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The Effect of Imbalanced Carrier Transport on the Efficiency Droop in GaInN-Based Blue and Green Light-Emitting Diodes

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Abstract: The effect of strongly-imbalanced carrier concentration and mobility on efficiency droop is studied by comparing the onset voltage of high injection, the onset current density of the droop, and the magnitude of the droop, as well as their temperature dependence, of GaInN-based blue and green light-emitting diodes (LEDs). An n-to-p asymmetry factor is defined as σ_n/σ_p, and was found to be 17.1 for blue LEDs and 50.1 for green LEDs. Green LEDs, when compared to blue LEDs, were shown to enter the high-injection regime at a lower voltage, which is attributed to their less favorable p-type transport characteristics. Green LEDs, with lower hole concentration and mobility, have a lower onset current density of the efficiency droop and a higher magnitude of the efficiency droop when compared to blue LEDs. The experimental results are in quantitative agreement with the imbalanced carrier transport causing the efficiency droop, thus providing guidance for alleviating the phenomenon of efficiency droop.

Keywords: nitride semiconductor; LED; efficiency droop; carrier transport

1. Introduction

Light-emitting diodes (LEDs) in a GaInN material system suffer from a reduction in efficiency at high injection currents, which is known as the "efficiency droop." An understanding of the physical origin of the efficiency droop is critical for future progress in LEDs, particularly when operated at high current densities. Various mechanisms to explain the efficiency droop have been proposed, including delocalization of carriers [1,2], Auger recombination [3,4], and electron leakage [5,6]. Auger recombination (i.e., an electron drops non-radiatively from the conduction band to the valence band while transferring its energy to another electron or hole) has been regarded as a major cause of efficiency droop. However, the Auger recombination coefficient, even if defect-assisted, has very small theoretical values ranging between ~10^{-34} and ~10^{-30} cm^6/s in nitride-based LEDs and weakly increases with temperature, making it difficult to explain various aspects of the efficiency droop [7–11]. Recently, a simple analytical theoretical model was formulated in support of electron leakage the cause of efficiency droop [7]. Lack of hole injection and electron leakage are equivalent phenomena, "two sides of the same coin," since for every hole not injected, an electron leaks out of the active region. The foundation of the model is the strong imbalance in electron and hole transport characteristics. In this model, the electron leakage depends on the third power of the carrier concentration and an associated third-order drift-leakage coefficient C_{DL} (as well as a smaller fourth-order coefficient). The term $C_{DL} \cdot n^3$ allows one to quantitatively estimate the efficiency droop, where C_{DL} is expressed based on the physical parameters of the pn-junction as follows [7]:

$$C_{DL} = \frac{\delta \mu_n}{\mu_p p_{p0}} B \quad (1)$$

where μ_n, μ_p, and p_{p0} are the electron and hole mobility and equilibrium hole concentration in the p-type layer, respectively, B is the bi-molecular radiative recombination coefficient, and δ is the ratio of the electron concentration in the barrier to the electron concentration in the quantum well ($\delta = n_{barrier}/n_{well}$, estimated to be about 10^{-3} to 10^{-4}) [7]. Based on the analytic result given in Equation (1), we can learn that C_{DL}, and thus the efficiency droop, can be reduced by the following measures: (i) lowering δ, (ii) increasing p_{p0}, and (iii) increasing μ_p. Much published research on the efficiency droop can be interpreted and understood by the analytic model. Several research groups reported that the polarization fields in the multi-quantum well (MQW) and electron blocking layer (EBL) enhance δ and thus facilitate electron leakage from the MQW into the p-type region, thereby causing a larger efficiency droop [6,12,13]. In addition, there have been several reports on the lack of hole injection and electron leakage being caused by a much lower concentration and mobility of holes compared to those of electrons, leading the authors to the conclusion that electron leakage contributes to the efficiency droop [14–17]. Furthermore, the onset current density of the efficiency droop, $J_{\text{Onset-of-droop}}$, i.e., the current density where the peak point of the efficiency is found, can be expressed by the electron leakage model as [7]:

$$J_{\text{Onset-of-droop}} = e d_{active} \frac{A_{SRH} B}{C_{DL}} = e d_{active} A_{SRH} \frac{\mu_p p_{p0}}{\delta \mu_n} \quad (2)$$

where A_{SRH}, e, and d_{active} are the Shockley-Read-Hall (SRH) coefficient, the elementary charge, and the thickness of the active region, respectively. Based on the equation, the onset of droop point is expected to shift to a lower current density in LEDs with greater asymmetry in carrier transport, i.e., greater asymmetry in carrier concentration and mobility. Although the analytical electron leakage model provides a useful foundation to explain the phenomenon of efficiency droop, additional experimental data are highly desirable to confirm the model, fully understand efficiency droop, and ultimately overcome the droop.

