Temperature-dependent efficiency droop behaviors of GaN-based green light-emitting diodes*

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(Received 10 September 2012; revised manuscript received 28 September 2012)

The efficiency droop behaviors of GaN-based green light-emitting diodes (LEDs) are studied as a function of temperature from 300 K to 480 K. The overall quantum efficiency of the green LEDs is found to degrade as temperature increases, which is mainly caused by activation of new non-radiative recombination centers within the LED active layer. Meanwhile, the external quantum efficiency of the green LEDs starts to decrease at low injection current level (< 1 A/cm^2) with a temperature-insensitive peak-efficiency-current. In contrast, the peak-efficiency-current of a control GaN-based blue LED shows continuous up-shift at higher temperatures. Around the onset point of efficiency droop, the electroluminescence spectra of the green LEDs also exhibit a monotonic blue-shift of peak energy and a reduction of full width at half maximum as injection current increases. Carrier delocalization is believed to play an important role in causing the efficiency droop in GaN-based green LEDs.

Keywords: GaN, green light-emitting diode, efficiency droop, electroluminescence

PACS: 78.55.Cr, 85.60.Jb, 78.60.Fi **DOI:** 10.1088/1674-1056/22/4/047805

1. Introduction

III-nitride semiconductors have been attracting extensive attention as promising materials for many important applications, especially for solid state lighting.[1,2] One critical technical challenge for realizing high-brightness and high-efficiency GaN-based light-emitting diodes (LEDs) is a phenomenon called "efficiency droop", which refers to a reduction in emission efficiency of the LEDs at relatively high injection current levels.[3,4] Although several mechanisms such as electron overflow,[5] Auger recombination,[6] hole shortage,[7] and carrier delocalization from In-rich regions[8] have been proposed to explain efficiency droop, its underlying physics is still debated and multiple mechanisms might be involved simultaneously.

Meanwhile, GaN-based green LEDs are of particular importance and interest for white light generation and full-color display applications. However, due to the difficulty in growing high-quality high-In content InGaN alloys, the external quantum efficiency of green LEDs is commonly much lower than that of shorter-wavelength GaN-based blue LEDs and longer-wavelength InAlGaP-based red LEDs. In addition, GaN-based green LEDs also suffer from efficiency droop and their efficiency can drop more rapidly than that of blue LEDs as the injection current increases.[9] Although several theoretical and experimental studies[8,10–13] on temperature-dependent electroluminescence (EL) of green LEDs have been reported, until recently there is still very limited literature on how their efficiency droop characteristics evolve under elevated temperature environment, while such a study would be important for both physical understanding and practical applications.

In this report, the efficiency droop behaviors of GaN-based green LEDs are studied as a function of temperature ranging from 300 K to 480 K. It is found that efficiency droop of the green LEDs occurs at a fairly low injection current density (< 1 A/cm^2). As temperature increases, while the overall quantum efficiency (QE) of the green LEDs degrades, their peak-efficiency current is temperature insensitive. Based on rate-equation and EL spectrum analysis, the major mechanisms affecting the efficiency droop characteristics of GaN-based green LEDs are discussed.

2. Experimental details

The LED epi-wafers used in this study are grown on *c*-plane sapphire substrates using metal–organic chemical vapor deposition. The device structure consists of a low temperature GaN buffer layer, a 2.0-μm n-GaN layer (Si $\sim 5\times10^{18}$ cm^{-3}), a seven-period InGaN/GaN multiple-quantum-well (MQW) active layer, a 20-nm p-type AlGaN electron blocking layer,

*Project supported by the State Key Program for Basic Research of China (Grant Nos. 2010CB327504, 2011CB301900, and 2011CB922100), the National Natural Science Foundation of China (Grant Nos. 60825401, 60936004, and 11104130), and the Natural Science Foundation of Jiangsu Province, China (Grant Nos. BK2012110, BK2011556, and BK2011050).

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and a 0.2-μm p-GaN contact layer (Mg $\sim 1\times10^{19}$ cm^{-3}). The nominal indium mole fraction of the InGaN sub-layers is $\sim$ 0.35. Top-emitting LEDs with a chip size of 300 μm×300 μm are fabricated using standard photolithography and dry etch techniques. Annealed Ni/Au and Ti/Al/Ti/Au metal stacks deposited by e-beam evaporation are used as semi-transparent p-contact and n-contact respectively. Meanwhile, 450-nm blue LEDs based on $In_{0.2}Ga_{0.8}N$/GaN MQWs are also fabricated as control samples, which have similar layer structure and chip size as those of the green LEDs.

