Green Light Emitting Diodes under Photon Modulation

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ABSTRACT

With an external laser excitation, the electroluminescence (EL) of GaInN/GaN green light emitting diodes (LEDs) grown on sapphire by metal organic vapor phase epitaxy has been investigated. The EL was found significantly enhanced under this bias and the difference can not merely be attributed to additional photoluminescence (PL). Under 325 nm photon bias, the EL enhancement starts at its highest value and decreases along with an increase of the LED current. Under 408 nm and 488 nm bias, it increases first to a value smaller than that of the 325 nm bias and then decreases with a much lower rate along the current increase. The EL enhancement is attributed to the more efficient carrier injection into quantum wells (QWs) resulting from the screening of the QW polarization by photon bias. Therefore, an enhanced balance of majority and minority carriers was obtained resulting in a better radiative recombination rate. Meanwhile, the current-voltage characteristics show a negative current first and then a voltage reduction as forward voltage increases. The reverse photocurrent indicates carrier loss due to the solar cell effect in our LED device while at high current region the carrier loss is attributed to another effect controlled by the external electrical field. At the balance point of those two effects, the EL enhancement is the highest. These findings clarify the transition from highly efficient radiative recombination at low current density to the region of efficiency droop at high current densities.

INTRODUCTION

Although great improvements have been achieved in GaInN/GaN LEDs, the “green efficiency gap” still remains as a big scientific challenge. Many works have been done about improving the efficiency as well as eliminating the “droop effect” under high current density. Piezoelectric polarization of the QWs is believed to be one of the main reasons of inefficient radiative recombination.\textsuperscript{1} Recently, this problem has partly been solved by growing QWs along non-polar or semi-polar crystal axes.\textsuperscript{2} However, the role that carrier dynamics plays in determining the EL efficiency in the polarized structure still remains unclear. In our experiment, by applying different photon bias, we modulate the QW to different extent. From significant EL enhancements in combination with other results, we find evidence that polarization indeed is one of the reasons of low radiative recombination efficiency. We find that a balance of the majority and minority carriers in QWs is the physical origin of the efficiency maximum at low current densities.
EXPERIMENT

We use two green LEDs in our experiment that share many characteristics with a large set of samples. We use the same samples as in previous studies\(^3\). Sample A (highest external quantum efficiency (EQE) of 5% at RT with EL peak position at 538 nm at 10 mA) and sample C (EQE of 2% with EL peak position at 520 nm at 10 mA) are 300 x 300 \(\mu\)m\(^2\) bare epi dies. Samples A and C are grown under nominally identical conditions: pseudomorphic GaInN/GaN multiple QW structures have been grown by metal organic vapor phase epitaxy (MOVPE) on [0001] plane sapphire substrates using the technique of low temperature deposited buffer layers. A bottom n-GaN layer was doped with Si to a concentration of n\(~1\times10^{19}\)cm\(^{-3}\). Five periods of GaInN/GaN MQWs with well width of 3 nm were grown above. A 0.03 \(\mu\)m p-type AlGaN cladding layer was then grown on top of the quantum wells followed by a 0.2 \(\mu\)m p-doped GaN with Mg concentration of 1x10\(^{19}\) cm\(^{-3}\). At last 5nm Ni/Au contact was evaporated onto the p-type GaN layer and annealed for high spectral transparency. All samples were fabricated and thinned to individual LED dies and mounted on TO-18 headers. Efficiency measurements were performed of the bare mounted die without encapsulation in an integration sphere and a properly scaled spectrophotometer. The different optical and electrical properties of two samples have been studied: Sample C has a higher internal quantum efficiency (IQE) concluded from the temperature dependent PL measurement. In PL spectra, it also shows that sample C has a higher GaN band gap emission than sample A does. The current voltage characteristics show that the p-layer conductivity of C is lower.

Selected wavelengths of a multiline Ar-Ion laser (454 nm to 514 nm), a 408-nm diode laser and a 325-nm HeCd laser were used as sources of photon bias. The power densities are 0.5 kW/cm\(^2\), 3.0 kW/cm\(^2\) and 7.5 kW/cm\(^2\) for the 325-nm, 408-nm and 488-nm laser lines, respectively. The continuous wave laser beams were focused on a circular area of 700 \(\mu\)m\(^2\) (about 1/100 of whole mesa area) at the center of A, C. The EL from the same area with and without bias is analyzed by a grating monochromator and detected by a photomultiplier.

