Chapter 2

Efficiency Droop in III-nitride LEDs

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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].

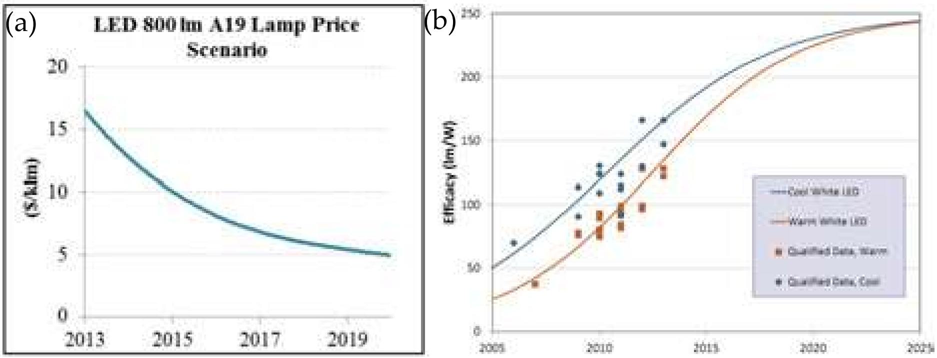

Fig. 1 (*a*) A price scenario of 800 lm LED in the range of 2013 to 2020; (*b*) white light LED efficiency projection from 2005 to 2025.

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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 pave 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, typical GaN LEDs are facing a substantial decrease in efficiency as injection current increases, and we call this efficiency droop effect or 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, nearly all of the proposed mechanisms stem from such origins as Auger recombination, electron leakage, delocalization of carriers and poor hole injection. Historically, phonon-assisted Auger processes were first considered to explain the droop in GaN-LEDs, because Auger recombination in InGaN would promote carriers at energies well beyond the hetero-barriers, and therefore would provide an important contribution to leakage [3–6]. In recent years, polarization fields induced band bending in active regions and electron-blocking layers were reported to enhance the leakage of injected 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 be a key issue in identifying the origin of efficiency droop [11–13]. Furthermore, an LED is a bipolar device relying on the efficient injection of both minority carriers, and both holes and electrons need to be injected and to be distributed optimally in the active region (QWs) to combine 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 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.

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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

$$IQE = \frac{I_0 / E_{ph}}{J_{in} / q} \tag{1}$$

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:

$$R_0 \approx \frac{N}{\tau} = Bn^2 \tag{2}$$

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:

$$\frac{I_0}{E_{ph}} = R_0 V_{QW} = Bn^2 V_{QW} \tag{3}$$

Then the IQE can be expressed in the form:

$$IQE = \frac{Bn^2 V_{QW}}{J_{in}/q} \tag{4}$$

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:

$$\frac{J_{in}}{q} = RV_{QW} \tag{5}$$

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]:

$$R = An + Bn^2 + Cn^3 \tag{6}$$

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

$$\begin{aligned} R &= An + Bn^2 + f(n) \\ &= An + Bn^2 + Cn^3 + C_{DL}n^3 \end{aligned} \tag{7}$$

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

$$J_{drift} = qV_{QW}C_{DL}n^3 \tag{8}$$

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

$$J_{drift} = q\mu_n \Delta n_p(0)E \tag{9}$$

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

$$J_{in} = q\mu_p P_{p0} E \tag{10}$$

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:

$$J_{in} \approx qV_{QW} Bn^2 \tag{11}$$

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

$$J_{drift} = qV_{QW} \frac{\Delta n_p(0)}{n} \frac{\mu_n}{\mu_p P_{p0}} Bn^3 \tag{12}$$

$$C_{DL} = \frac{\mu_n \delta}{\mu_p P_{p0}} B \tag{13}$$

where $\delta = \Delta n_p(0) / n$. From Eqs. 8, 12 and 13, we can see that J_{drift} depends on V_{QW}, δ, μ_n, μ_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:

$$J_{drift} = q\mu_n \Delta n_p(0) E = qD_n \frac{q}{kT} \Delta n_p(0) \frac{J_{in}}{\sigma_p} \tag{14}$$

where D_n and σ_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 δ, 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 $(\Delta E_{C1}:\Delta E_{V1})$ and GaN and AlGaN $(\Delta E_{C2}:\Delta E_{V2})$ 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 $(\Delta E_{C2}:\Delta E_{V2})$ should be kept at 70:30 [2]. In order to balance the electrons and holes in an active region, the InGaN/GaN band offsets $(\Delta E_{C1}:\Delta E_{V1})$ 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.

