Chapter 2

Efficiency Droop in III-nitride LEDs

Jie Zhang, Dongyan Zhang, Daqian Ye, Chenke Xu and Meichun Huang

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/60454

Abstract

To dominate the illumination market, applications of high-power, group III-nitride light-emitting diodes (LEDs) with lower cost and higher efficiency at high injection current density must prevail. In this chapter, three possible origins of efficiency droop (including electron leakage, poor hole injection, and delocalization of carriers) in III-nitride LEDs are systematically summarized. To seek a more comprehensive understanding of the efficiency droop, experimental results based on commercialized LEDs are obtained to explain the physical mechanisms. Proposals for droop mitigation, such as (1) improving hole injection, and (2) increasing effective optical volume or reducing carrier density in the active region, are introduced. Finally, a simple expression for the effects of V-shaped pits on the droop is demonstrated.

Keywords: Efficiency droop, III-nitride, LEDs, Electron blocking layer (EBL), Physical mechanisms

1. Introduction

Lighting is, and always has been, a global market. Today, as Gallium nitride (GaN) light-emitting diodes (LED) technology gains a commercialized market, the demand for lighting continues to grow throughout the world. The transition to solid-state lighting (SSL) technology and the growth in lighting demand, coupled with the sharp growth in LED backlighting for displays, has led to a rapid expansion of LED manufacturing capacity over the last few years. Most of people find the merits of LED engineering—high efficiency and low energy consumption—obviously attractive. A recent U.S. Department of Energy (DOE) analysis by Navigant
Consulting, Inc. (Navigant) reviewing the adoption of LED-SSL technology in the U.S. concluded that annual source energy savings from LED lighting in 2013 more than doubled from the previous year to 188 trillion British thermal units (BTUs), which is equivalent to an annual energy cost savings of about $1.8 billion [1]. In order to further match product demands for specific lighting applications and clean energy principles, one particular trend is the introduction of high-performance, low-cost, high-power LEDs. Therefore, the cost-per-lumen of packaged LEDs is estimated to be lower than 5 $/klm and efficacy projections need to improve to 220 lm/W after 2020, as shown in Fig. 1a, b [1].

![Fig. 1 (a) A price scenario of 800 lm LED in the range of 2013 to 2020; (b) white light LED efficiency projection from 2005 to 2025.](image)

In response to this LED-related energy saving projection, maximizing the efficiency of LED is an important innovation along the path to highly practical products. Especially for LEDs that need to be used in general lighting applications and to provide the way for high-power, high-dimension devices, it is imperative to produce high luminous fluxes with high efficiency, which necessitates high current levels. However, conventional GaN LEDs suffer from high quantum efficiency, insufficient efficiency and low efficiency droop. For more than a decade, many research ideas pertaining to efficiency droop have been proposed [2]. While the real culprit is still under debate, defects in the efficiency as injection current increases, which we call this efficiency droop effect or droop, have been observed in GaN-LEDs, because Auger recombination in InGaN would promote nearly all of the proposed mechanisms stem from such origins as Auger recombination, electron leakage, delocalization of carriers at energies well beyond the hetero-barriers, and therefore would provide an important contribution to leakage [4-6]. In recent years, polarization fields induced band bending in active regions and electron-blocking layers were reported to enhance the leakage of electrons into the p-type GaN cladding layer [7–10]. At the same time, most discussions point out that the distribution and densities of carriers in the quantum wells (QWs), and the carrier injection into the active region, can make the carrier escape from localized states, forming leakage currents, which may play a role in determining the origin of efficiency droop [11]. Furthermore, LED is a bipolar device relying on the efficient injection of both minority carriers, and both holes and electrons into the active region, can make the carrier escape from localized states, forming leakage currents, which may play a role in determining the origin of efficiency droop [11]. In addition to the proposals mentioned above, other models have also considered facilitating efficiency enhancement by reducing the density of states in the conduction band [12–14], which may be a key issue in determining the origin of efficiency droop [11, 15]. In addition to the proposals mentioned above, other models have also considered facilitating efficiency enhancement by reducing the density of states in the conduction band [12–14], which may be a key issue in determining the origin of efficiency droop [11] [12].

Based on such mechanisms of physics, many remedies to suppress the droop have been explored by many scientific researchers. Junction heating and contact degradation, both of which are the subject of vigorous research efforts, can be mitigated by increasing the efficiency and employment of packages capable of removing the dissipated heat very efficiently [25]. The intrinsic Auger losses in wide band gap semiconductors are also considered to be relatively small. Meanwhile, unfortunately, most high carrier temperatures and saturation of the radiative recombination rate, as well as current crowding and related contact degradation [22–24]. In summary, the efficiency droop effect critically depends on several main mechanisms and is associated with several different promoting factors.
carriers, and both holes and electrons need to be injected and to be distributed optimally in the active region to recombine for the effective operation of LEDs. Therefore, the low hole concentration, low hole mobility, and potential barriers for hole transport are also possible mechanisms responsible for high-current efficiency droop [14–18]. In addition to the proposals mentioned above, other models have also considered facilitating factors for electron leakage and droop, including defect-assisted tunneling effects [19, 20], junction heating [21], high plasma carrier temperatures (hot carriers) and saturation of the radiative recombination rate, as well as current crowding and related contact degradation [22–24]. In summary, the efficiency droop effect critically depends on several main mechanisms and is associated with several different promoting factors.

Based on such mechanisms of physics, many remedies to suppress the droop have been explored by many scientific researchers. Junction heating and contact degradation, both of which are the subject of vigorous research efforts, can be mitigated by increasing the efficiency and employment of packages capable of removing the dissipated heat very efficiently [25]. The intrinsic Auger losses in wide band gap semiconductors are also considered to be relatively small. Meanwhile, unfortunately, most conclusions regarding efficiency droop from Auger processes are based on theory calculations. Thus far, there is little direct experimental evidence of the Auger carrier recombination mechanism in GaN/InGaN LEDs by observing the remaining higher energy Auger electrons, which would require a spectroscopic measurement of hot electrons in the device [26, 27]. In turn, as mentioned above about the origins of droop, the radical treatments of these diseases focus on other methods in industrial mass production.

Firstly, in studies where the polarization charge has been widely proposed as the reason for electron leakage and thus efficiency droop, LEDs with an inserted electron blocking layer, generating multi-quantum barriers (QBs) and graded QBs, are expected to reduce the polarization mismatch between the QW and the barrier [28–31]. In these cases, droop is strongly attenuated in fabricated devices at the cost of reduced internal quantum efficiency (IQE) value. Interestingly, based on these conclusions, there are also reports that we can build a deeper potential well at the interface between the electron blocking layer (EBL) and the last QB, resulting in better electron confinement and improving hole injection [17, 32]. Secondly, at high driving currents, the carrier density reducing the effective active volume will get very high and lead to saturation of the radiative recombination rate, which in turn increases the carrier density. For the purpose of avoiding the droop, the ability of carriers to be captured in QWs and the mechanisms related to carrier distribution must be analyzed in terms of the quantum mechanical dwell time (the time an electron dwells over the QW) and carrier distribution. Further, increasing the QW thickness or numbers also increase the dwell time, and therefore should lead to a higher capture probability [13, 22, 33]. Thirdly, for maximum efficiency, the goal is to have equal numbers of electrons and holes injected into the active region. As reported in [18, 34–36], by employing p-type–doped barriers or other band engineering, such as using a lightly n-type-doped GaN injection layer below the InGaN multiple quantum wells (MQWs) on the n side, intended to bring electron and hole injection to comparable levels, better efficiency retention has been observed at higher current levels.
The above discussions show that the droop has been studied deeply, and some of these approaches have been successfully demonstrated in laboratory LED prototypes. However, a solution to improve efficiency droop effect requires the examination of numerical results based on commercialized LEDs. For mass production, some measures are able to inhibit the LED efficiency droop effect, yet there is still need for in-depth study of each production process, as manufacturers of market-adopted LEDs prioritize product cost reductions and quality improvements. In this chapter, we devote ourselves to finding a simple, high efficiency way to suppress the droop and trying to import it into the production flow process. First, a theoretical analysis on the physical mechanisms of efficiency droop is briefly given in Sect. 2. According to this analysis, the main factors contributing to droop are pointed out. Next, we introduce some recent reports recently to support our theoretical results. Then we present the structural design, characterization and discussion of three approaches: 1) optimization of EBL and QBs, 2) investigation of the active-volume effect in a multiple quantum well (MQW) region and 3) the use of intentionally formed V-shaped pits (V-pits) are proposed in Sect. 3. Finally, in Sect. 4, a simple summary is presented.