RESULTS

![EL spectra of sample C under photon bias (circle) of 325 nm, 408 nm and 488 nm and dark EL (square) at 0.5 mA. Shown also are the PL spectra (triangle).](image-url)
A significant EL output power enhancement for both samples was observed when simultaneously a photon bias excitation was provided with the laser light. Figure 1 shows the EL spectrum of sample C at 0.5 A without photon bias (labeled dark EL). Also shown are the PL spectra at 325 nm, 408 nm and 488 nm photon bias, and the spectra of simultaneous photo and electro excitation. It is noticed that EL intensity significantly increases to a value that is larger than the sum of PL and dark EL. For sample C, the EL peak intensity increases 145% under 325 nm photon bias, which has the lowest power density, followed by an increase of 58 % under 408 nm photon bias that has the medium power. The 488-nm laser light, which exhibits the highest power density here, only increases EL by about 15 %. For sample A, the EL increases are 25%, 40% and 15% for the three photon bias, respectively. The EL enhancement is found photon wavelength dependent: At 0.5 mA, sample C under 325 nm bias has the highest EL enhancement while for sample A, 408 nm bias has the highest EL enhancement. For sample A, the highest PL signal and EL enhancement is reached under a 408 nm bias. This strongly suggests a correlation between the PL intensity and EL enhancement. We use $I_{EL}$, $I_{PL}$ and $I_{EL, dark}$ to represent the intensity of EL with and without photon bias and the PL. Then the EL enhancement ratio $R$ is calculated by $(I_{EL} - I_{PL}) / I_{EL, dark}$. We calculate the PL efficiency as the PL intensity at RT scaled to that at 7 K. This quantity also is an indicator of the IQE of the device. We found the following correlation: the higher the PL efficiency, the higher is the EL enhancement factor $R$. This result suggests that the EL of samples with higher IQE performance can be more improved under photon bias. However, when the current is decreased, for sample A, $R$ increases rapidly and then is much higher than $R$ under 408 nm bias. We can see more clearly in the following current dependent EL enhancement analysis.

![Figure 2 EL enhancement-ratios as a function of current of sample A (square) and C (circle) under 325 nm, 408 nm and 488 nm photon bias, respectively.](image)

In figure 2, $R$ is plotted as a function of current for the three different bias wavelengths. It is obvious that $R$ under 325 nm bias is always the highest and it decreases rapidly and monotonically to 1 with increasing current. 408 nm photon bias has a smaller $R$ and $R$ under 488 nm bias is the smallest. In addition, $R$ under 408 nm and 488 bias has a different relationship with current. It goes up first and then decreases at a much lower rate towards 1. We define the
current density where $R$ starts to drop as $j(R_{\text{max}})$. Samples A and C behave different in the aspect of $j(R_{\text{max}})$ and so does their absolute EL enhancement. Under 325 nm bias, sample C’s EL gets enhanced 2 times more than that of A while for longer wavelength their maximum $R$ is about the same. Also $j(R_{\text{max}})$ of A is always smaller than that of C.

![Figure 3](image1.png)

**Figure 3** Current-voltage characteristics of sample A under bias of 325 nm (square), 408 nm (circle), 488 nm (up triangle) photon bias and without bias (down triangle).

![Figure 4](image2.png)

**Figure 4** Current density of $R$ maximum $j(R_{\text{max}})$ scales with current density when solar cell effect turns off $j(s)$ for A and C.

