Electronic Materials Letters, Vol. 6, No. 2 (2010), pp. 51-53
DOI: 10.3365/eml.2010.06.051 Published 30 June 2010

Characteristics of Blue and Ultraviolet Light-Emitting Diodes with Current Density and Temperature

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Temperature and injection-current dependencies of radiant flux from blue and ultraviolet GaInN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) were investigated. Experimental results indicate that, compared to blue LEDs, the radiative efficiency of ultraviolet LEDs is relatively insensitive to injection current. It is expected that shallow potential minima caused by indium fluctuation in high-indium-containing GaInN quantum wells for blue LEDs result in a high radiative efficiency at low injection currents due to the localization of carriers; however, the radiative efficiency decreases rapidly with increasing injection current due to the delocalization of carriers.

Keywords: light-emitting diodes, efficiency droop, carrier localization

The wavelength of GaInN-based light-emitting diodes (LEDs) can be very broad, from the ultraviolet-A (UV-A) to the red spectrum region, by varying the In mole fraction. Thus, there has been huge interest in improving the performance of GaInN-based LEDs for solid-state lighting and full-color displays.[1,2] Although there has been remarkable progress in performance, maintenance of radiant efficiency at high current density and high junction temperature remains a pressing issue in the LED community.[3] It has been reported that there are distinct differences in device performance between relatively high-In-containing green and blue LEDs and UV LEDs with relatively low In compositions, even though other epi layers are identical.[4] While the internal electric field and crystal quality are directly influenced by the In composition in the active region, the effects of the radiant flux from GaInN LEDs on junction temperature and current density with various In compositions have not been studied intensively.

In this study, we have investigated temperature and injection-current dependencies of radiant flux from blue and ultraviolet GaInN/GaN multiple quantum well (MQW) LEDs. A near-UV LED (400 nm) and a blue LED (460 nm) were grown on a c-plane sapphire substrate, processed into devices, and their radiant flux was measured as a function of temperature and injection current. Our experiment shows that the effect of potential minima of indium is dominant in the case of the blue LED, but small in the case of the UV LED, resulting in a distinct difference in radiative efficiency behavior with increasing temperature and injection current.

The epitaxial LED wafers used in this study were grown on (0001) sapphire substrates by metalorganic vapor phase epitaxy. The two fabricated LED structures consist of a 5 μm Si-doped *n*-type GaN layer, five pairs of $Ga_{1-x}In_xN$/GaN MQWs, a 50 nm Mg-doped $Al_{0.2}Ga_{0.8}N$ cladding layer, and a 0.1 μm Mg-doped *p*-type GaN layer, respectively. The In mole fraction (x) for the blue LED is 0.15 and that for the 460 nm UV LED is 0.08. A standard LED fabrication process was used; *p*-type GaN was partially etched to form mesas with an area of 1×1 mm^2 by using an inductively coupled plasma etching system after thermal activation of *p*-type GaN. Ti/Al and reflective Ag ohmic contacts were deposited on the exposed *n*-type GaN and the untouched *p*-type GaN mesas, respectively. Finally, a 0.2 μm thick SiO_2 layer was deposited to protect the mesa sidewalls from unintentional leakage. The LEDs were then flip-bonded on silicon submounts and attached to metal-based packages by using die and wire bonding processes after a chip-isolation process. Characteristics of the radiant flux were measured using a calibrated spectrophotometer with an integrating sphere, a digital source meter, and a pulsed current source.