2. Investigation of physical mechanisms for efficiency droop

Internal quantum efficiency (IQE) is the ratio of photons emitted from the active region of the semiconductor to the number of electrons injected into the p-n junction of an LED. One can define the IQE as

\[
IQE = \frac{I_0}{\frac{E_{ph}}{J_{in}/q}}
\]

where \( I_0 \) is the optical power at the central wavelength, \( E_{ph} \) is the photon energy, \( J_{in} \) is the current injected into the LED active region and \( q \) is the electron charge.

According to the van Roosbroeck–Shockley equation model [37], the rate of radiative recombination per unit volume \( R_0 \) has been treated by the photon density divided by the mean lifetime of photons:

\[
R_0 \approx \frac{N}{\tau} = Bn^2
\]

where \( B \) is the radiative recombination coefficient, and \( n \) is the carrier concentration. Because the \( I_0/E_{ph} \) is the number of photons emitted per unit time by the active region, we can obtain:

\[
\frac{I_0}{E_{ph}} = R_0 N_{QW} = Bn^2 V_{QW}
\]

Then the IQE can be expressed in the form:
In order to better understand the physical mechanisms inside an LED, the current injected into the QW region ($J_{in}$) can be investigated by the equation:

$$\frac{J_{in}}{q} = RV_{QW}$$

($R$ is the carrier recombination rate and we can discuss $R$ instead of $IQE$ for the physical mechanisms of efficiency droop.

Commonly, the recombination in LEDs is described by the ABC model [38]:

$$R = An + Bn^2 + Cn^3$$

This simplistic model considers $A$, $B$, and $C$ to represent the Shockley-Read-Hall (SRH), radiative, and Auger coefficients, respectively. However, this mode has a good fit only for the efficiency curve at low injected current below that of the LED peak efficiency, and the model fails to keep pace with the decline in efficiency at higher carrier densities. This suggests that there are some additional processes not included in the three conventional processes of the ABC model, such as carrier leakage or poor hole efficiency. For this reason, J. Cho et al. extended the ABC model by adding another recombination term, $f(n)$, to the model, where $f(n)$ includes carrier leakage and is allowed to contain more higher order terms of $n$ [39]. The recombination rate can be written as

$$R = An + Bn^2 + f(n)$$

$$= An + Bn^2 + Cn^3 + C_{DL}n^3$$

where $C_{DL}$ is a proportionality constant associated with the lowering of the injection efficiency due to drift of electrons in the p-type layer (drift leakage). The drift current of electrons injected into the p-type neutral layer, or drift-induced leakage, is given by

$$J_{drift} = qV_{QW}C_{DL}n^3$$

Whereas the $J_{drift}$ at the edge of the neutral layer is

$$J_{drift} = q\mu_p\Delta n_p(0)E$$
where $\Delta n_p(0)$ is the injected electron concentration at the edge of the p-type neutral region of a p-n junction, and $E$ is the electric field in the p-type layer.

The current injected into the QW region can be obtained by

$$I_{in} = q \mu_p P_{p0} E$$  \hspace{1cm} \text{(10)}$$

where $P_{p0}$ is the concentration of holes in the P region. In the region close to the peak-efficiency point, where radiative recombination dominates, the current depends on the carrier concentration in the QW, according to:

$$I_{in} \approx q V_{QW} B n^2$$  \hspace{1cm} \text{(11)}$$

The $C_{DL}$ can be obtained from relationships (8), (9), (10) and (11):

$$I_{drift} = q V_{QW} \frac{\Delta n_p(0)}{n} \frac{\mu_p}{\mu_p P_{p0}} B n^3$$  \hspace{1cm} \text{(12)}$$

$$C_{DL} = \frac{\mu_p \delta}{\mu_p P_{p0}} B$$  \hspace{1cm} \text{(13)}$$

where $\delta = \Delta n_p(0) / n$. From Eqs. 8, 12 and 13, we can see that $I_{drift}$ depends on $V_{QW}$, $\delta$, $\mu_n$, $\mu_p$, and $P_{p0}$. These factors correspond to the physical mechanisms of droop, such as effective active volume, the electrons injected to the p-region, p-type carrier density, and low hole injection efficiency. Furthermore, from the Einstein relation at the edge of the neutral layer, as shown here, we can see that the drift-induced leakage current increases with the total current, and will become significant at a sufficiently large current:

$$I_{drift} = q \mu_n \Delta n_p(0) E = q D_n \frac{q}{kT} \Delta n_p(0) \frac{I_{in}}{\sigma_p}$$  \hspace{1cm} \text{(14)}$$

where $D_n$ and $\sigma_p$ are the electron diffusion coefficient in the p-type GaN, and the p-type layer conductivity ($\sigma_p = qP_{p0}\mu_p$), respectively.

In the above discussions, it is noteworthy that the electron leakage into the p-region, the carrier density reducing effective active volume and the poor hole injection efficiency are the three main physical mechanisms for droop. We will discuss them one by one, and introduce related pathways to overcome them.
2.1. Electron leakage

As we know, only the electrons captured by the MQWs in LED are able to participate in radiative recombination and contribute to the optical power that is produced. From Eqs. 12, 13 and 14, we know that the leakage current is proportional to \( \delta, n \), and \( J_{in} \), which indicates that the electrons that spill over to the p-region play a very important role in causing efficiency droop. In the process of being injected into the MQWs, the electrons face large QB barriers, and there is an EBL layer intended to confine the electrons in the active region. But, due to the mismatch polarization of InGaN and GaN, GaN and AlGaN, some sheet charges exit and attract electrons, which pull down the barrier and EBL heights [7–9]. Therefore, the QBs and the EBL layer have a triangular shape and electrons can escape to form a significant leakage current. In device simulations, J. Piprek et al. have pointed out that the band offset ratio of GaN and InGaN \((\Delta E_C^1: \Delta E_V^1)\) and GaN and AlGaN \((\Delta E_C^2: \Delta E_V^2)\) are important parameters associated with band bending [40, 41]. As a matter of fact, G. Verzellesi suggests that for an EBL with “nominal” electron confinement capability, the AlGaN/GaN band offset \((\Delta E_C^2: \Delta E_V^2)\) should be kept at 70:30 [2]. In order to balance the electrons and holes in an active region, the InGaN/GaN band offsets \((\Delta E_C^1: \Delta E_V^1)\) should be symmetric (50:50) to reduce polarization charges [2].

