Investigation of Efficiency Droop for InGaN-based LEDs with Carrier Localization State and Polarization Effect

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Abstract

We prepared wavelength-dependent InGaN-based light emitting diodes (LEDs) with peak emissions ranging from 400 to 445 nm, and investigated their efficiency droop characteristics at injection currents of up to 1 A. We found that the emissions of the wavelength-dependent InGaN LEDs underwent blue shifts at elevated currents. In addition, although the external quantum efficiencies (EQEs) changed dramatically when the critical current was less than 350 mA, the efficiency droop of each device exhibited a similar negative slope upon increasing the current from 350 mA to 1 A. Whereas the effects of piezoelectric polarization and different localized states in the active layer of the near-UV–to–blue LEDs influenced the peak EQEs and the dramatic decays of the EQE droops at lower injection currents, they were not responsible for the EQE droops at higher current levels. In addition, the piezoelectric effect and Auger non-radiative recombination were not dominating influences determining the efficiency droops of the wavelength-dependent LEDs at higher carrier densities.

INTRODUCTION

Gallium nitride (GaN)–based light-emitting diodes (LEDs) operate with several attractive features, including long lifetimes, low energy consumption, high durability, design flexibility, and ecological friendliness. As a result, they are promising candidates for use in solid-state lighting to replace traditional incandescent (containing toxic mercury) and fluorescent (relatively low energy efficiency) light sources. Outdoor and indoor lighting applications require high operation currents—typically greater than 350 mA and in some cases greater than 1 A. Notably, however, high-power LEDs exhibit unsatisfactory efficiency at high injection currents, with the efficiency further declining monotonically upon increasing the current density—a well-established phenomenon known as "efficiency droop." Many physical mechanisms have been proposed to explain this behavior, including Auger recombination [1], current roll-off [2], carrier delocalization [3-5], and the effects of the carrier injection rate, [6-8] and polarization field [9-10]. Nevertheless, the main principle behind the efficiency droop remains unknown because of the complicated nature of the efficiency droop process. In addition, substantially different wavelength-dependent droop effects have been noted in InGaN-based LEDs [5, 11]. Accordingly, higher peak levels and lower droop decays have been observed in short-wavelength LEDs (near-UV region), with lower peak levels and severe droops in long-wavelength LEDs (green region) Green LEDs have suffered, however, from poor crystal quality in the active layer, due to their relatively low growth temperatures. In addition, at higher indium contents, the effects of strain and indium phase separation tend to deteriorate the crystal quality. UV LEDs, on the other hand, are strongly affected by threading dislocations (TDs), such that the entire external quantum efficiency (EQE) might suddenly deteriorate because of remarkable degrees of nonradiative recombination. Therefore, it remains difficult to objectively determine the dominant phenomena affecting the efficiency droops in such systems.

In this paper, we demonstrate the wavelength-dependent droop effects of InGaN-based LEDs emitting in the range from 400 to 445 nm (but not for green-region LEDs—the behavior of which is related to crystal quality issues). From EQE measurements performed while elevating the current density, herein we attempt to realize the leading effects on the efficiency droops in InGaN-based LEDs.

EXPERIMENT

All the InGaN/GaN multiple quantum well (MQW) LEDs were grown on (0001) sapphire substrates using an atmospheric-pressure metalorganic chemical vapor deposition (AP-MOCVD) system. Prior to growth, the substrate was heated at 1180 °C in H_2 ambient to remove any surface contaminants. A 25-nm-thick low-temperature GaN nucleation layer, a 1-μm-thick undoped GaN buffer layer, and a 3-μm-thick n-GaN layer, using SiH_4 as the n-type dopant, were then deposited. Next, wavelength-dependent InGaN/GaN active layers with emitting peaks at 401.6, 408.7, 419.5, 426.8, 432.4, and 443.4 nm under 350 mA (chip size: 1 × 1 mm^2) were fabricated by adjusted the TMI (Trimethylindium) flow rate. Note that, to ensure consistent crystal quality, different growth temperatures were not employed to tune the emitting wavelength of the LEDs. Subsequently, a 20-nm-thick p-AlGaN electron blocking layer (EBL) and a

100-nm-thick p-GaN layer, using Cp_2Mg as the p-type dopant, were deposited. LEDs having dimensions of 1 × 1 mm^2 were formed using conventional photolithography.

The electrical characteristics of the wavelength-dependant LEDs were examined through electroluminescence (EL) measurements using an Agilent B1500A semiconductor parameter analyzer. The output power and center wavelength shift were measured using an integrated sphere detector. To determine the effect of current on the EQE, pulsed mode measurement was employed to avoid thermally induced degradation of the LED output power. For pulsed measurement, a pulse width of 1 ms and a duty cycle of 0.1% were used with a maximum injection current of up to 1 A.