The electrical characteristics of the LEDs are measured from 300 K to 480 K by using a Keithley 2636 SourceMeter, when the unpackaged LED chip is placed on a hot chuck with controllable testing temperature. The EL spectra and relative output power are measured by using an Ocean Optics (HR4000 CG) Spectrometer as a function of injection current. The inset of Fig. 1 shows a typical room temperature EL spectrum of the green LEDs ($I = 1$ mA). Based on Gaussian fitting, its peak wavelength is $\sim$ 533 nm with a full width at half maximum (FWHM) of $\sim$ 35 nm.

3. Results and discussions

Figure 1 shows the current–voltage (I–V) curves of the green LED measured from 300 K to 480 K. Clearly both the reverse and low-forward-bias leakage currents continuously increase as a function of temperature, which is caused by activation of a new defect-related tunneling component. In low biases (< 2 V) range, the forward I–V relationship can be simply described by $I = I_0(e^{qV/nkT} - 1)$, where the ideality factor n of the LED rises from 2.32 to 2.53 in the same temperature range, which agrees with the enhanced leakage current. Meanwhile, the turn-on voltage (defined at $I = 20$ mA) of the green LED decreases from 3.5 V to 2.75 V as the temperature increases from 300 K to 480 K. The corresponding series resistance of the LED reduces from 15.1 Ω to 10.4 Ω, which must be due largely to the enhanced ionization of Mg dopants within the p-GaN contact layer.[14]

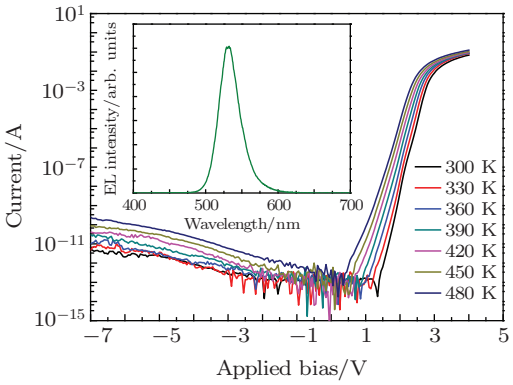


Fig. 1. (color online) Temperature-dependent I–V characteristics of the green LED measured from 300 K to 480 K plotted in semi-log scale. The inset shows a typical room-temperature EL spectrum of the green LED measured at 1 mA.

The relative external quantum efficiency of the green LED is plotted in Fig. 2(a) as a function of injection current at various temperatures. Efficiency droop is observed at a fairly low injection current level of < 0.9 mA. The corresponding current density is < 1 A/cm^2, at which the influence of self-heating effect should be negligible.[8] As temperature increases, the overall quantum efficiency of the green LED drops continuously, while its peak-efficiency current is temperature insensitive. The quantum efficiency degradation at high temperatures must be caused by activation of new non-radiative recombination centers within the active region of the LED.[15] The efficiency droop properties of the control 450-nm blue LED are also measured and shown in Fig. 2(b) for comparison. In contrast, the blue LED has a relatively higher peak-efficiency current (~ 9 mA at 300 K), which shows consistent up-shift at higher temperatures.