In recent years, many researchers have sought methods to overcome the shortcomings of polarization fields. It is possible to engineer QBs and EBL layers to achieve these objectives.

### Table 1. Development of engineered QBs/QWs for improving droop

| Year | Engineered QBs/QWs | Droop* | Test current (A or A/cm²) | Chip size (mm×mm) | Experiment and/or simulation | Ref. |
|------|---------------------|--------|---------------------------|-------------------|-----------------------------|-----|
| 2008 | AlInGaN QBs        | Reduced droop | 300                  | 1×1               | Experiment                  | [8] |
| 2009 | InGaN/GaN/InGaN QBs | 1.60 %       | 35                    | 1×1               | Experiment                  | [28]|
| 2010 | Insert an AlGaN spacer | 5.66 %     | 521                   | 0.295×0.325       | Experiment                  | [42]|
| 2011 | GaN/InGaN/GaN QBs  | Small droop   |                       | 0.3×0.000         | Simulation                  | [31]|
| 2011 | AllInGaN QBs       | 13 %          | 100                   | 1×1               | Experiment and simulation   | [43]|
| 2011 | Graded in composition in multiple InGaN QBs | 6 %          | 200                   | 0.3×0.3           | Experiment and simulation   | [17]|
| 2011 | linearly graded the last InxGa1-xN barrier | 13 %          | 26.7                  | 0.3×0.3           | Simulation                  | [32]|
| 2012 | InGaN/AlGaN/InGaN QBs | Small droop   | 0.3A                  |                   | Simulation                  | [30]|
| 2013 | Graded in content in QWs | 47 %          | 160                   | 0.2×0.25          | Experiment                  | [44]|

*The droop in Tables 1 and 2 is defined as \( \left( \frac{\eta_{peak} - \eta_{test-current}}{\eta_{peak}} \right) \), where \( \eta \) are the EQE or IQE motioned in the references
The device designs of EBL also have a relationship with hole injection efficiency, which will be discussed later. The engineering work on QBs is summarized in Table 1, and the main strategies can be grouped as follows:

a. Use of multilayer QBs (H. Chung, 2009), for example, select InGaN/GaN/InGaN structures, as QBs. In this way, the crystal quality of epitaxy films can be ensured, and the polarization field was reduced 19% by the time-resolved PL measurements under reverse bias. It has also been shown that the use of MLB structures increases optical power and decreases the efficiency droop [28].

b. Insertion of an AlGaN barrier between the n-type GaN layer and the MQWs (R. Lin, 2010). It was found that the EQE was improved by 5.7% over that of a sample without an AlGaN barrier at a current density of 104.3 A/cm² [42].

c. Quaternary InAlGaN QBs (M. Schubert, P. Tu, 2008, 2011). The electroluminescence results indicated that the light performance could be effectively enhanced, and simulation results showed that the GaN LEDs with quaternary InAlGaN barrier exhibited a 62% higher radiative recombination rate and a low efficiency droop of 13% at a high injection current [8, 43].

d. Replacing the last GaN barrier by a linearly graded InₓGa_{1-x}N barrier (C. Xia, 2011). The formation of a deep potential well in the GLB can enhance electron confinement. The forward voltage was reduced from 3.60 V to 3.25 V, and the efficiency droop was improved from 36% to 13% [32].

e. Use of step-stage multiple-quantum-well (MQW) structure with Si-doped hole-blocking barrier (Z. Zheng, 2013). At high injection current levels, the efficiency droop behaviour and EL wavelength stability of this structure were significantly improved. The author ascribed these improvements to the enhanced carrier injection resulting from the reduction of the polarization field in the active region by step stage QWs, as well as the hole-blocking effect by the Si-doped barriers [44].

All these methods are possible ways to achieve an improved efficiency droop effect in GaN LEDs.

2.2. Effects of volume and carrier density in the active region

From the calculations in the last section, we can see that the volume of the active region \(V_{QW}\) is related to the drift current causing the droop. Most of time, it has been assumed that all the MQW layers act as light-emitting active regions and the carrier density in MQWs is uniform. However, actual carrier distribution in InGaN MQWs is significantly inhomogeneous and the effective light-emitting region can be greatly reduced for several reasons. N. F. Gardner and J. Son et al. have been investigated the relation of piezoelectric polarization and effect active regions in MQWs [45, 46]. The simulation results showed that the strong internal polarization fields cause the electron and hole wave functions to be mainly distributed near the edge of the QW in the opposite direction, and the small overlap of electron and hole wave functions effectively reduced the active volume. When the severe band bending in InGaN quantum-well
was improved as the piezoelectric polarization was reduced, the improved overlap of electron and hole wave functions increased the internal quantum efficiency and reduced efficiency droop significantly. Another reason for the reduction of the effected active region was the strong fluctuation of In composition inside InGaN QWs. Since the recombination of electrons and holes mainly occurred in the In-rich region, A. Kaneta and J. I. Shim et al. have pointed out that the active volume acting as a light-emitting region would be much smaller than the physical volume of QWs, and the carrier density around the In rich cluster should be higher than the one in the uniformity distribution region [47, 48].

Another reason for effective volume reduction is the inefficient hole transport through QWs. Due to the low mobility and low hole density, hole carriers are mostly distributed at a few QWs closest to the p-side layers, and only a limited number of QW layers act as effective carrier recombination regions [16, 49]. Because of this aforementioned effect, the effective active volume could be greatly reduced. Hole injection efficiency will be discussed in the next section. In fact, research regarding the effected active region has long utilized two methods: optimization of the QW thickness and of the numbers. In 2007, N. F. Gardner et al. compared the LED having 9-nm thick QWs and another one with 2.5-nm thick QWs [45]. The results exhibit a significantly reduced droop in the former device, which is attributed to the reduced Auger recombination resulting from affected carrier density distribution in QW volumes. M. Maier et al. have investigated the optimal QW thickness for LEDs fabricated on sapphire substrate and free-standing GaN substrate [50]. From the electroluminescence (EL) efficiency results, LEDs on freestanding GaN with an 18-nm thick InGaN wide-well active region show the highest efficiency. In contrast, LEDs on sapphires grown with conventional low temperatures exhibit optimum well width at 3 nm. S. Tanaka et al. improved the droop property by increasing the QW number from 6 to 9 on a patterned sapphire substrate (PSS). The droop ratio was improved from 45.9 to 7.6 % [51]. At a wavelength of 447 nm, and with standard on-header packaging, the 9 QW PSS-LED had an output power of 27.6 mW and an EQE of 49.7 % at a current of 20 mA. The output power of the 9 QW PSS-LED remains linear with increasing drive current, and the EQE is almost constant, even up to a relatively high current density. X. Li et al. studied the efficiency droop of double heterostructure (DH) LEDs with different active region thicknesses separated by thin and low barriers for LEDs at high injection, and experimental results were supported by numerical simulations [52]. They concluded that the use of thin and low barriers was crucial to enhance carrier transport across the active region, and increasing active region thickness from 3 to 6 nm resulted in a decrease in IQE; however, the peak EQE increased. A further increase of the DH active region thickness to 9 nm improved EQE only at very high injection levels, while 11-nm thick DH showed significantly lower EQE.

All of this progress has provided us with QW active region design, the main physical mechanism and an estimation of conclusion. We now have a clearer physical picture, and the main experimental basis of droop improvement is considered to be the design of effective volume and optimization of carrier density in the active region.

