideration of various LED efficiencies including the voltage efficiency, LEE, and the IQE droop.

4. Summary

We theoretically investigated the relationship between current spreading and the efficiency droop of an InGaN blue LED structure with lateral injection geometry based on device simulations. In this structure, the current is mainly crowded near the mesa edge of the n-GaN layer, which results in significantly inhomogeneous carrier distribution in the plane of QWs. This nonuniform carrier distribution causes large carrier loss at high current and hence increases the IQE droop. Moreover, the current spreading length was found to decrease as injection current increases, which intensifies the efficiency droop problem at high current. Simulation results revealed that the IQE droop could be reduced considerably as the uniformity of current spreading was improved by increasing the resistivity of the ITO layer or decreasing the sheet resistance of the n-GaN layer. The reduction in the IQE droop was well interpreted by the uniformity of carrier distribution in the horizontal direction of a QW plane. In particular, due to the large decrease in the IQE with decreasing resistivity of the ITO layer, the power conversion efficiency was found to be improved only slightly even for the large decrease in the resistivity of the ITO layer. In addition, it was observed that the IQE droop could be reduced by increasing the thickness or doping concentration of the n-GaN layer without increasing the forward voltage. However, the possibility of the decrease in the LEE by a thick heavily doped layer was also discussed. The results of this work reveal the important role of current spreading layers in the characteristics of IQE as well as other efficiencies, such as forward voltage and the LEE. The careful design of current spreading layers will lead to high-efficiency LEDs for practical applications in future solid-state lighting.

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