RESULTS and DISSCUSSIONS

To investigate the wavelength-dependent droop effects, we measured the EQEs upon increasing the current with pulse operation (Fig. 1). To systematically analyze the wavelength-dependent droop effects, we separated the EQE droop effects into two regions: one where the peak EQE begins to roll off at a certain current and the other where the EQE characteristics have a negative slope with respect to the increase in current. At emission wavelengths of 401.6, 408.7, 419.5, 426.8, 432.4, and 443.4 nm, the peak efficiencies reached 22, 27, 27.5, 29, 30, and 30%, respectively. In addition, the peak efficiency shifts toward lower current and EQE were also enhanced upon increasing the emission wavelength over the range from 0 to 200 mA. This phenomenon is presumably related to two dominant mechanisms: the localized state and the variation in the internal piezoelectric polarization upon changing the indium content. The localization effect increased dramatically upon increasing the indium content in the active layer [12], exhibiting a trend similar to those previously found experimentally [5, 11] and theoretically [13]. Although a localization effect induced by a higher indium content would prevent nonradiative recombination from TD defects at lower currents, the delocalization effect was revealed by band-filling upon increasing the current, with the EQE beginning to decay spectacularly as a result of the participation of severe nonradiative recombination. In contrast, because the short-wavelength LED featured a less-localized state from the onset, we did not expect the delocalization effect to occur upon increasing the current; therefore, the EQE of the short-wavelength LED rose monotonically under a lower current. On the other hand, we expected the higher indium content of the longer-wavelength LED to result in a strong internal field across the MQWs, naturally inducing a quantum-confined Stark effect (QCSE); this behavior is well established as causing red-shifts of the QW energy and decreases in electron/hole wave function overlap, meaning that a radiative recombination decline could be expected for the longer emission wavelength. From simulations, Chen et al. [13] proposed a relatively uniform electron/hole concentration distribution in short-wavelength LEDs in

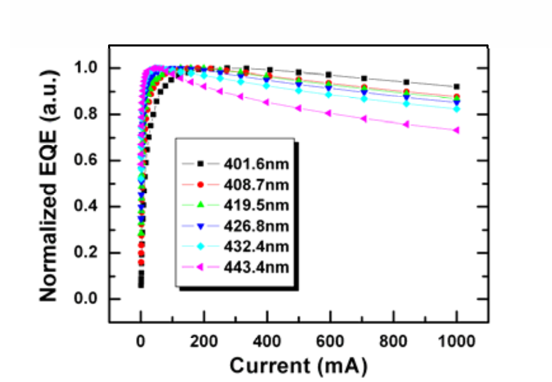

Fig.1. External quantum efficiency with wavelength dependent LEDs as a function of forward current.

addition to a higher-magnitude radiative recombination rate in low-indium-content LEDs, due to the lower piezoelectric field. This phenomenon might be another reason for the lack of a droop effect for the short-wavelength LED under lower current levels. Although the EQE–*I* curve of the shortest-wavelength LED was quite flat, the total EQE deteriorated dramatically over the whole current level because of sensitive nonradiative recombination with the TDs [3] and the lower barrier potential height in the MQWs.

Figure 2 presents the relative center wavelength shifts of the LEDs plotted with respect to the forward current. The 443.4 nm LED featured the largest blue-shift, by almost 10 nm, upon increasing the forward current to 1 A; the total blue-shift decreased upon decreasing the LED wavelength. This behavior resulted from (i) screening of the piezoelectric field in the MQWs by the injected carriers, leading to blue-shifts of emission peaks, and (ii) carriers filling up to a higher energy level upon increasing the current density (the so-called "band-filling effect"). In contrast, the peak shift for the 401.6 nm LED was quite stable over the entire current range, consistent with its lowest internal piezoelectric field and lowest potential barrier height. We used the equation

$$EQE(\%) = \frac{P}{I \times Eg} = \frac{P}{I \times \frac{1240}{\lambda}} = \frac{P \times \lambda}{I \times 1240}, \quad (1)$$

where P is the output power and E_g is the energy bandgap, to further determine the characteristics of the droop effect. We found that the percentage EQE was proportional to λ, meaning that the variation in EQE would be affected by the shift in λ, which might also contribute to the EQE droop. Although, for example, the 443.4 nm LED underwent the largest blue-shift, from 436.2 to 445.3 nm, upon increasing the forward current from 5 to 1000 mA, in percentage terms this wavelength shift varied by only 2%. That is, the ratio of the change in the forward current to the change in the wavelength shift was approximately 10,000, indicating that the change in the wavelength shift played a minor role in the variation of the EQE. Although the wavelength shift did

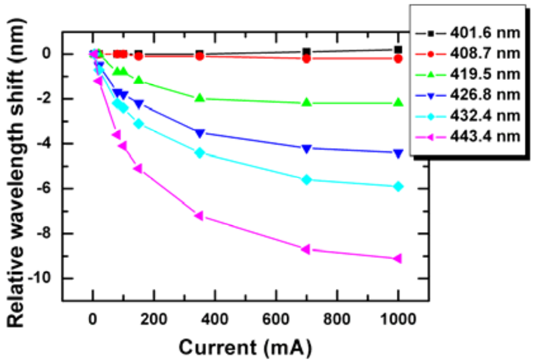

Fig. 2. Relative wavelength shift with wavelength dependent LEDs as a function of forward current.