2.3. Low efficiency of hole injection and transportation

Electron and hole transport characteristics in GaN-based devices are vastly different. On the one hand, electrons typically have a fairly high mobility of 200 cm$^2$ V$^{-1}$s$^{-1}$ or more, but holes in
GaN have a lower mobility with values on the order of $10 \text{ cm}^2\text{ V}^{-1}\text{s}^{-1}$, which is less than an order of magnitude than for electrons. On the other hand, due to the relatively low ionization energy of the n-type doping Si, high electron concentrations are easily achievable. By contrast, the ionization energy of the p-type dopant Mg is around 170 meV, and therefore, high hole concentrations are difficult to achieve. Such asymmetrical transportation behaviours of electrons and holes enhance electron overflow and lower the effective volume of the active region. Inefficient transportation of holes as the major reason for efficiency droop has also been identified in our calculations, as demonstrated in Eqs. 12 and 13, where the low $\mu_p$ and $P_{p0}$ can lead to the high drift leakage current mentioned in section 2.1. Approaches focused on the aim of improving hole injection into the LED active region include p-type doping in the QBS and engineering of the EBL, and some of these results will be briefly reviewed and are summarized in Table 2.

| Year | Engineered QBS/EBL | Droop | Test current (A/cm$^2$) | Chip size (mm×mm) | Experiment and/or simulation | Ref |
|------|---------------------|-------|------------------------|------------------|-----------------------------|-----|
| 2008 | p-doping QBS        |       | efficiency peak occurs at 900 A/cm$^2$ | 900 0.250 mm diameter | Experiment | [53] |
| 2010 | p-doping the last QB| 24.2% | 167 0.3×0.3            | Simulation       | [54] |
| 2010 | graded EBL          | 4%    | 200 0.3×0.3            | Experiment and simulation | [18] |
| 2010 | InAlN EBL           | 18%   | 350 0.35×0.35         | Experiment       | [55] |
| 2011 | superlattice (SL) EBL | 17% | 300 0.2×0.5           | Experiment       | [56] |
| 2012 | N-polar MQW         | 7%    | 192 0.25×0.25         | Experiment       | [14] |
| 2013 | Graded SL-EBL       | 8%    | 28 0.6×0.6            | Experiment       | [57] |

*The droop in Table 2 is defined as $(\eta_{\text{peak}} - \eta_{\text{test-current}}) / \eta_{\text{peak}}$, where $\eta$ are the EQE or IQE motioned in the references.

Table 2. Development of engineered EBLs for improving hole injection

In 2008, J. Q. Xie et al. used pulsed electroluminescence measurements to show that droop can be mitigated by p-doping all QBS, and the current density at the efficiency peak can be moved up to ~900 A/cm$^2$ [53]. Along the way, Y. K. Kuo simulated the results that only p-doped the last barrier (closest to EBL) with a doping concentration of $10^{17}$ cm$^{-3}$ compared with the LEDs with no doped barrier [54]. The simulation results show that the efficiency droop is significantly improved when the last undoped GaN barrier in a typical blue LED is replaced by a p-type GaN barrier. The results suggest that the improvement in efficiency droop is mainly due to the decrease of electron current leakage and the increase in hole injection efficiency. At the
same time, C. H. Wang et al. designed a graded-composition electron blocking layer (GEBL) with aluminium composition increasing along the (0001) direction [18]. The experiments and simulation results demonstrate that such GEBL can effectively enhance the capability of hole transportation across the EBL, as well as electron confinement. Consequently, the efficiency droop is reduced from 34% in conventional LEDs to only 4% from the maximum value at low injection current to 200 A/cm$^2$. In order to avoid the added polarization effects caused by the AlGaN EBL, S. Choi et al. used an InAlN EBL instead of an Al$_{0.2}$Ga$_{0.8}$N EBL in visible LEDs [55]. A significant enhancement of the EL intensity and light output in blue LEDs with an In$_{0.18}$Al$_{0.82}$N EBL was demonstrated. Also, it has been shown that an In$_{0.18}$Al$_{0.82}$N EBL is more effective than a conventional Al$_{0.2}$Ga$_{0.8}$N EBL in improving quantum efficiency and reducing efficiency droop at high injection current densities. To investigate the effect of electron blocking layer (EBL) on the efficiency droop, R. B. Chung et al. studied two different types of EBLs—single AlInN:Mg layer and AlInN:Mg (2 nm)/GaN:Mg (2 nm) superlattice (SL) structure with seven periods [56]. It was found that the output power and operating voltage of a single EBL LED were sensitive to EBL thickness. On the other hand, an LED with SL EBL showed no deterioration of optical power and operating voltage, while its efficiency droop (17% at 300A/cm$^2$) was reduced by more than one-half compared to a conventional Al$_{0.2}$Ga$_{0.8}$N (20 nm) EBL LED (36% at 300A/cm$^2$). Furthermore, J. H. Park et al. introduced Al$_{1-x}$Ga$_x$N/GaN superlattice EBLs with gradually decreasing Al composition toward the p-type GaN layer. It was experimentally demonstrated that GaInN/GaN LEDs with the GSL-EBL show lower efficiency droop and higher EQE, as well as comparable or even lower operating voltage, compared to LEDs with conventional AlGaN EBLs[57].

3. Experimental procedures, results and discussion — Structure design, characterizations and study of mechanisms

3.1. Preparation and measurements of the LEDs

A set of epitaxial structures (emitting at 455 nm) were grown on c-plane PSS in a high-speed, rotating-disk metal organic chemical vapour deposition (MOCVD) system (Veeco K465i). All structures had a similar structure, consisting of 7–11 periods of ~3-nm thick InGaN wells and ~5-nm thick GaN barriers. The underlying GaN buffer consisted of a ~1.5 μm nominally undoped GaN layer, followed by a 2-μm n-type GaN with an approximately $1 \times 10^{19}$ cm$^{-3}$ silicon doping level. The final Mg-doped p-GaN was about 100-nm thick with a nominal hole density of $3–7 \times 10^{17}$ cm$^{-3}$. For comparison, InGaN/GaN superlattices (SLs) or AlGaN/GaN EBLs were employed to investigate the effects on droop in some samples, as shown in Fig. 2a.

The device was designed in lateral injection geometry with a chip dimension of 0.76 x 0.25 mm$^2$ with Ti/Al/Ti/Au n-type contacts and Ni/Au p-type contacts, as shown in Fig. 2b. The surface of epitaxial structures was inspected by a Dimension 3100 AFM system in tapping mode.
introducing a highly p-doped AlGaN electron-blocking layer (EBL) with a high Al composition may mitigate the degree of asymmetry by means of a high potential barrier for electron leakage, but a low barrier for hole injection. However, it is extremely difficult to realize such an ideal EBL because of the high ionization energy of the p-type dopant Mg in the AlGaN layer and the potential barrier greatly blocking the hole by the piezoelectric polarization sheet charge at the interface between the GaN spacer and the AlGaN EBL.

In this study, we present the three different EBL structures—Bulk EBL, AlGaN/GaN SL-EBLs with different loops, and graded SL-EBL (GSL-EBL), which having a graded Al mole fraction (Fig. 3). For comparison, the ~20 nm-thick p-type Al0.20Ga0.80N bulk EBL structure was used. The 6, 8 and period SL-EBL consisted of AlxGa1-xN/GaN bi-layers with thicknesses of 1.6 nm for the AlGaN barriers and 1.8 nm for GaN wells, likewise, six-period GSL-EBL, consisting of six periods of AlxGa1-xN/GaN bi-layers (x varies from 0.4 to 0.01 and from 0.01 to 0.4) with a thickness of 2 nm for both barriers and wells, were fabricated for each, respectively. Both AlGaN and GaN in the GSL-EBLs are Mg doped to realize a low-doping effect.