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		0.3×000	Simulation	[31]
2011	AlInGaN 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 $(\eta_{peak}-\eta_{test-current})/\eta_{peak}$, where η are the EQE or IQE motioned in the references

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

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/cm^2 [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 $In_xGa_{1-x}N$ 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 cm^2 V^{-1}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 μ_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 Tables 1 and 2 is defined as $(\eta_{peak} - \eta_{test-current}) / \eta_{peak}$, where η 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 $Al_xGa_{1-x}N$/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 1×10^{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.

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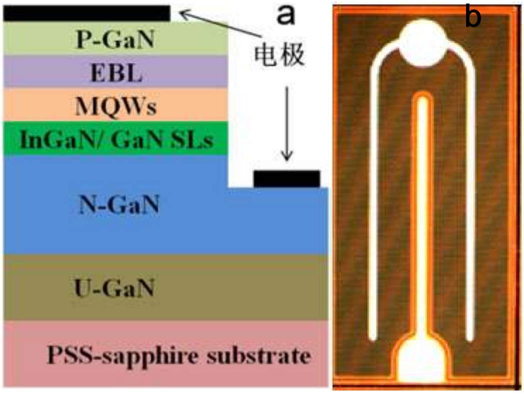

Figure 2. Schematic diagram of the studied epitaxial structures (*a*), and details of the graphical front surface of devices (*b*)

Fig. 2 Schematic diagram of the studied epitaxial structures (*a*), and details of the graphical front surfac devices (*b*)

3.2. Optimization of EBL to reduce polarization charges

3.2. Optimization of EBL to Reduce Polarization Charges

As we discussed in the last section, the asymmetry in carrier transport, caused by much lo concentration and mobility of holes compared to electrons, may be the dominant mechanism cau efficiency droop. Introducing a highly p-doped AlGaN electron-blocking layer (EBL) with a hig composition may mitigate the degree of asymmetry by means of a high potential barrier for elec leakage, but a low barrier for hole injection. However, it is very difficult to realize such an ideal because of the high ionization energy of the p-type dopant Mg in the AlGaN layer and the pote barrier greatly blocking the hole by the piezoelectric polarization sheet charge at the inter between the GaN spacer and the AlGaN EBL.

In this study, we present the three different EBL structures—Bulk EBL, AlGaN/GaN SL-E with different loops, and graded SL-EBL (GSL-EBL), which having a graded Al mole fraction (Fi For comparison, the ~20 nm-thick p-type $Al_{0.20}Ga_{0.80}N$ bulk EBL structure was used. The 6, 8 and period SL-EBL consisted of $Al_xGa_{1-x}N$/GaN bi-layers with thicknesses of 1.6 nm for the Al barriers and 1.8 nm for GaN wells. Likewise, six-period GSL-EBL, consisting of six period

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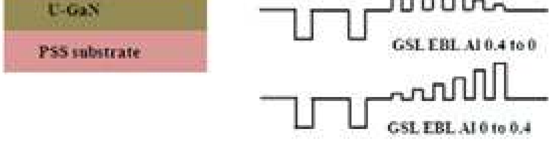
In this study, we present the three different EBL structures—Bulk EBL, AlGaN/GaN SL-EBL with different loops, and graded SL-EBL (GSL-EBL), which having a graded Al mole fraction (Fig. 3). For comparison, the ~20 nm-thick p-type $Al_{0.20}Ga_{0.80}N$ bulk EBL structure was used. The 6, 8 and 10-period SL-EBL consisted of $Al_xGa_{1-x}N$/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 $Al_xGa_{1-x}N$/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/cm^2. 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 strucrures.