Here, we investigate the effect of imbalanced carrier concentration and mobility in GaInN-based pn-junction diodes on efficiency droop by comparing GaInN-based green and blue LEDs. Compared with blue LEDs, a higher indium (In) content is required in the MQW active region of green LEDs. It is well known that GaInN MQWs with a high In content become unstable at high epitaxial growth temperatures, because of the high volatility of In and the tendency to form InN clusters [18,19]. To preserve the integrity of the high-In-content GaInN active region, the growth temperature for the subsequently grown p-type GaN layer is lowered for green LEDs. The following characteristics of green LEDs with a p-type GaN layer grown at a lower temperature are noteworthy: First, p-type doping is limited by the lower solubility of magnesium (Mg) in the GaN cladding layer of green LEDs, resulting in a lower equilibrium hole concentration p_{p0} in the p-type layer when compared to blue LEDs [20]. Second, grain boundaries and defects are more abundant for p-type GaN layers grown at lower temperatures, and thus the p-type GaN cladding layer has a poor hole mobility μ_p while the electron concentration n and mobility μ_n in the n-type GaN cladding layer of green LEDs are the same as those in blue LEDs [21]. Therefore, the comparison of green and blue LEDs in this study may contribute to a better understanding of the effect of asymmetry in carrier concentrations and mobilities on the efficiency droop in LEDs.

2. Experiment

Commercially-available high-performance GaInN LEDs used in this study had a chip size of 1.3 mm × 1.3 mm for the blue LEDs (λ = 450 nm) and 1.45 mm × 1.45 mm for the green LEDs (λ = 520 nm). For such a difference in wavelength (450 nm versus 520 nm), the In mole fraction in the quantum wells of the green LEDs was ~22%, i.e., higher than in those of the blue LEDs, ~14%, which was enabled by reducing the growth temperature for the active region and subsequent p-type layers (1050 °C and 950 °C for the blue and green LEDs, respectively). The typical values of hole concentration and mobility were about 1.1×10^{18} cm^{-3} and 16 cm^2/(V·s) in p-type GaN grown at 1050 °C, and 7.5 × 10^{17} cm^{-3} and 8 cm^2/(V·s) in *p*-type GaN grown at 950 °C, respectively [22,23]. Light output-current-voltage (*L-I-V*) characteristics for top-emitting packaged blue and green LEDs were measured at temperatures ranging from 80 to 300 K by using a vacuum chamber probe station equipped with an Agilent B2902 precision source-measurement unit. The light output power was collected by a silicon (Si) photodiode under pulsed current operation (pulse period = 5 ms, duty cycle = 0.5%) in order to minimize self-heating effects.

3. Results and Discussion

Let us consider a material system with strongly-imbalanced carrier mobility, for example, GaInN with $\mu_n > 10\ \mu_p$. The low-level-injection condition is given by $\Delta n_p(0)\mu_n \ll p_{p0}\mu_p$, where $\Delta n_p(0)$ is the injected electron concentration at the edge of the *p*-type neutral layer [7]. LEDs with asymmetric carrier concentration and mobility, especially the green LEDs used in this study, are more prone to enter into the high-level injection regime because of the green LEDs' smaller p_{p0} and μ_p when compared to those of blue LEDs. Assuming an electron concentration of $n = 2 \times 10^{18}$ cm^{-3} and an electron mobility of 150 cm^2/(V·s), which are typical values for conventional n-type GaN [24], allows us to calculate an *n*-to-*p* "asymmetry factor" that can be defined as the ratio of conductivities, σ_n/σ_p. Using the abovementioned hole transport characteristics for epitaxial GaN grown at 1050 °C (blue LEDs) and 950 °C (green LEDs), the asymmetry factor (σ_n/σ_p) has a value of 17.1 for blue LEDs but a value of 50.1 for green LEDs, illustrating the more strongly imbalanced *n*-to-*p* transport characteristics of green LEDs [22]. Figure 1 shows a comparison of the asymmetry of *n*-to-*p* transport characteristics of blue and green LEDs. Inspection of the figure shows that ratios of carrier concentration (*n*/*p*) and mobility (μ_n/μ_p), as well as the resultant asymmetry factor σ_n/σ_p, are subject to asymmetry, all of which are much greater for green LEDs ($\sigma_n/\sigma_p = 50.1$) than for blue LEDs ($\sigma_n/\sigma_p = 17.1$).

