2009

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APPLIED PHYSICS LETTERS **95**, 121107 (2009)

Efficiency retention at high current injection levels in *m*-plane InGaN light emitting diodes

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(Received 13 August 2009; accepted 2 September 2009; published online 22 September 2009)

We investigated the internal quantum efficiency (IQE) and the relative external quantum efficiency (EQE) of *m*-plane InGaN light emitting diodes (LEDs) grown on *m*-plane freestanding GaN emitting at ~400 nm for current densities up to 2500 A/cm^2. IQE values extracted from intensity and temperature dependent photoluminescence measurements were consistently higher, by some 30%, for the *m*-plane LEDs than for reference *c*-plane LEDs having the same structure, e.g., 80% versus 60% at an injected steady-state carrier concentration of 1.2×10^{18} cm^{-3}. With increasing current injection up to 2500 A/cm^2, the maximum EQE is nearly retained in *m*-plane LEDs, whereas *c*-plane LEDs exhibit approximately 25% droop. The negligible droop in *m*-plane LEDs is consistent with the reported enhanced hole carrier concentration and light holes in *m*-plane orientation, thereby enhanced hole transport throughout the active region, and lack of polarization induced field. A high quantum efficiency and in particular its retention at high injection levels bode well for *m*-plane LEDs as candidates for general lighting applications. © *2009 American Institute of Physics*. [doi:10.1063/1.3236538]

Nitride-based light emitting diodes (LEDs) have become the centerpiece in the debate for general lighting applications owing to significant advances in part due to advanced growth and packaging technologies. The major research activities and production have so far focused on the wurtzite *c*-plane variety, which is polar. Spontaneous and strain-induced piezoelectric polarizations inherent to *c*-plane introduces additional constraints to device designs, such as limiting the width of active region quantum wells to mitigate reduction in electron-hole overlap and injection level dependent emission wavelength.[1,2] When combined with poor hole concentrations and mobility and the related electron leakage, the quantum efficiency of *c*-plane GaN-based LEDs is adversely affected which manifests itself as efficiency degradation at high injection levels.[3,4] In contrast, for general lighting applications, demands for high quantum efficiency and more importantly its retention at high injection levels are continuously increasing. Retention of the quantum efficiency depends on not only the carrier spillover but also the nonradiative Auger recombination if present, the latter of which becomes increasingly notable at high injection levels. The use of nonpolar *m*-plane orientation is expected to alleviate at least some of these impediments, once again owing to the absence of polarization fields, reduced hole effective mass (supporting higher hole concentrations), and predicted large optical matrix elements.[5–7] The aforementioned features increase the radiative recombination rate as well as mitigating hole distribution throughout the active region. In this letter, we present internal and relative external quantum efficiency measurements on *m*-plane and *c*-plane InGaN LEDs on freestanding GaN, revealing higher efficiency and its nearly full retention at high injection in the *m*-plane variety.

Both *m*-plane and *c*-plane LED structures were grown on freestanding GaN in a vertical low-pressure metalorganic chemical vapor deposition system. They are composed of six period 2 nm $In_{0.14}Ga_{0.86}N$ quantum wells with 12 nm $In_{0.01}Ga_{0.99}N$ barriers, and a 60 nm Si-doped (2×10^{18} cm^{-3}) $In_{0.01}Ga_{0.99}N$ underlayer just beneath the active region for improved quality. A ~10 nm *p*-$Al_{0.15}Ga_{0.85}N$ electron blocking layer was deposited on top of the active quantum well region. The Mg-doped *p*-GaN layer that followed is about 100 nm thick having 7×10^{17} cm^{-3} hole concentration for the *c*-plane variety, as determined by Hall measurements on a calibration sample, which is expected to be higher for the *m*-plane orientation due to lighter hole effective mass for the same Mg chemical content. Due to the fact that the *m*-plane LED sample is extremely small, we did not perform Hall measurements. Further details and the schematic of the LED structures can be found in Ref. 8. After mesa (250 μm diameter) etching, Ti/Al/Ni/Au (30/100/40/50 nm) metallization annealed at 800 °C for 60 s was used for *n*-type ohmic contacts and 5/5 nm Ni/Au contacts were used for the semitransparent *p*-contacts. Finally, 30/50 nm Ni/Au contact pads were deposited on the top of part of the mesa. The 500 μm thick *m*-plane freestanding GaN templates, produced at Kyma Technologies, Inc. by using hydride vapor phase epitaxy growth along *c*-direction, followed by slicing perpendicular to the surface, have a threading dislocation density of $< 5 \times 10^6$ cm^{-2} and are off-cut by 0.2° toward the GaN *a*-axis and 0.3° toward the GaN *c*-axis. The *c*-plane freestanding GaN is around 250 μm thick.