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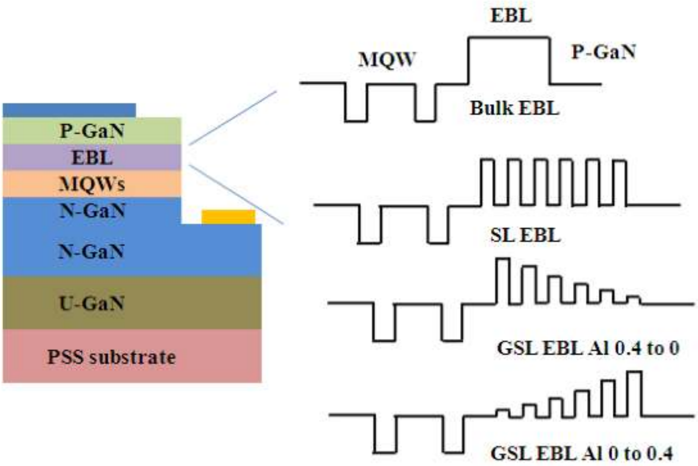

Fig. 3 Schematic co... e conventional bulk EBL, the supper latti...

Figure 3. Schematic conduction band diagrams showing the three different EBL structures—the conventional bulk EBL, the supper lattice EBL and the graded supper lattice EBL

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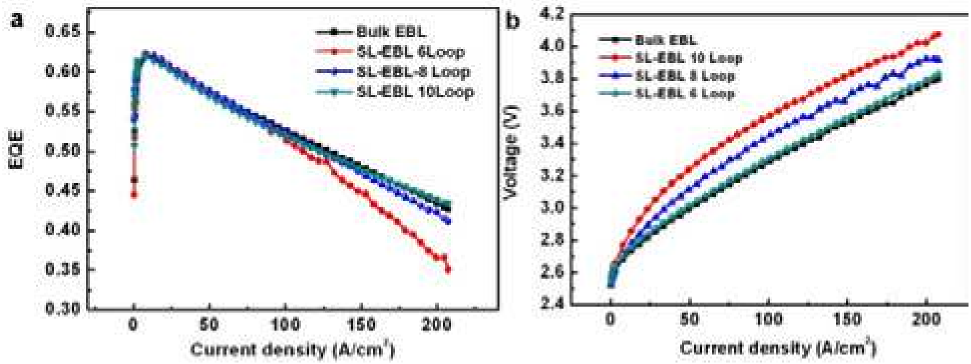

Fig. 4 EQE (*a*) and I–V (*b*) characteristics as a function of injection current for the LEDs with Bulk EBL and SL-EBL with different loop numbers

Figure 4. EQE (*a*) and I–V (*b*) characteristics as a function of injection current for the LEDs with Bulk EBL and SL-EBL with different loop numbers

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 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 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.

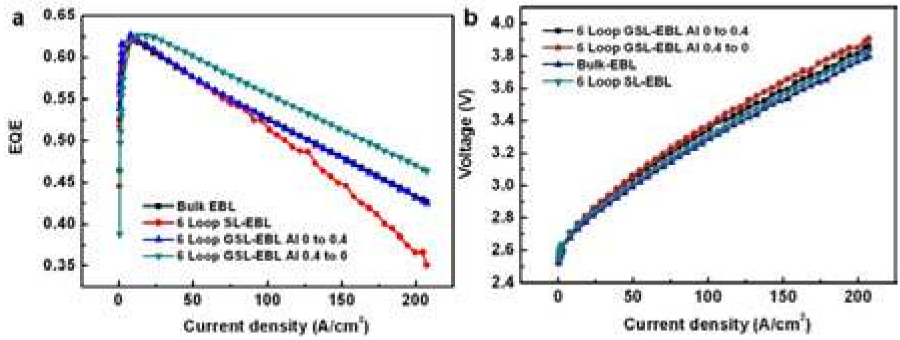

Fig. 5 EQE (*a*) and I-V characteristics (*b*) as a function of injection current for the LEDs with Bulk EBL and SL-EBL with graded Al composition