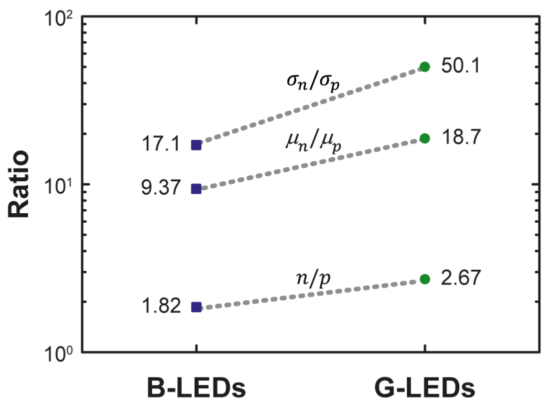

Figure 1. Ratios of carrier concentration (*n*/*p*), mobility (μ_n/μ_p), and resultant conductivity σ_n/σ_p, defined here as the asymmetry factor, of blue and green light-emitting diodes (LEDs), showing an asymmetry in carrier transport characteristics.

Given the greater asymmetry of green LEDs, the onset voltage of high injection is expected to be lower for the green LEDs than that for the blue LEDs. To determine the onset of the high-injection point in the *I-V* characteristic, we determined the point at which the *I-V* characteristics transition from the exponential to the linear regime. Figure 2a shows the d(*Ln(I)*)/d*V* plot converted from the typical *I-V* measurements at room temperature, showing the onset of high injection for 450-nm and 520-nm GaInN-based blue and green LEDs. As can be seen in the d(*Ln(I)*)/d*V* plot, there is a clear transition point from the low injection to the high injection regime [25], and the onset of high injection is observed at a voltage of 2.52 V for the blue LED and 1.91 V for the green LED, which is consistent with the prediction. Under high-level injection, an incremental voltage begins to drop over the *p*-type region (including the EBL), resulting in an electric field building up in the *p*-type region. The electric field will naturally occur in the most resistive part of the *p*-type region, which is the EBL; that is, under high injection conditions, the EBL becomes less effective in blocking electrons. The electron leakage from the active region is exacerbated by the electric field in the *p*-type region [25], and thus the lower onset of high injection in the green LEDs can cause a stronger efficiency droop in the green LEDs than in the blue LEDs.

Figure 2b shows the external quantum efficiency (EQE) as a function of current density for the blue and green LEDs measured at room temperature. The figure is plotted on a log-log scale to show a wider range of currents. The amount of the efficiency droop is 18% for the blue LED and 47% for the green LED. The efficiency droop in the green LED is much larger than that in the blue LED, which is consistent with our expectations. Compared to the blue LED, this larger magnitude of the efficiency droop in the green LED can be understood by the transport properties (i.e., lower p_{p0} and μ_p) of the *p*-type GaN layer that is grown at a lower temperature to preserve the integrity of the GaInN MQW. Note that, according to Equation (1), low p_{p0} and μ_p increase the drift-leakage coefficient C_{DL}, and thus cause a larger droop at high current densities. In addition, the internal polarization electric field in the epitaxial layers is intensified with the necessary increase of indium content in the GaInN well layer of green LEDs. The internal polarization field is known to further increase the electron leakage from the active region [13], which is linked to the value of the δ parameter, $\delta = n_{barrier}/n_{well}$, in Equation (1). Therefore, the green LED may have a larger δ value than the blue LED, resulting in a larger electron leakage. This could further explain as to why the green LED has a more significant efficiency droop than the blue LED.

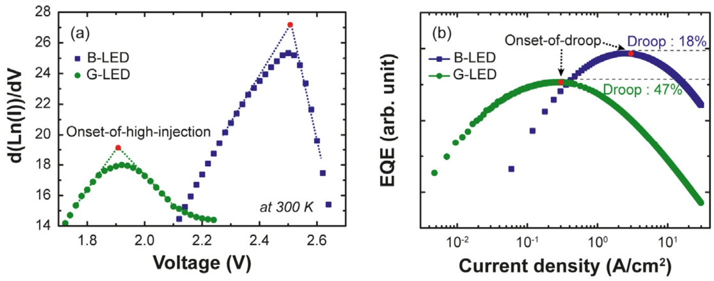

Figure 2. (**a**) The d(*Ln(I)*)/d*V* plot, as determined from the *I-V* characteristics of 450-nm and 520-nm GaInN-based blue and green LEDs, to identify the onset of high injection point which is the transition point from a low injection to a high injection regime in a *pn* junction; (**b**) the external quantum efficiency as a function of current density of 450-nm and 520-nm GaInN-based blue and green LEDs.