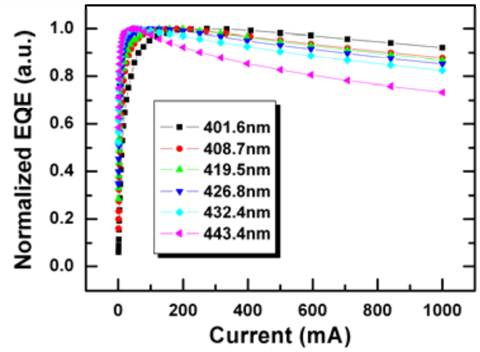

Fig. 3. Normalized external quantum efficiency with wavelength dependent LEDs as a function of forward current.

not appear to influence the droop effect of the LEDs, it does strongly impact the stability of the color temperature of white-light LEDs in practical usage at different current levels. To further investigate the characteristics of the wavelength-dependant droop effect, Fig. 3 presents the normalized EQEs of the InGaN/GaN LEDs with different emission wavelengths, plotted with respect to the forward current. Again, the EQEs varied significantly upon increasing the current from 5 to 350 mA, but each featured an EQE droop with a similar negative slope upon increasing the current thereafter (i.e., from 350 to 1000 mA). It seems that the two suggested mechanisms—the internal polarization effect in the MQWs and the carrier delocalization from the In-rich region—were not the dominant factors affecting the EQE decay at higher currents (350–1000 mA), although they were the cause of the EQE behavior at lower currents (5–350 mA). In Fig. 3, the blue-shifts became stable when the forward current exceeded 350 mA, suggesting that the screening and band-filling effects were almost saturated. Further increases in the injected current would lead to carrier overflow for all the samples. Even though the highest-indium-content LED had the highest potential barrier height, the high indium content induced a polarization effect that tilted the energy band of the QW, thereby decreasing the effective barrier height. Therefore, the carrier confinement ability remained weak, even in the higher-indium-content LEDs. Another potential mechanism explaining the efficiency droop is Auger recombination, because the Auger nonradiative recombination rate is proportional to Cn^3 (where C is the Auger recombination coefficient and n is the carrier density), meaning that the influence of the Auger process will increase upon increasing the injection current and become dominant at high currents [14, 15]. In addition, simulation data [13] has suggested that the Auger recombination rate would increase upon increasing the indium content, with the EQE droop becoming worse in higher-indium-content LEDs under high current injection. We found, however, that the droop rates were alike in the different-emission-wavelength LEDs under high current injection (>350 mA; Fig. 3). Accordingly, we suggest that Auger recombination was not the dominant factor affecting the wavelength-dependant efficiency droops under high current densities in the emission region from the near-UV to blue.

CONCLUSIONS

In summary, the characteristics of the wavelength-dependant efficiency droops in the emission range from 400 to 445 nm were significantly different for currents of less than 350 mA. According to our experimental findings, the variation in the localization effect upon changing the indium composition was the dominant factor affecting the peak EQE and the saturated EQE at a certain current. Consequently, the delocalization and polarization effects would lead to distinctive rates of decay of the efficiency droop from the peak EQE at currents of less than 350 mA. We also investigated the efficiency droops under high current injection (>350 mA); we found, however, that the slopes of the efficiency droops for the various systems were similarly negative upon increasing the current from 350 to 1000 mA. This behavior revealed that the effects of carrier delocalization and built-in internal polarization might not have been the main contributors to the wavelength-dependant efficiency droops at high currents. In terms of Auger recombination, if the Auger coefficient were to vary with respect to the indium content, then we would expect the EQE droops under high currents to be different for each of the LEDs. Because our findings were inconsistent with this hypothesis, we suggest that Auger recombination was also not the main cause of the wavelength-dependant efficiency droops under high current densities. We conclude that the most likely impact on EQE behavior occurs at low currents—not at high current injection—in the emission regions for InGaN-based near-UV–to–blue LEDs. In addition, objective discussions of the efficiency droop issue require the study of LEDs with similar emission wavelengths—to avoid the natural changes in the efficiency characteristics upon varying the emission wavelengths of the LEDs.

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