Figure 1 shows the relative radiant flux as a function of

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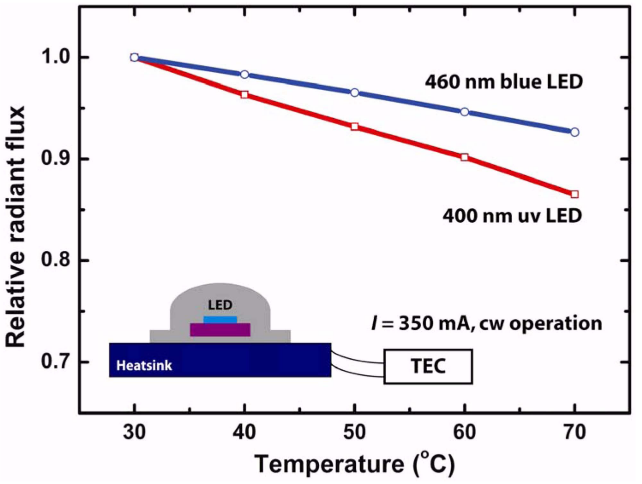

Fig. 1. Radiant flux of GaInN LEDs as a function of heatsink temperature at 350 mA current injection.

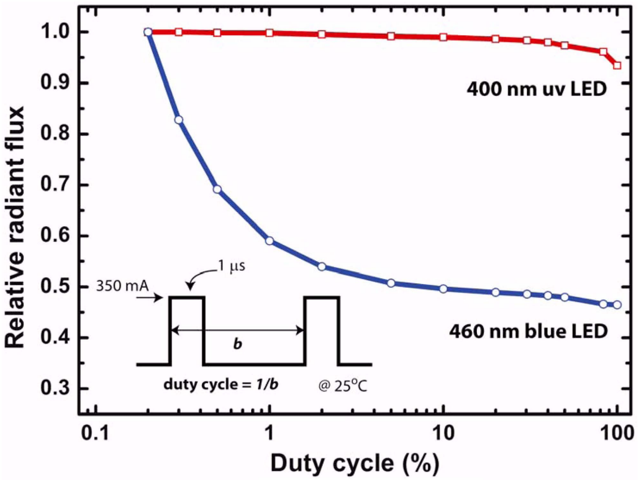

Fig. 2. Radiant flux of GaInN LEDs as a function of duty cycle of injection current.

heatsink temperature at 350 mA continuous wave (*cw*) current injection. With increasing temperature, the radiant flux of both LEDs gradually decreases. However, the radiant flux of the UV LED decreases much more rapidly than that of the blue LED. For example, at a heatsink temperature of 70°C, the radiant flux of the UV LED decreases by approximately 14%, while that of the blue LED decreases by only 7%. The slopes in Fig. 1 are -1.8×10^{-3} /K for the blue LED and -3.3×10^{-3} /K for the UV LED, and the experimentally determined values of the characteristic temperature (T_0) were 551 K for the blue LED and 277 K for the UV LED. The T_0 value for the blue LED is comparable with that of a reported value, 493 K.[4] The small T_0 of the UV LED suggests that radiant flux is strongly influenced by temperature. Differences in T_0 between the UV and blue LEDs can be explained in terms of the differences in the quantum band structure. Since the GaN barrier in the MQW active region and the Mg-doped $Al_{0.2}Ga_{0.8}N$ cladding layer are identical for both LEDs, the band offset for the UV LED is shallower than that for the blue LED. Therefore, carrier overflow to a *p*-type GaN occurs more readily in the UV LED than in the blue LED, and hence relatively rapid reduction of radiant flux is expected for the UV LED with increasing temperature. This result seems reasonable given that the injected current was 350 mA *cw*; thus the current density could screen out band bending caused by the internal electric field, which could also account for the temperature-dependency when the injection current is relative low.