It is worthwhile contemplating that the green LEDs may have a lower onset of high injection voltage because they have a smaller bandgap energy compared to the blue LEDs. Considering that the bandgap energy corresponding to the wavelengths of 450 and 520 nm are 2.75 and 2.38 eV for the blue and green LEDs (ΔE_g = 0.37 eV), respectively, the voltage difference of 0.37 V could be assumed as the contribution from the difference in bandgap energy for the difference in the onset of high injection voltages. However, the actually measured difference in the onset of high injection voltages between the green and blue LEDs is 0.61 V, which means that the lower onset of high injection in the green LED cannot be solely explained by the difference in the bandgap energy. Other factors, such as a lower p_{p0} and μ_p in the green LEDs, need to be taken into account to explain the difference.

The imbalanced carrier concentration and mobility have an apparent impact on the onset of the efficiency droop $J_{\text{Onset-of-droop}}$, as indicated in Equation (2). The green LEDs that have lower p_{p0}, μ_p, and a higher δ value than the blue LEDs' counterparts should have not only a larger C_{DL}, but also a lower $J_{\text{Onset-of-droop}}$, according to Equations (1) and (2). The onset of the efficiency droop is observed at current densities of 2.96 A/cm^2 for the blue LED and 0.33 A/cm^2 for the green LED, consistent with our expectation, and with results reported in the technical literature [26–29]. It is worthwhile to note that the green LEDs typically have a higher SRH non-radiative recombination coefficient A_{SRH} than the blue LEDs, because of more defect sites in the epitaxial films caused by the larger lattice mismatch between the GaInN well and GaN barrier [30]. Based on Equation (2), this will shift the $J_{\text{Onset-of-droop}}$ of a green LED to a higher current density. However, in our samples, we found that the $J_{\text{Onset-of-droop}}$ in the green LED is lower than that of the blue LED, indicating that the effect of the asymmetric carrier concentration and mobility in the green LED on the $J_{\text{Onset-of-droop}}$ is stronger than the effect of SRH recombination.

To further validate our arguments and experiments, all data measured from the five blue and five green LED samples were statistically evaluated and treated. The results are shown in Figure 3a–c. All results consistently indicate that the green LEDs, with their more strongly imbalanced carrier concentration and mobility, have a lower voltage of the onset of high injection, a lower current density of the onset of droop, and a more significant magnitude of the efficiency droop as compared to blue LEDs. Note that these distinct differences in the two types of LEDs can be attributed to the difference occurring in the *p*-type layer of the LED epitaxial structure.

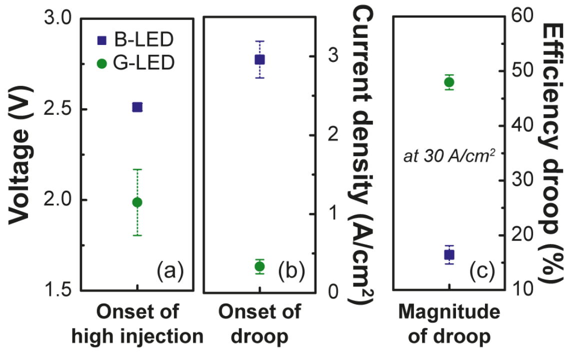

Figure 3. (**a**) The voltage at the onset of high injection for blue and green LEDs; (**b**) the current density at which the peak efficiency is found; and (**c**) the magnitude of efficiency droop at 30 A/cm². The symbols with error bars represent the average values and standard deviations calculated from the five blue and five green LED samples, respectively.