Figure 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 we 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 is attributed to the large lattice mismatch at the AlGaN/GaN hetero-interfaces causing large polarization-induced electric fields, as well as to the higher overall Al composition of the SL-EBL compared to the bulk EBL, which is the hard doping Mg element. By grading the Al composition, the voltage drop across the GSL-EBL becomes smaller than that for the SL-EBL, due to the smaller lattice mismatch between AlGaN and GaN layer sand lower overall Al content in the EBL. As shown in Fig. 5b, there are slight operating voltage changes in the bulk and GSL-EBL LEDs, which is as expected from our discussion.

3.3. Investigation of Active Volume Effect in Multiple Quantum Well (MQW) Region Under High Driving Current

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

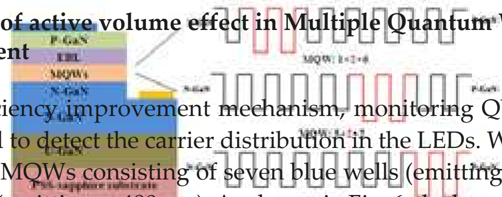

Fig. 6 Schematic diagrams of the LEDs with different remarkable MQWs

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 in the range of 1 mA to 300 mA were demonstrated. It is interesting to find out that the intensity of the monitor wells changes greatly as the test current increases. The intensity of the wavelength 480 nm peak includes two parts: 1) from the recombination of electron and holes excited by the electroluminescence (EL); and 2) from the photoluminescence (PL) excited by the 455

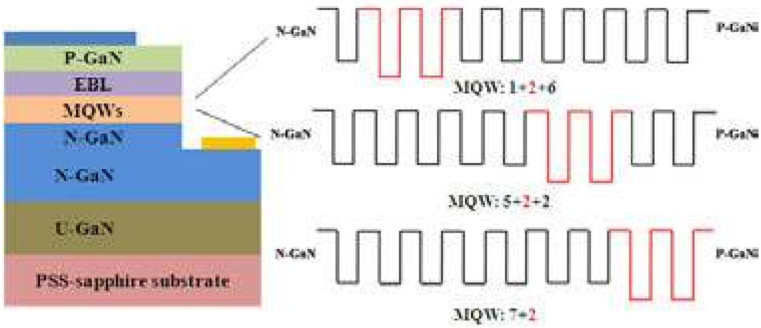

Figure 6. Schematic diagrams of the LEDs with different remarkable MQWs

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 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