This analysis of the EL behavior complemented current-voltage data under photon bias is shown in figure 3. In the low forward current region, the I-V curve was measured in constant voltage mode and negative currents were observed. When increasing the forward voltages, the negative current turns positive and even exceeds the current of the samples in normal operation. At even higher voltages, the photon bias produces a rigid voltage reduction by 10-20 meV when measured in constant current mode. The reverse current is a clear evidence of a solar cell effect.
within the operating LED device. The photocurrent starts to be suppressed when the solar cell effect begins to turn off. Under different photon bias, we observe the photocurrent suppression at a different threshold voltage. The longer the wavelength of the photon bias, the lower the threshold voltage of the solar cell effect. The corresponding threshold current density is named \( j(s) \). We scaled the threshold current density \( j(s) \) properly to the area under illumination and plotted it against \( j(R_{\text{max}}) \) (408 nm and 488 nm bias) in figure 4. It is found that there is a strong correlation between both quantities. \( R \) is the largest when the solar cell effect is just turning off. After this critical point, the \( R \) decrease again due to another effect that we will also address in the following discussion session.

DISCUSSION

By means of the photo-generated carriers, additional minority carriers will be made available in those QWs that are otherwise unbalanced. This not just makes additional PL possible, but also results in a local additional screening of the piezoelectric polarization and its associated local potential barriers. This, in turn, allows the influx of additional minority carriers into QWs from other regions. Radiative recombination will dominate in those QWs where the rate of incoming holes matches the rate of incoming electrons. According to this, if there are more photocarriers, there should be a higher EL enhancement. Our experiments show those results: EL enhancement is higher when PL intensity is higher at shorter wavelength photon bias. EL enhancement is lower at long wavelength and so is the PL intensity.

According to our current-voltage characteristics result, under photon bias, there is a reverse photocurrent flow when the device is operated under small forward voltage. This solar cell effect causes the photocarrier loss at small current region so that \( R \) drops. But under 325 nm bias, instead of a drop, actually a rapid increase of \( R \) is observed. This is due to the compensation of photocarriers generated in the p-type GaN layer. Extra carrier injection overcomes the carrier loss resulting from the solar cell effect. According to our previous PL experiments, sample C has a higher GaN band gap emission. Therefore, it has more photocarriers flowing into the QWs from the p-layer. As a result, its EL enhancement is higher. However, this is not true for a longer wavelength photon bias because photocarriers are generated only in the QWs. As a result, a drop of \( R \) is observed. As forward voltage increases, the enhancement drops again due to the carrier sweeping effect. In this effect the photon generated \( e^- - h^+ \) pairs are broken apart by the large electrical filed. This reduces the overlap of electron and hole wave function. Not being able to recombine fast enough, the separated electrons and holes are more likely to escape the quantum well through thermal activation. From there they are then swept away in the external electrical field and flow to the contacts in opposite directions. This picture is consistent with models ascribing the efficiency droop at higher current densities to a carrier overflow, primarily electron overflow into the p-region. The p-type GaN layer is the first layer to be swept out. Thus a rapid decrease of \( R \) is observed under the 325 nm bias. Under longer wavelength bias, \( R \) decreases due to the sweeping effect, too. At the balance point \( j(R_{\text{max}}) \) of both effects, the concentration of photocarriers in the QWs is at its highest and the maximum in \( R \) is achieved.

It is noticed that the balance points for samples A and C are different. The sample with the poor p-layer conductivity has a higher forward voltage drop across this layer. Therefore, under the same forward voltage, the sweeping effect in QWs in poor p-layer conductivity samples is weaker. As a result, the solar cell effect in sample C is turned off at a higher voltage compared to sample A. Therefore, in our experiment this balance point is reached at a higher voltage (current).
The poor p-layer conductivity of sample C also explains why the IQE of C is higher but its EQE is lower.

CONCLUSIONS

Direct photon injection of extra $e^- - h^+$ pairs into the active region of GaInN/GaN multiple QW green LEDs was demonstrated to enhance the EL efficiency. The effect clearly supersedes the mere addition of a second excitation source. We suggest that photon screening of the polarized QWs lowers the internal potential barriers so that more efficient and uniform carrier injection into QWs is achieved and thus the radiative recombination rate is enhanced. We also find EL enhancement to be highest at conditions where the induced photocurrent is suppressed. The carrier loss due to sweeping effect is found to contribute to the efficiency drop at higher current. The sample with the poor p-layer conductivity has the higher IQE but lower EQE. Its EL is also found to have more room to improve. Based on these results, it seems possible to develop alternate methods to determine the internal quantum efficiencies and ultimately higher efficiency LED devices.

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REFERENCES