Fig. 4 (a) shows the representative external quantum efficiency (EQE) of LEDs, with bulk EBL and SL-EBLs increasing the loop number from 6 to 10 as a function of current density; Fig. 4b shows the I–V characteristics. From the results, we can see that, as expected, the LEDs with a reduced number of periods from the six-period GSL-EBL show the lowest operating voltage and a much reduced efficiency droop at a driving current density of 200 A/cm². However, the LEDs with an eight-period SL-EBL loop had poor efficiency droop compared to that of the bulk EBL and ten-loop SL-EBL LEDs, as well as a higher operating voltage than bulk and six-loop SL-EBL structures.

The device was designed in lateral injection geometry with a chip dimension of 0.76 × 0.25 mm² with Ti/Al/Ti/Au n-type contacts and Ni/Au p-type contacts, as shown in Fig. 2b. The surface epitaxial structures was inspected by a Dimension 3100 AFM system in tapping mode.
Fig. 3 Schematic conduction band diagrams showing the three different EBL structures—the conventional bulk EBL, the upper lattice EBL and the graded upper lattice EBL.

Fig. 4 (a) shows the representative external quantum efficiency (EQE) of LEDs, with bulk EBL and SL-EBL increasing the loop number from 6 to 10 as a function of current density; Fig. 4b shows the I–V characteristics. From the results, we can see that, as expected, the LEDs with a reduced number of periods from the six-period GSL-EBL show the lowest operating voltage and a much reduced efficiency droop at a driving current density of 200 A/cm². However, the LEDs with an eight-period SL-EBL loop had poor efficiency droop compared to that of the bulk EBL and ten-loop SL-EBL LEDs, as well as a higher operating voltage than bulk and six-loop SL-EBL structures.

We know that SL-EBLs cause a penalty in operating voltage, due to hole transport that is hindered by the series of potential barriers at the AlGaN/GaN hetero-interfaces of the SL EBL. But in our experiments, when we reducing the loop numbers of SL-EBL to 6, the operating voltage of this LED was similar to that of bulk EBL LED, although this lower voltage is at the cost of EQE efficiency. Based on the low operating voltage results, Fig. 5a shows EQE measured as a function of current density for bulk and GSL-EBL LEDs. The LED with six-period GSL-EBL and an Al composition increasing from 0 to 0.4 shows the same EQE throughout the whole injection current density range.
Efficiency droop in III-nitride LEDs

Fig. 5 EQE (a) and I-V characteristics (b) as a function of injection current for the LEDs with Bulk EBL and SL-EBL with graded Al composition.

But when we graded the Al composition from 0.4 to 0, the efficiency droop at 200 A/cm$^2$ was measured to be 25.5%, which is higher than 32.3% of bulk EBL LEDs and 43.8% of 6-loop SL-EBL LED. As discussed above, the lower Al composition on the p-type side can reduce the potential barrier for hole injection, leading to less electron leakage and a higher hole concentration at the last grown quantum well where most of the radiative recombination occurs. We think such a process clearly improved the efficiency droop. In addition, the high operating voltage of SL-EBL LED was measured to be 97 V/cm, which is lower than that of bulk EBL LED due to the low Al composition.

3.3. Investigation of active volume effect in Multiple Quantum Well (MQW) region under high driving current

To reveal the efficiency improvement mechanism, monitoring QW with longer wavelength (480 nm) was used to detect the carrier distribution in the LEDs. We designed such a series of samples, with the MQWs consisting of seven blue wells (emitting at 455 nm) and two longer wavelength wells (emitting at 480 nm). As shown in Fig. 6, the longer wavelength wells located at different positions were introduced to experimentally clarify the carrier distribution in the MQWs. Especially at high driving currents, the carrier transport behavior in GaN/InGaN MQW LEDs can be quantitatively investigated.

As shown in Fig. 7a–f, different light output-current-voltage (L-I-V) spectra at the drive current range from 1 mA to 300 mA were measured to explore the spatial carrier distribution in the MQWs. Especially at high driving currents, the carrier transport behavior in GaN/InGaN MQW LEDs can be quantitatively investigated.
nm light in other QWs. But we know that the blue shift comes from the polarization effect, and the PL peaks alone don’t give rise to the blue shift. So, we can monitor the blue shift of the 480 nm peak to see the carrier distribution in the MQWs at different drive currents. From Fig. 7a–c, when the monitor wells are located at the positions close to the p-GaN side, the 480 nm peak shows significant blue shift behavior as the drive current increases, which indicates that these two wells play an important role in carrier recombination. Meanwhile, as we put the monitor wells at the middle of MQWs, the blue shift behavior is weakly observed. Furthermore, in the spectra from the monitor wells located at the places close to N-GaN side, we can identify that there is nearly no blue shift. Such results imply that the carriers, and especially the holes, mainly distribute at the wells close to the p-GaN side. And when the LEDs work at high drive current, the holes move to the n-GaN side, but this move behavior is very limited.

As shown in Fig. 7d–f, in order to carefully study carrier transport behavior in the MQWs at high drive current, we demonstrate the I-V characteristics of LEDs with different monitor well positions at driving currents of 100 mA, 200 mA and 300 mA, respectively. For comparison, the test condition is kept at the same integrated time and external environment. At the driving current of 100 mA, in the case of monitor wells located at the middle of the MQWs, the intensity of the peak at 480 nm is clearly higher than the intensity of the 455 nm peak, which is different with the monitor wells at other places. We can conclude that at a high drive current of 100 mA, the carriers mainly distribute on these two wells, and the holes move to these two wells at the electrical driving force. When the driving current increases to 200 mA, at first the peak intensity of 455 nm increases greatly, and this implies a significant improvement in carrier distribution. Secondly, at higher driving current, the intensity at 480 nm in the monitor wells close to the p-GaN side is lower than that for monitor wells close to the n-side. When we increase the driving current to 300 mA, the intensity of the 455 nm peak increases greatly, and the variation tendency of the peak intensity of 480 nm is also apparent. We think that at this state, the wells close to the p-side show a weak contribution for lighting.

As we have investigated the active volume effect in multiple quantum well (MQW) regions under high driving current, we designed MQW structures to improve the efficiency droop. At
first, we changed the MQW loop numbers from 7 to 11 with the QWs and QBs at the same thickness; secondly, based on the LEDs with MQW loop numbers of 11, we kept the thickness of QW at 3 nm and reduced the thickness of QBs from 5 nm to 2.5 nm. As shown in Fig. 8a, we found that when we increased the MQW loop numbers, the efficiency peak occurs at a higher current density of 20 mA/cm$^2$ rather than at 10 mA/cm$^2$. This conclusion is consistent with the previous report that increasing QW numbers can lead to more uniform electron and hole distribution across the active region and reduced peak carrier densities. When we reduce the thickness of QBs, we can see that the thinner QBs structure results in a better efficiency droop. Fig. 8b shows the enlarged efficiency peaks. We think the thinner QBs effectively reduce the irradiative recombination, leading to much more uniform hole distribution. The uniform hole distribution means a relatively lower carrier density, which is likely the reason for the improved efficiency at higher current densities.