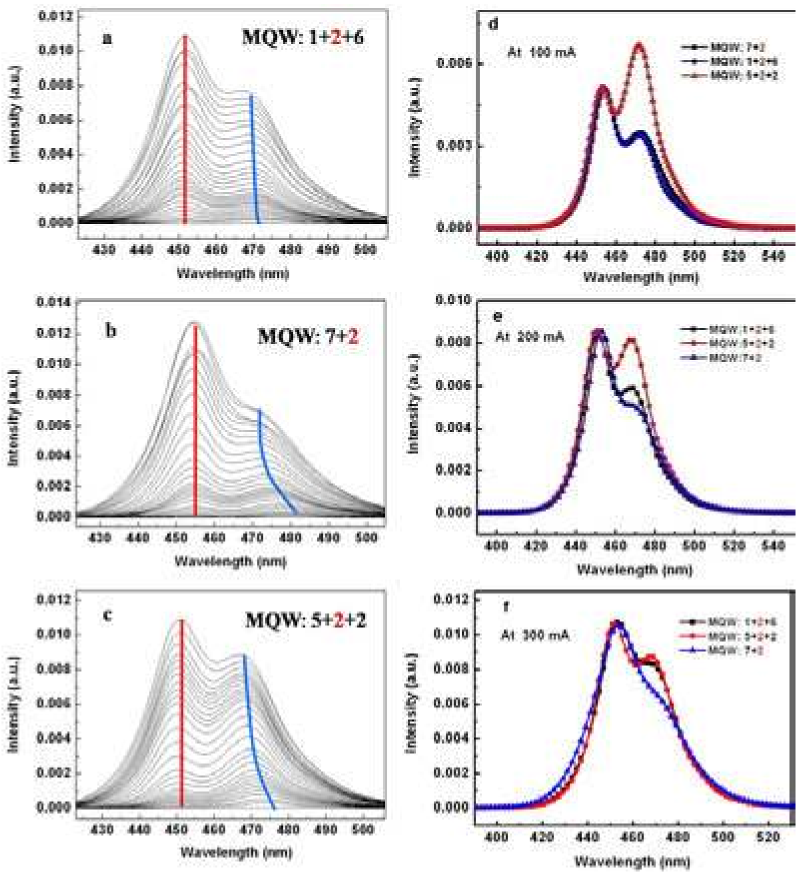

Figure 7. Light output-current-voltage (L-I-V) characteristics of the LEDs with monitor wells located at different positions. (*a–c*): driving current varied from 1 mA to 300 mA; (d–f): L-I-V characteristics at driving currents of 100 mA, 200 mA and 300 mA

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.

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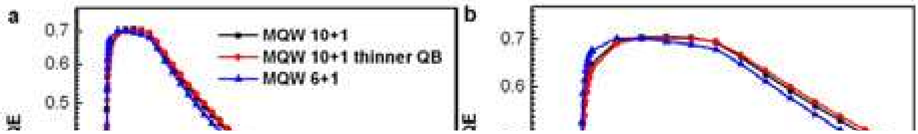
Efficiency droop in III-nitride LEDs 13



Efficiency droop in III-nitride LEDs 13

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Fig. 8 EQE as a function of injection current for the LEDs with different MQW loop numbers and QB thicknesses

3.4 Using Intentionally Formed V-shaped Pits (V-Pits) to mitigate Efficiency Droop Current

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.

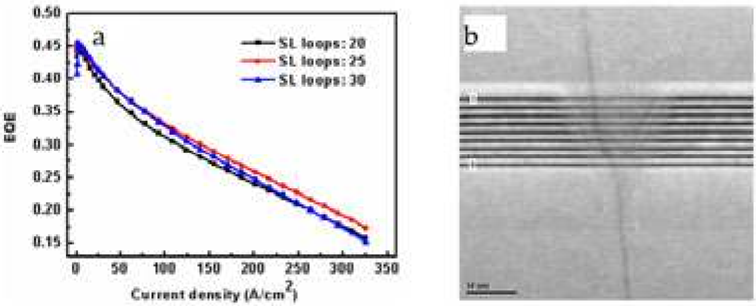
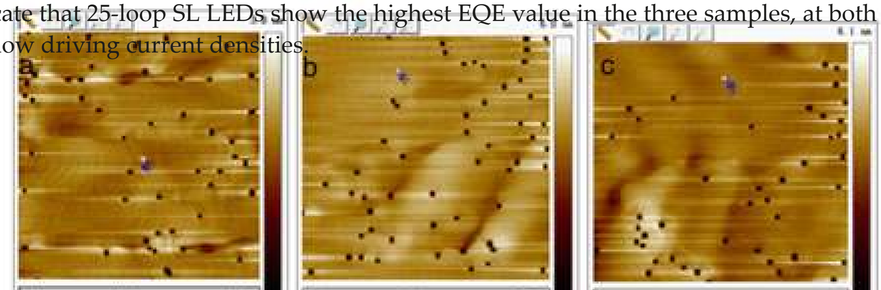


Fig. 9 EQE as a function of the current density for three LEDs with 20-loop, 25-loop and 30-loop InGaN/GaN superlattices (*a*); transmission electron microscope (TEM) image of MQW region in LEDs with 20-loop SLs (*b*)

Figure 9. EQE as a function of the current density for three LEDs with 20-loop, 25-loop and 30-loop InGaN/GaN superlattices (*a*); transmission electron microscope (TEM) image of MQW region in LEDs with 20-loop SLs (*b*)

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 45.3 % 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 J~2.95 A/cm^2. The LEDs with 20-loop and 30-loop SLs show an efficiency droop of 45.5 % at a driving current density of 250 A/cm^2, 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/cm^2. 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.