Figure 2 shows the radiant flux as a function of the duty cycle of the injection current. The pulse width was 1 μs and the current was 350 mA at room temperature. To vary the duty cycle from 0.2% to 100%, only the duration time (*b*) was changed; therefore, only the frequency was affected. In contrast to the effect of temperature dependency, the blue LED shows a rapid reduction with increasing duty cycle while the UV LED shows only a minor change in radiant flux up to a duty cycle of 100%. It should be noted that the decrease in radiant flux of the blue LED is very steep at low duty cycles. This might stem from the blue LED having an "abnormally high" efficiency at the low current injection regime. The high efficiency at low injection current is caused by localized carriers in shallow potential minima, which are formed by fluctuation in the In mole fraction in the MQW active region of typical blue LEDs.[6,7]

Shallow minima prevent carriers from being captured in nonradiative recombination centers, such as vacancies and threading dislocations. Therefore, the radiative efficiency of the blue LED in particular exhibits low sensitivity to the presence of high density defects at low injection currents. However, when the injection current is increased, the localized carriers in potential minima will be delocalized and free to move to nonradiative recombination centers, causing a steep decrease in the radiant flux. On the other hand, the radiant flux from the UV LED, which has relative low In composition and thus less potential minima by In fluctuation, is relatively insensitive to the injection current density.

Figure 3 shows typical radiant efficiency versus current curves for both LEDs. A gradual decrease in the radiant efficiency occurs with increasing current density, a phenomenon known as efficiency droop.[8] Note that the efficiency droop of the blue LEDs is much more severe than that of the UV LED. A similar dependency to that observed for the blue and UV LEDs was also reported by Yamada *et al.*[9] for low-flux LEDs. In Fig. 3, abnormally high efficiency of the blue LED is also apparent below a current of 0.1 A. In fact, because of the high efficiency of the blue LED at low current density, its efficiency droop is quite drastic compared to that of the UV LED. Moreover, because the internal polarization field is higher for the blue LED than for the UV LED, carrier leakage toward a *p*-type GaN would be more severe in the

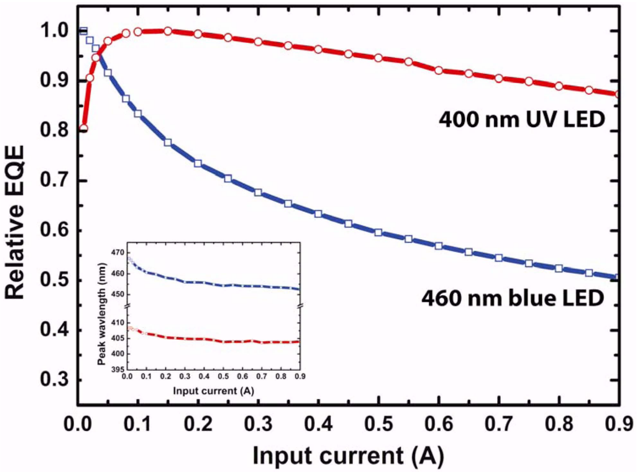

Fig. 3. Radiant efficiency of GaInN LEDs as a function of injection current. Inset shows change in peak wavelength of LEDs.

former with increasing current. The inset of Fig. 3 shows the electroluminescence (EL) peak wavelength of the blue and UV LEDs as a function of the injection current. As the injection current increases, the peak wavelength shift toward a shorter wavelength for the blue LED is much more apparent than that for the UV LED. The magnitude of the peak shift is the sum of the band filling of the potential minima through Indium fluctuation and the internal electric field caused by the quantum confinement Stark effect. The peak emission wavelengths in the blue device are 467 nm at 10 mA and 452 nm at 0.9 A. The differences in the EL peak are as large as 14 nm. However, the EL peak shift for the UV LED is only 4 nm for the same current interval, thus indicating that the band-filling effect is clearly suppressed and/or the internal electric field is less than that for the blue LED.

In summary, temperature and injection-current dependencies of radiant flux from 460 nm blue and 400 UV LEDs were compared. The radiant efficiency of the blue LED shows a steep decrease with current density. Although shallow potential minima from In fluctuation are beneficial for high efficiency at low injection currents, the benefit is lost with increasing injection current, resulting in a large efficiency droop. However, the radiant efficiency of the UV LED is less sensitive to injection current as a result of having fewer shallow potential minima than the blue LED.

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