Figure 7. Light output-current-voltage (L-I-V) characteristics of the LEDs with monitor wells located at different positions. (a–c): driving current varied from 1 mA to 300 mA; (d–f): L-I-V characteristics at driving currents of 100 mA, 200 mA and 300 mA.
Implementing a single or multiple InGaN/GaN superlattice (SL) structure formed by low content between the n-type GaN region and the MQW region could influence the distribution of strain and the morphology of V-pits. The InGaN/GaN SLs with 20 loops have a total thickness of ~50 nm, and a schematic diagram is shown in Fig. 2.

To clarify the effects of various InGaN/GaN SLs on the efficiency droop, the EQE of LEDs with different SL structure are calculated and plotted versus current density in Fig. 9. After a rapid increase at low driving current densities, all the LEDs show a monotonic efficiency drop with increasing current. The sharp peak EQE is about 46% at the current density of J~2.95 A/cm². The LEDs with 20-loop and 30-loop SLs show an efficiency droop of 45.5% at a driving current density of 250 A/cm², which is 4.4% worse than that of LEDs with 25-loop SLs. But LEDs with 25-loop and 30-loop SLs show a 2% higher EQE in the range of 30–150 A/cm². The results indicate that 25-loop SL LEDs show the highest EQE value in the three samples, at both high and low driving current densities.

EQE as a function of injection current for the LEDs with different MQW loop numbers and QB thicknesses are calculated and plotted versus current density in Fig. 9. After a rapid increase at low driving current densities, all the LEDs show a monotonic efficiency drop with increasing current. The sharp peak EQE is about 46% at the current density of J~2.95 A/cm². The LEDs with 20-loop and 30-loop SLs show an efficiency droop of 45.5% at a driving current density of 250 A/cm², which is 4.4% worse than that of LEDs with 25-loop SLs. But LEDs with 25-loop and 30-loop SLs show a 2% higher EQE in the range of 30–150 A/cm². The results indicate that 25-loop SL LEDs show the highest EQE value in the three samples, at both high and low driving current densities.
different SL structure are calculated and plotted versus current density in Fig. 9. After a rapid increase at low driving current densities, all the LEDs show a monotonic efficiency drop with increasing current. The sharp peak EQE is about 46% at the current density of 1.9 A/cm². The LEDs with 20-loop and 30-loop SLs show an efficiency droop of 45.5% at a driving current density of 250 A/cm², which is 4.4% worse than that of LEDs with 25-loop SLs. But LEDs with 25-loop and 30-loop SLs show a 2% higher EQE in the range of 30–150 A/cm². The results indicate that 25-loop SL LEDs show the highest EQE value in the three samples, at both high and low driving current densities.

As shown in Fig. 10, the dimension of V-pits from AFM images in MQWs on 30-loop and 25-loop SLs increase to 170 and 140 nm, respectively, from 100 nm for that on 20-loop SLs. The enlarged V-pits suppress non-radiative carriers captured by threading dislocation more effectively, which leads to an increase in EQE in LEDs with 25-loop and 30-loop SLs in the range of 30–150 A/cm². However, the higher droop in LEDs with 30-loop after 150 A/cm² is attributed to the distribution of holes closer to n-type, which results from the deep tail of the Mg distribution on the SIMS spectrum (not shown here).

Figure 10. Atomic force microscope image of 9-MQW on 20-loop (a), 25-loop (b), and 30-loop (c) SLs.

The output power and EQE measured at current density from 0 to 300 mA are plotted in Fig. 11 for three LEDs with InGaN/GaN SLs grown at 810, 835 and 870 °C. The output power of

Fig. 11. Experimental light output (a) and EQE (b) of LEDs with InGaN/GaN SLs grown at 810, 835 and 870 °C.
three LEDs rises with increasing current density, rolls off as current exceeds a characteristic current density, and decreases monotonously toward higher currents. The characteristic current density increases from 200 A/cm$^2$ to 240 A/cm$^2$ when the growth temperature of InGaN/GaN SLs ramps down to 835 °C from 870 °C. However, if the growth temperature decreases lower to 810 °C, the characteristic current density drops to 225 A/cm$^2$. In fact, EQE of the LEDs with SLs grown at 835 °C reaches its peak at ~9.9 A/cm$^2$ compared to ~5 A/cm$^2$ for LEDs with SLs grown at 810 and 870 °C. At the same time, the droop effect for LEDs with SLs grown at 835 °C is ~45.2 %, which is 2.3 % better than that of LEDs with SLs grown at 810 °C. Actually, if the growth temperature of InGaN/GaN SLs decreases, V-pits with larger dimensions can be obtained in the MQW region. Similar to the effects of V-pits with different sizes mentioned above, the better droop effect is due to the larger dimension of V-pits in LEDs with InGaN/GaN SLs grown at 835 °C compared to those grown at 870 °C. But again, the degradation in LEDs with SLs grown at 810 °C is ascribed to the asymmetry in distribution of electrons and holes in the MQW region at high driving current densities.

4. Summary

Herein, we have presented a summary of the current state of efficiency droop research and reviewed mechanisms potentially causing the droop. At the same time, we have demonstrated three epi-layer engineered structures that offer some pathways to droop mitigation without compromising other device performance. In our study, we conclude that 1) the structure including an EBL composed of a p-doped graded-composition AlGaN/GaN superlattice can enable better hole injection and reduce electron leakage. It is experimentally shown that GaInN/GaN MQW LEDs with GSL-EBL show lower efficiency droop and higher EQE, as well as comparable or even lower operating voltage, compared to LEDs with conventional bulk AlGaN EBLs. 2) Under high driving current, we remarked on the hole shift behavior by using monitor wells at different MQW positions. Because of the asymmetry in carrier transport, caused by much lower concentration and mobility of holes even at a driving current of 300 mA, the holes move slightly to the n-GaN side and mainly concentrate at the middle well close to the p-side. Accordingly, we investigated the influence of QW numbers and the thickness of QBs for the efficiency droop. The experiments results show that increasing QW numbers and thinner QBs are helpful for carrier extending and hole mobility. 3) we used intentionally formed V-shaped pits (V-pits) to mitigate efficiency droop current. By varying the growth conditions of the SL layer, we obtained different sizes of V-pits and found that proper, larger V-pits can provide a benefit to the mitigation of droop effect.

Acknowledgements

This work was supported by a grant from the National High Technology Research and Development Program (i.e., 863 program) (No. 2014AA032604).
Author details

Jie Zhang¹, Dongyan Zhang¹, Daqian Ye¹, Chenke Xu¹ and Meichun Huang²,³
1 Xiamen San’an Optoelectronics Co., Xiamen, China
2 Department of Physics, Xiamen University, Xiamen, China
3 CCAST (World Laboratory), Beijing, China

References

[1] U.S. Department of Energy, Solid-State Lighting Research and Development: Manufacturing Roadmap. Available online at http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html. Accessed August 2014.

[2] Verzellesi G, Saguatti D, Meneghini M, Bertazzi F, Goano M, Meneghesso G, and Zannoni E. Efficiency droop in InGaN/GaN blue light-emitting diodes: Physical mechanisms and remedies. Journal of Applied Physics, 2013; 114(7) 071101.

[3] Delaney K T, Rinke P, and Van de Walle C G. Auger recombination rates in nitrides from first principles. Applied Physics Letters, 2009; 94(19) 191109.

[4] Kioupakis E, Rinke P, Delaney K T, and Van de Walle C G. Indirect Auger recombination as a cause of efficiency droop in nitride light-emitting diodes. Applied Physics Letters, 2011; 98(16) 161107.