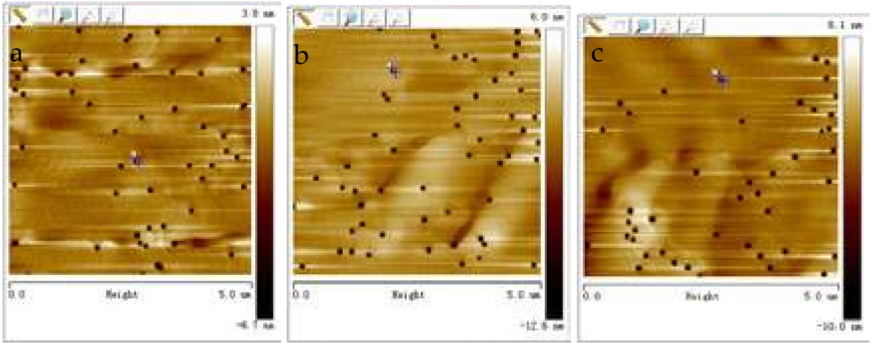


Fig. 10 Atomic force microscope image of 9-MQW on 20-loop (*a*), 25-loop (*b*), and 30-loop (*c*) SLs

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

As we know, in InGaN/GaN MQW LEDs, V-shaped pits (V-pits) tend to be easily formed at the interface between InGaN and GaN layers due to lattice mismatch. As shown in Fig. 9b, insertion of InGaN/GaN SLs leads to large sized V-pits going though the MQW region. Threading dislocations penetrate through the central region of V-pits from their apices, which makes semi-polar planes surrounding the threading dislocation act as irradiative recombination centers in the MQW region. The higher energy state of thinner wells on semi-polar can screen the carrier, which diffuses from c-plane wells and enhances the IQE [58]. As shown in Fig. 10, the dimension of V-pits from AFM imagines in MQWs on 30-loop and 25-loop SLs increase to 170 and 140 nm, respectively, from 100

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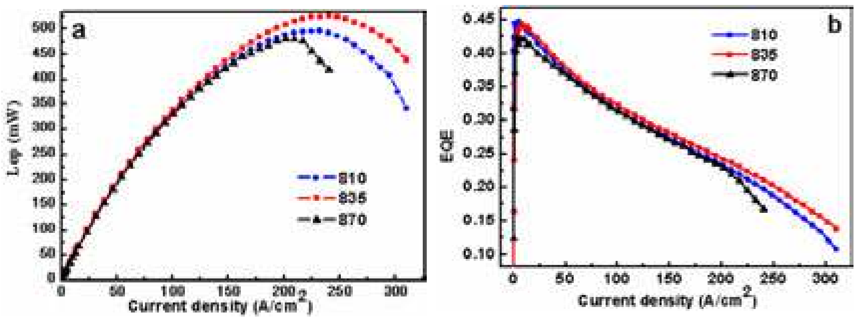

Figure 11. Experimental light output (*a*) and EQE (*b*) of LEDs with InGaN/GaN SLs grown at 810, 835 and 870 °C

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 ^{o}C from 870 ^{o}C. However, if the growth temperature decreases lower to 810 ^{o}C, the characteristic current density drops to 225 A/cm^2. In fact, EQE of the LEDs with SLs grown at 835 ^{o}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 ^{o}C. At the same time, the droop effect for LEDs with SLs grown at 835 ^{o}C is ~45.2 %, which is 2.3 % better than that of LEDs with SLs grown at 810 ^{o}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 ^{o}C compared to those grown at 870 ^{o}C. But again, the degradation in LEDs with SLs grown at 810 ^{o}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).

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