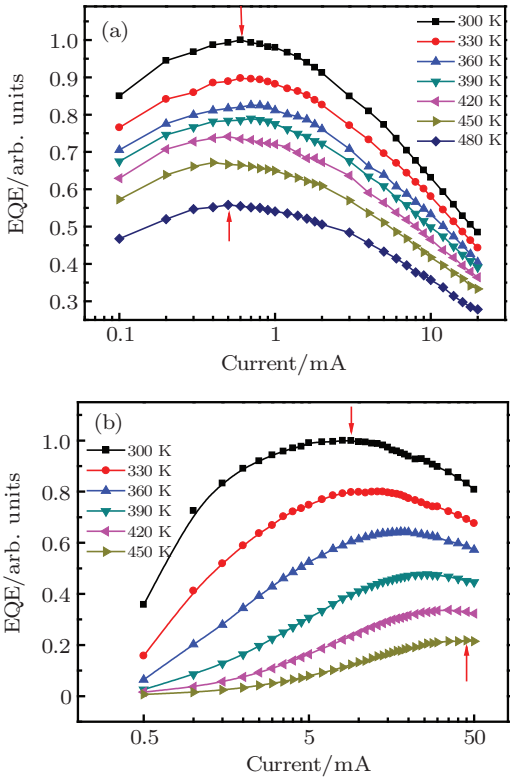


Fig. 2. (color online) External quantum efficiency as a function of injection current at various temperatures: (a) the green LED, and (b) the control blue LED.

For the control blue LED, the increase of its peak-efficiency current at higher temperatures is easily understood and can be explained by the classical rate equation, in which the internal quantum efficiency of a GaN-based LED can be described by:[16]

$$\eta_{\mathrm{IQE}} = \eta_{\mathrm{inj}} \frac{Bn^2}{An + Bn^2 + Cn^m}, \tag{1}$$

where n is carrier density, A and B are non-radiative recombination and radiative recombination coefficients respectively, and Cn^m ($m > 2$) represents a higher-order carrier

loss mechanism, such as Auger recombination and electron overflow.[16,17] In the simplified *ABC* model, coefficients *A*, *B*, and *C* in Eq. (1) are independent of injection current level.[4] Thus, by assuming that the injection efficiency $\eta_{\rm inj}$ would quickly approach unity at high currents, efficiency droop should start to occur at the current density when $\partial\eta_{\rm IQE}/\partial n = 0$, which gives

$$n_{\rm peak} = \left[\frac{A}{C(m-2)}\right]^{1/(m-1)}. \qquad (2)$$

Based on Eq. (2), it is clear that the peak-efficiency current $I_{\rm peak}$ is proportional to the non-radiative recombination coefficient *A*, as numerically $I_{\rm peak}$ would increase as $n_{\rm peak}$ increases. Since non-radiative carrier loss mechanisms, such as Shockley–Read–Hall recombination, are strong functions of temperature in GaN-based LEDs,[15] as is also evidenced by the overall efficiency drop of the LED as temperature increases (Fig. 2), the enhanced coefficient *A* at higher temperature could cause the efficiency droop to occur at higher current.

The above rate-equation analysis could nicely explain the evolution of efficiency droop behaviors of the control blue LED as a function of temperature, but is apparently not accurate enough for the green LED studied in this work. Since activation of non-radiative recombination centers must also happen within the green LEDs at higher temperatures, there must be an additional counteracting mechanism which causes the efficiency droop to happen at lower current levels. Such a mechanism should be highly correlated with the high In-content MQWs of the green LEDs and is not considered by the classical ABC model.

There are two droop-related effects that are clearly stronger for higher In-content MQWs. The first one is the enhancement of the polarization effect (spontaneous and piezoelectric polarizations) within the device structure of green LEDs.[10] The corresponding polarization fields would not only separate electron–hole wave functions and thus lower the radiative recombination rate within the MQWs, but also reduce the effective barrier height of the AlGaN electron blocking layer and then cause severe electron leakage.[3] Nevertheless, until recently, available results commonly suggest that polarization fields in III-nitride semiconductors are not very sensitive to temperature – a conclusion supported by the stable density of two-dimensional electron gas within the AlGaN/GaN heterostructures at various temperatures.[18]

The second effect is the enhanced carrier delocalization and its impact on radiative efficiency at higher temperatures.[8,11] For GaN-based blue and green LEDs, carrier localization in nano-scale In-rich regions plays an important role in enhancing the LEDs' efficiency, which prevents the carriers within the MQWs from escaping to the defective non-radiative recombination centers.[19] As injection current increases, more carriers are released from the localized regions due to the band filling effect and then recombine non-radiatively at defect sites. Such a delocalization effect has been suggested as a possible mechanism causing the efficiency droop.[8,11,20] Meanwhile, increasing temperature could induce a similar delocalization effect through thermal activation of carriers from localized states.[21] Physically, carrier delocalization would happen in both GaN-based blue and green LEDs, but the effect itself and its impact on light-emission efficiency should be stronger in green LEDs. This is because: first, the density of localized states is likely to be higher in higher In-content MQWs, so the corresponding delocalization effect would be more remarkable; second, with increasing In content within the MQWs, the effect of strain and phase separation could severely deteriorate the crystalline quality of InGaN and a large number of misfit defects would form, acting as non-radiative recombination centers. That is, the higher defect density within the active region makes the efficiency of green LEDs more sensitive to carrier delocalization.[11] Therefore, in the studied green LED, the stronger impact of carrier delocalization effect would cause the efficiency droop to occur at lower currents, which counteracts the up-shift of peak-efficiency current caused by the generation of new non-radiative recombination centers at elevated temperatures, leading to a temperature-insensitive droop onset point.