[5] Scheibenzuber W G, Schwarz U T, Sulmoni L, Dorsaz J, Carlin J F, and Grandjean N. Recombination coefficients of GaN-based laser diodes. Journal of Applied Physics, 2011; 109(9) 093106.

[6] Shen Y C, Mueller G O, Watanabe S, Gardner N F, Munkholm A, and Krames M R. Auger recombination in InGaN measured by photoluminescence. Applied Physics Letters, 2007; 91(14) 141101.

[7] Kim M-H, Schubert M F, Dai Q, Kim J K, Schubert E F, Piprek J, and Park Y. Origin of efficiency droop in GaN-based light-emitting diodes. Applied Physics Letters, 2007; 91(18) 183507.

[8] Schubert M F, Xu J, Kim J K, Schubert E F, Kim M H, Yoon S, Lee S M, Sone C, Sakkong T, and Park Y. Polarization-matched GaInN/AlGaInN multi-quantum-well light-emitting diodes with reduced efficiency droop. Applied Physics Letters, 2008; 93(4) 041102.

[9] Xu J, Schubert M F, Noemaun A N, Zhu D, Kim J K, Schubert E F, Kim M H, Chung H J, Yoon S, Sone C, and Park Y. Reduction in efficiency droop, forward voltage, ide-
ality factor, and wavelength shift in polarization-matched GaInN/GaInN multi-quantum-well light-emitting diodes. Applied Physics Letters, 2009; 94(1) 011113.

[10] Zhang L, Wei X C, Liu N X, Lu H X, Zeng J P, Wang J X, Zeng Y P, and Li J M. Improvement of efficiency of GaN-based polarization-doped light-emitting diodes grown by metalorganic chemical vapor deposition. Applied Physics Letters, 2011; 98(24) 241111.

[11] Bochkareva N I, Rebane Y T, and Shreter Y G. Efficiency droop and incomplete carrier localization in InGaN/GaN quantum well light-emitting diodes. Applied Physics Letters, 2013; 103(19) 191101.

[12] Hammersley S, Watson-Parris D, Dawson P, Godfrey M J, Badcock T J, Kappers M J, McAleese C, Oliver R A, and Humphreys C J. The consequences of high injected carrier densities on carrier localization and efficiency droop in InGaN/GaN quantum well structures. Journal of Applied Physics, 2012; 111(8) 083512.

[13] Ryu H-Y, Shin D-S, and Shim J-I. Analysis of efficiency droop in nitride light-emitting diodes by the reduced effective volume of InGaN active material. Applied Physics Letters, 2012; 100(13) 131109.

[14] Akyol F, Nath D N, Krishnamoorthy S, Park P S, and Rajan S. Suppression of electron overflow and efficiency droop in N-polar GaN green light emitting diodes. Applied Physics Letters, 2012; 100(11) 111118.

[15] Dai Q, Shan Q, Cho J, Schubert E F, Crawford M H, Koleske D D, Kim M-H, and Park Y. On the symmetry of efficiency-versus-carrier-concentration curves in GaInN/GaN light-emitting diodes and relation to droop-causing mechanisms. Applied Physics Letters, 2011; 98(3) 033506.

[16] Liu J P, Ryou J H, Dupuis R D, Han J, Shen G D, and Wang H B. Barrier effect on hole transport and carrier distribution in InGaN/GaN multiple quantum well visible light-emitting diodes. Applied Physics Letters, 2008; 93(2) 021102.

[17] Wang C H, Chang S P, Ku P H, Li J C, Lan Y P, Lin C C, Yang H C, Kuo H C, Lu T C, Wang S C, and Chang C Y. Hole transport improvement in InGaN/GaN light-emitting diodes by graded-composition multiple quantum barriers. Applied Physics Letters, 2011; 99(17) 171106.

[18] Wang C H, Ke C C, Lee C Y, Chang S P, Chang W T, Li J C, Li Z Y, Yang H C, Kuo H C, Lu T C, and Wang S C. Hole injection and efficiency droop improvement in InGaN/GaN light-emitting diodes by band-engineered electron blocking layer. Applied Physics Letters, 2010; 97(26) 261103.

[19] Akyol F, Krishnamoorthy S, and Rajan S. Tunneling-based carrier regeneration in cascaded GaN light emitting diodes to overcome efficiency droop. Applied Physics Letters, 2013; 103(8) 081107.

[20] Bochkareva N I, Voronenkov V V, Gorbunov R I, Zubrilov A S, Lelikov Y S, Latyshev P E, Rebane Y T, Tsyuk A I, and Shreter Y G. Defect-related tunneling mechanism of
efficiency droop in III-nitride light-emitting diodes. Applied Physics Letters, 2010; 96(13) 133502.

[21] Efremov A A B N I, Gorbunov R I, Larinovich D A, Rebane Y T, Tarkhin D V, and Shreter. Effect of the joule heating on the quantum efficiency and choice of thermal conditions for high power blue InGaN/GaN LEDs. Semiconductors, 2006; 40(5) 605.

[22] Hader J, Moloney J V, and Koch S W. Temperature-dependence of the internal efficiency droop in GaN-based diodes. Applied Physics Letters, 2011; 99(18) 181127.

[23] Kudryk Y Y and Zinovchuk A V. Efficiency droop in InGaN/GaN multiple quantum well light-emitting diodes with nonuniform current spreading. Semiconductor Science and Technology, 2011; 26(9) 095007.

[24] Malyutenko V K, Bolgov S S, and Podoltsev A D. Current crowding effect on the ideality factor and efficiency droop in blue lateral InGaN/GaN light emitting diodes. Applied Physics Letters, 2010; 97(25) 251110.

[25] Chu C -F C C-C, Liu W -H, Chu J -Y, Fan F -H, Cheng H -C, Doan T, and Tran C A. High-brightness GaN vertical light-emitting diodes on metal alloy for general lighting application. Proceeding of the IEEE, 2010; 98(7) 2455.

[26] Bertazzi F, Goano M, and Bellotti E. A numerical study of Auger recombination in bulk InGaN. Applied Physics Letters, 2010; 97(23) 231118.

[27] Bertazzi F, Goano M, and Bellotti E. Numerical analysis of indirect Auger transitions in InGaN. Applied Physics Letters, 2012; 101(1) 011111.

[28] Chung H J, Choi R J, Kim M H, Han J W, Park Y M, Kim Y S, Paek H S, Sone C S, Park Y J, Kim J K, and Schubert E F. Improved performance of GaN-based blue light emitting diodes with InGaN/GaN multilayer barriers. Applied Physics Letters, 2009; 95(24) 241109.

[29] Han S-H, Lee D-Y, Shim H-W, Kim G-C, Kim Y S, Kim S-T, Lee S-J, Cho C-Y, and Park S-J. Improvement of efficiency droop in InGaN/GaN multiple quantum well light-emitting diodes with trapezoidal wells. Journal of Physics D: Applied Physics, 2010; 43(35) 354004.

[30] Kuo Y-K, Wang T-H, and Chang J-Y. Advantages of blue InGaN light-emitting diodes with InGaN-AlGaN-InGaN barriers. Applied Physics Letters, 2012; 100(3) 031112.

[31] Kuo Y-K, Wang T-H, Chang J-Y, and Tsai M-C. Advantages of InGaN light-emitting diodes with GaN-InGaN-GaN barriers. Applied Physics Letters, 2011; 99(9) 091107.