Lastly, to assess the effect of asymmetric carrier concentration on the efficiency droop, the temperature dependence of $J_{\text{Onset-of-droop}}$ was considered. Figure 4 shows $J_{\text{Onset-of-droop}}$ as a function of temperature (from 80 to 300 K) for the blue and green LEDs. A gradual decrease in the $J_{\text{Onset-of-droop}}$ values is clearly shown for both LEDs with the decrease of temperature. The *n*-type and *p*-type dopants, as temperature decreases, cannot be fully ionized because of the insufficient ionization at cryogenic temperatures, called the "freeze-out" of free carriers. The freeze-out of the free carriers in the *n*-type and *p*-type regions has a quite different effect by temperature because the free carrier concentration is determined by the dopant ionization energy. The ionization energy of Mg acceptor used in *p*-type doping ($E_{A,GaN}$ ~170 meV) is much higher than the Si donor ionization energy ($E_{D,GaN}$ ~15 meV) [31–33]. As a result, the asymmetry in carrier concentration is exacerbated at cryogenic temperatures, leading to a decrease in the value of p_{p0} and a decrease in the δ parameter (in Equation (2)) at cryogenic temperatures (the decrease in δ may not be pronounced since it depends on the carrier temperature and not on the lattice temperature). Additionally, the SRH non-radiative recombination coefficient decreases with decreasing temperature [34]. Taken together, the value of $J_{\text{Onset-of-droop}}$ is expected to decrease with decreasing temperature for both types of LEDs, and was further confirmed experimentally, as shown in Figure 4.

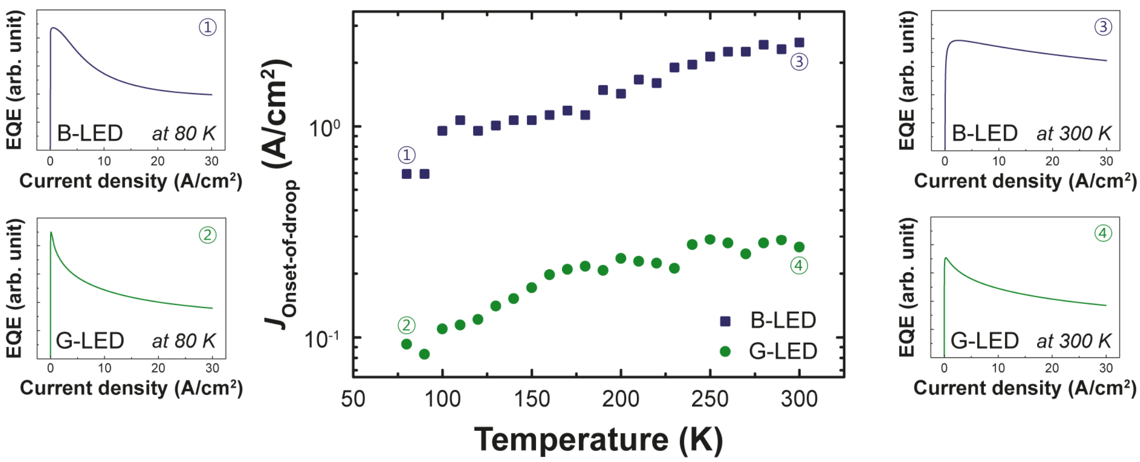

Figure 4. Current density where the efficiency peak is observed as a function of temperature for the blue and green LEDs, and the droop characteristics of blue and green LEDs at room temperature (300 K) and cryogenic temperature (80 K).

4. Conclusions

In conclusion, we compared GaInN-based blue and green LEDs in terms of their *p*-type transport properties, as well as their high-injection and efficiency-droop characteristics, including their temperature dependence. The lower growth temperature for the *p*-type layer typically used to preserve the high-In-content GaInN green-emitting active region results in poor hole mobility and a low equilibrium hole concentration in green LEDs. The *n*-to-*p* asymmetry factor, defined as the ratio of conductivities, σ_n/σ_p, has a value of 17.1 for blue LEDs but a value of 50.1 for green LEDs, illustrating the more strongly imbalanced *n*-to-*p* transport characteristics of green LEDs. We found experimental evidence that the imbalance in carrier concentration and mobility is closely related to the efficiency droop. According to the electron leakage model, the green LEDs, having a greater imbalance in carrier concentration and mobility, are expected to have a lower onset of droop current density, a lower onset of high injection voltage, and a higher magnitude of efficiency droop compared to the blue LEDs. All experimental results were consistent with these expectations, confirming that the efficiency droop and high-injection phenomena can be understood based on the differences in transport characteristics of blue and green LEDs. The findings are consistent with the electron leakage model, thereby providing further confidence that the model can provide useful guidelines for solving the efficiency droop problem and for understanding the effects of high temperature and long operating time on the efficiency of LEDs.

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