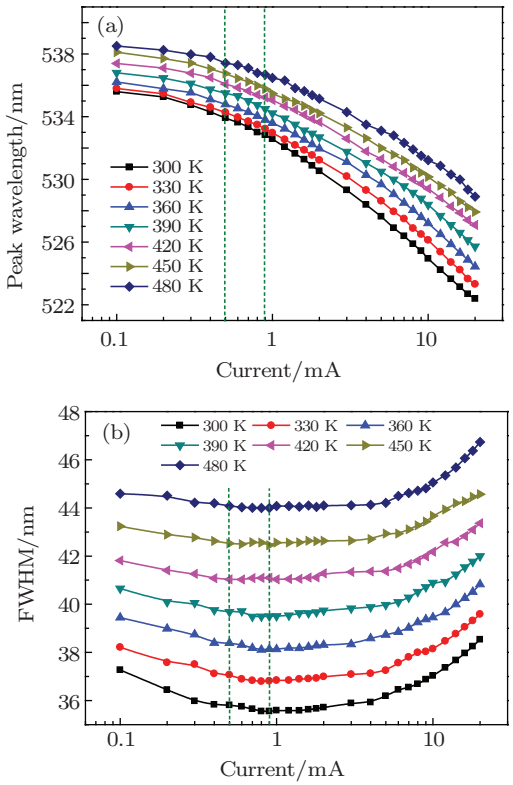


Fig. 3. (color online) (a) The EL peak wavelengths of the green LED as a function of injection current at various temperatures; (b) The FWHMs of the EL spectra as a function of injection current at various temperatures. The pair of green dashed lines in each graph marks the current density range where the peak-efficiency current of the green LED occurs in the studied temperature range.

The strong carrier delocalization effect occurring within the green LEDs is evidenced by EL spectra analysis. As shown in Fig. 3(a), at various temperatures, the efficiency droop is accompanied by a monotonic blue-shift of the EL peak wavelength as the injection current increases. Since at low current levels screening of the polarization field by injected carriers is weak, the blue-shift is mainly attributed to the filling up of localized states within the MQWs. Meanwhile, as temperature increases, the EL peak wavelength shows a bandgap-shrinkage-related red-shift. However, the amount of energy shift from 300 K to 480 K (measured at $I = 0.1$ mA as an example) is $\sim$ 17 meV, which is only half of the theoretical value ($\sim$ 35 meV) calculated from Varshni's formula,[22] further substantiating the thermally-enhanced carrier delocalization process. In addition, as shown in Fig. 3(b), the FWHMs of the EL peak decrease as injection current rises until $\sim$ 1 mA, which is just above the current level of the droop onset points in the studied temperature range. The FWHM reduction could also be explained by the filling up of localized states. Since the localized states within the MQWs normally follow a band-tail-like distribution, those localized states with higher energy must have a higher density of states.[21] Moreover, as the injection current increases further, overflow of carriers from localized states and filling up the normal conduction band would cause an increase of the FWHMs (Fig. 3(b)), which would be accompanied by a drop of the light-emission efficiency.

4. Summary

In summary, the efficiency droop behaviors of GaN-based green LEDs are studied in an elevated temperature environment. The overall QE of the fabricated green LED degrades at higher temperatures, which is mainly caused by the activation of new non-radiative recombination centers within the active region. The green LED exhibits a low peak-efficiency current of less than 1 A/cm^2 which is found to be temperature insensitive, while that of the control blue LED shows an up-shift as temperature rises. Based on rate-equation and EL spectrum analysis, carrier delocalization is believed to play an important role in determining the efficiency droop characteristics of green LEDs.

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