[32] Sheng Xia C, Simon Li Z M, Lu W, Hua Zhang Z, Sheng Y, and Wen Cheng L. Droop improvement in blue InGaN/GaN multiple quantum well light-emitting diodes with indium graded last barrier. Applied Physics Letters, 2011; 99(23) 233501.
[33] Meynard D S, Shan Q, Cho J, Fred Schubert E, Han S-H, Kim M-H, Sone C, Jae Oh S, and Kyu Kim J. Temperature dependent efficiency droop in GaInN light-emitting diodes with different current densities. Applied Physics Letters, 2012; 100(8) 081106.

[34] Hangleiter A, Hitzel F, Netzel C, Fuhrmann D, Rossow U, Ade G, and Hinze P. Suppression of nonradiative recombination by V-shaped pits in GaInN/GaN quantum wells produces a large increase in the light emission efficiency. Physical Review Letters, 2005; 95(12) 127420.

[35] Hwang S, Jin Ha W, Kyu Kim J, Xu J, Cho J, and Fred Schubert E. Promotion of hole injection enabled by GaInN/GaN light-emitting triodes and its effect on the efficiency droop. Applied Physics Letters, 2011; 99(18) 181115.

[36] Li Z, Lestrade M, Xiao Y, and Li Z S. Improvement of performance in p-side down InGaN/GaN light-emitting diodes with graded electron blocking layer. Japanese Journal of Applied Physics, 2011; 50(8) 080212.

[37] Shuji Nakamura S F C. Introduction to nitride semiconductor blue lasers and light emitting diodes. London: Taylor & Francis, 2000; 5–7.

[38] Dai Q S, Cho J, Schubert E F, Crawford M H, Koleske D D, Kim M-H, and Park Y. On the symmetry of efficiency-versus-carrier-concentration curves in GaInN/GaN light-emitting diodes and relation to droop-causing mechanisms. Applied Physics Letters, 2011; 98(3) 033506.

[39] Cho J, Schubert E F, and Kim J K. Efficiency droop in light-emitting diodes: Challenges and countermeasures. Laser & Photonics Reviews, 2013; 7(3) 408.

[40] Piprek J. Efficiency droop in nitride-based light-emitting diodes. Phys.Status Solidi A, 2010; 207(10) 2217.

[41] Saguatti D, Bidinelli L, Verzellesi G, Meneghini M, Meneghesso G, Zanoni E, Butendeich R, and Hahn B. Investigation of efficiency-droop mechanisms in multi-quantum-well InGaN/GaN blue light-emitting diodes. IEEE Transactions on Electron Devices, 2012; 59(5)1402.

[42] Lin R-M, Lai M-J, Chang L-B, and Huang C-H. Effect of an asymmetry AlGaN barrier on efficiency droop in wide-well InGaN double-heterostructure light-emitting diodes. Applied Physics Letters, 2010; 97(18) 181108.

[43] Tu P-M, Chang C-Y, Huang S-C, Chiu C-H, Chang J-R, Chang W-T, Wuu D-S, Zan H-W, Lin C-C, Kuo H-C, and Hsu C-P. Investigation of efficiency droop for InGaN-based UV light-emitting diodes with InAlGaN barrier. Applied Physics Letters, 2011; 98(21) 211107.

[44] Zheng Z, Chen Z, Chen Y, Wu H, Huang S, Fan B, Wu Z, Wang G, and Jiang H. Improved carrier injection and efficiency droop in InGaN/GaN light-emitting diodes with step-stage multiple-quantum-well structure and hole-blocking barriers. Applied Physics Letters, 2013; 102(24) 241108.
[45] Gardner N F, Muller G O, Shen Y C, Chen G, Watanabe S, Gotz W, and Krames M R. Blue-emitting InGaN–GaN double-heterostructure light-emitting diodes reaching maximum quantum efficiency above 200A/cm$^2$ Applied Physics Letters, 2007; 91(24) 243506.

[46] Son J H and Lee J-L. Numerical analysis of efficiency droop induced by piezoelectric polarization in InGaN/GaN light-emitting diodes. Applied Physics Letters, 2010; 97(3) 032109.

[47] A. Kaneta T M, Y. Kawakami, S. Fujita, G. Marutsuki, Y. Naru-kawa, and T. Mukai. Discrimination of local radiative and nonradiative recombination processes in an InGaN/GaN single-quantum-well structure by a time-resolved multimode scanning near-field optical microscopy. Applied Physics Letters, 2003; 83(17) 3462.

[48] Shim J I, Kim H, Shin D S, and Ryu H Y. An explanation of efficiency droop in ingan-based light emitting diodes: saturated radiative recombination rate at randomly distributed in-rich active areas. Journal of the Korean Physical Society, 2011; 58(3) 503.

[49] Ni X, Li X, Lee J, Liu S, Avrutin V, Ozgur U, Morkoc H, and Matulionis A. Hot electron effects on efficiency degradation in InGaN light emitting diodes and designs to mitigate them. Journal of Applied Physics, 2010; 108(3) 033112.

[50] Maier M, Kohler K, Kunzer M, Pletschen W, and Wagner J. Reduced nonthermal rollover of wide-well GaInN light-emitting diodes. Applied Physics Letters, 2009; 94(4) 041103.

[51] S. Tanaka Zhao Y, Koslow I, Pan C-C, Chen H-T, Sonoda J, DenBaars S P and Nakamura S. Droop improvement in high current range on PSS-LEDs. Electronics Letters, 2011; 47(5) 335.

[52] Li X, Okur S, Zhang F, Avrutin V, Ozgur U, Morkoc H, Hong S M, Yen S H, Hsu T S, and Matulionis A. Impact of active layer design on InGaN radiative recombination coefficient and LED performance. Journal of Applied Physics, 2012; 111(6) 063112.

[53] Xie J, Ni X, Fan Q, Shimada R, Ozgur U m, and Morkoc H. On the efficiency droop in InGaN multiple quantum well blue light emitting diodes and its reduction with p-doped quantum well barriers. Applied Physics Letters, 2008; 93(12) 121107.

[54] Yen-Kuang Kuo M-C T, Sheng-Horng Yen, Ta-Cheng Hsu, and Yu-Jiun Shen. Effect of P-type last barrier on efficiency droop of blue InGaN light-emitting diodes. IEEE Journal of Quantum Electronics; 2010; 46(8) 1214.

[55] Choi S, Kim H J, Kim S-S, Liu J, Kim J, Ryou J-H, Dupuis R D, Fischer A M, and Ponce F A. Improvement of peak quantum efficiency and efficiency droop in III-nitride visible light-emitting diodes with an InAlN electron-blocking layer. Applied Physics Letters, 2010; 96(22) 221105.

[56] Chung R B, Han C, Pan C-C, Pfaff N, Speck J S, DenBaars S P, and Nakamura S. The reduction of efficiency droop by Al0.82In0.18N/GaN superlattice electron blocking
layer in (0001) oriented GaN-based light emitting diodes. Applied Physics Letters, 2012; 101(13) 131113.

[57] Park J H, Yeong Kim D, Hwang S, Meyaard D, Fred Schubert E, Dae Han Y, Won Choi J, Cho J, and Kyu Kim J. Enhanced overall efficiency of GaInN-based light-emitting diodes with reduced efficiency droop by Al-composition-graded AlGaN/GaN superlattice electron blocking layer. Applied Physics Letters, 2013; 103(6) 061104.

[58] Hangleiter A, Hitzel F, Netzel C, Fuhrmann D, Rossow U, Ade G, and Hinze P. Suppression of nonradiative recombination by V-shaped pits in GaInN/GaN quantum wells produces a large increase in the light emission efficiency. Physical Review Letters, 2005; 95(12) 127402.
