Photon modulated electroluminescence of GaInN/GaN multiple quantum well light emitting diodes

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1 Introduction

The efficiency of GaInN light emitting diodes (LED) is often found to decrease at high injection current density. This has been named "efficiency droop". For some of the devices, poor performance is also found under low current. Recently, the limiting factors have been studied intensively. It has been proposed that the droop might be due to an overflow of electrons over the thin quantum wells [1]. Alternatively, it has been suggested that it might be due to a leakage of electrons through the AlGaN electron blocking layer [2]. Here, we report on the direct observation of a modulation of the electroluminescence (EL) of GaInN/GaN green light emitting diodes (LEDs) grown on sapphire by metal organic vapor phase epitaxy. The EL intensity was found to be greatly enhanced under the photon bias. This enhancement strongly supersedes the photoluminescence (PL) signal. The EL enhancement varied with injection carrier density. The relative EL enhancement under 325-nm laser bias starts with a high ratio and decreases monotonically. This increase of the EL intensity is tentatively attributed to a balance between photocarrier screening and carrier drift within the active region. These findings elucidate the transition from highly efficient recombination at low current density to the region of efficiency droop at high current densities.

2 Experimental

In this study, we used two unencapsulated LED die samples: green LED sample A (maximum EQE of 5% at RT with EL peak position at 538 nm @ 10 mA); sample C (maximum EQE of 2% at RT with EL peak position at 520 nm @ 10 mA); Samples A and C are grown under nominally identical conditions but show different optical and electrical properties. C has a higher internal quantum efficiency (IQE) than A, as concluded from the PL intensity variation between 7 K and RT. Sample C also shows the higher GaN band gap emission efficiency of the p-layer in PL. Both samples have been characterized in earlier studies [3-5]. 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~1x10¹⁹ cm⁻³. Five periods of GaInN/GaN MQWs with well width of 3 nm are grown above. A 0.03 µm p-type AlGaN cladding layer was then grown on top of the quantum wells followed by a 0.2 µm p-doped GaN with Mg concentration of 1x10¹⁹ cm⁻³. For comparison, commercial green LEDs provided by Nichia Inc. were studied.

A 325-nm HeCd laser was used as the source of bias excitation. The power density is 0.5 kW/cm². The continuous wave laser beams were focused on an area of 700 µm².
EL from the same area with and without laser is analyzed by a grating monochromator and detected by a photomultiplier.

3 Results All studied samples, including the commercial LEDs, show a boost in their EL output power when a photon bias excitation was provided simultaneously. This effect varies with the wavelength of the photon bias. Figure 1 depicts the EL spectrum of samples A and C at 0.5 mA without bias light (labelled “dark EL”). Also shown are the PL spectra at 325 nm photon excitation, and the spectra of joint photo and electro excitation. We find that the EL intensity significantly increased to a value that exceeds the sum of PL and dark EL. Under 325 nm photon bias, the EL peak intensity of A and C increase about 25% and 145 %, respectively. Apparently, sample C has a higher EL enhancement than A under the same bias condition. Also, sample C has a much stronger PL intensity than A. Meanwhile there is an observable blue shift of EL peak emission with photon bias in C, but not a clear one in A. The strong PL intensity indicates that sample C has a smaller photon carrier loss. In addition, the blue shift shows that the QW structure in C is less polarized. It is hypothesised that this may also lead to the higher EL performance under photon bias.

We use $I_{EL}$, $I_{EL,dark}$ and $I_{PL}$ to represent the intensities 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 found that $R$ of both samples changes along the forward current (Fig. 2). Under 325 nm bias, $R$ decreases monotonically with current from 3.07 and 4.96 to 1 for A and C, respectively. C has a much faster decrease than A. Over the whole tested current region, the poor performance sample C shows a higher EL enhancement than the good performance sample A.

The current-voltage data under photon bias is shown in Fig. 3. In the low forward current region, the I-V curve was measured in constant voltage mode. In this range, negative currents were observed. For higher forward voltages, the negative current turns positive and finally merges into the normal I-V curve at around 0.4 mA. The reverse photocurrent is a clear evidence of a solar cell effect within the operating LED device. Since the solar cell effect is dominant below 0.4 mA and most of the photon carriers are lost due to such effect, there should be a photo carrier injection into the QWs from other regions that produce the large EL enhancement.

4 Discussion In the following, we propose a model that can well describe our observations. At zero forward voltage, photocarriers generated within the wells are separated within the field of the built-in voltage. This appears as a negative LED current and describes the normal operation of a solar cell. However, at the same time, the photocarriers generated in the p-layer will flow into the QW and compensate the carrier loss. 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 from other regions. The radiative recombination will be highest, where the rate of incoming holes matches the rate of incoming electrons. Consequently, an increase in the radiative recombination rate is obtained. If the bias voltage on the LED is increased, the solar cell effect is gradually being suppressed and a forward current becomes dominant. However, photocarriers, both in QWs and in p-layer, are then swept away by the large electrical
field. Even the solar cell induced carrier loss is minimized; the photocarriers will be swept away from the QWs into the contact layers. Such a carrier loss mechanism is accompanied by the observation of a forward current increase. This sweeping effect [6] instead produces a rapid drop in $R$.

From our temperature dependent PL data, we calculate the GaN band edge emission efficiency by scaling the GaN peak intensity at RT to that at 7 K. We found that sample C has a higher p-GaN layer band edge emission than sample A. This indicates a larger quantity of compensating photocarriers generated in p-GaN layer of C than in that of A. On the other hand, the blue shift in EL under bias compared to a negligible shift in sample A indicates that there are actually more photocarriers to screen the piezoelectric QWs in sample C than in sample A. Therefore, the radiative recombination rate in sample C should be even higher.

5 Conclusion A photo injection of additional electron-hole 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 propose that the screening of polarized QWs by photocarriers provides a more uniform distribution of electrically injected carriers within the QWs and so enhances the radiative recombination rate. Photocarriers generated in the p-layer plays an important role in compensating the photocurrent in the small current region. However, at higher current, the sweeping effect introduces a carrier loss and EL enhancement disappears. Based on these results, it seems possible to develop alternate methods to determine the internal quantum efficiency and ultimately to develop higher efficiency LED devices.

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References