Photoluminescence (PL) measured using a frequency doubled Ti:Sapphire laser and electroluminescence (EL) from both the *m*-plane and the *c*-plane LEDs peaked at ~400 nm. Figure 1 shows the room temperature internal quantum efficiency (IQE) values of an *m*-plane LED sample versus the induced carrier concentration measured from reso-

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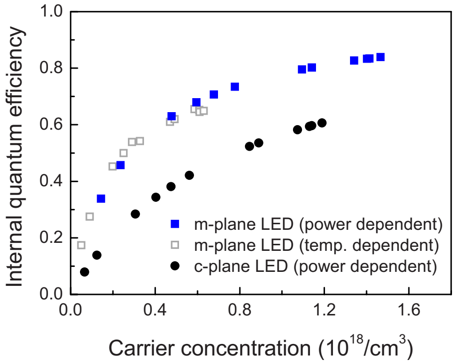

FIG. 1. (Color online) IQE values determined from power-dependent PL and also temperature-dependent PL measurements for the *m*-plane and *c*-plane LEDs. For the calculation of carrier concentrations, the *B* value was assumed to be 1×10^{-11} cm^3 s^{-1}.

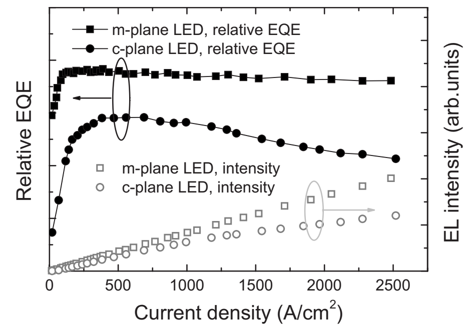

FIG. 3. Relative external quantum efficiency and integrated EL intensity of the *m*-plane LED on freestanding GaN and the reference LED on *c*-plane bulk GaN as a function of pulsed injection current density (0.1% duty cycle and 1 kHz frequency). Both samples have the same device structure (MQW active region with 2 nm $In_{0.14}Ga_{0.86}N$ quantum wells, 12 nm $In_{0.01}Ga_{0.99}N$ barriers, and *p*-$Al_{0.15}Ga_{0.85}N$ electron blocking layers).

nant PL measurements using both excitation power dependence[9] and temperature dependence.[10] The excitation wavelength from the frequency doubled Ti:sapphire laser was set to 370 nm, below the bandgap of the $In_{0.01}Ga_{0.99}N$ quantum barriers. Therefore, the photoexcited electron-hole pairs were generated only within the quantum wells, thereby avoiding optical carrier generation in the barriers and also nonuniform carrier injection into the active region which has been observed to cause efficiency droop in EL.[11,12] At relatively high carrier concentrations, the IQE values of the *m*-plane LEDs are ~30% higher than those of their *c*-plane counterparts (80% and 60%, respectively, at a carrier concentration of 1.2×10^{18} cm^{-3}). For confirmation, we also determined the IQE values of the *m*-plane LEDs from temperature-dependent PL at various excitation densities, where IQE at low temperature (e.g., 15 K in our case) was assumed to be 100%.[10] The IQE values extracted as such were nearly identical to those obtained from the excitation density dependence, e.g., 66% versus 68% at a carrier concentration of 1.2×10^{17} cm^{-3}. The carrier densities used for the temperature dependent PL were obtained from the intensity-dependent PL measurements at room temperature.

The *m*-plane LEDs were confirmed to exhibit polarized EL due to the in-plane polarization anisotropy in *m*-plane, which is further enhanced by large valence band splitting induced by the anisotropic biaxial strain within the quantum wells.[13,14] Figure 2 shows the EL intensity of an *m*-plane LED as a function of the polarization analyzer angle, where

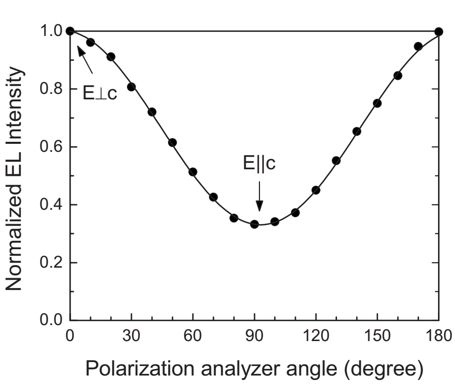

FIG. 2. EL intensity as a function of the polarizer angle of the *m*-plane LED sample grown bulk *m*-plane GaN. The polarizer angles of 0° correspond to the $E\perp c$ and the polarizer angles of 90° correspond to the $E\parallel c$. The solid line is a guide to the eye.

0° corresponds to polarization perpendicular to the *c*-axis. As can be seen the electric field component of the EL is mainly polarized in the GaN *m*-plane and perpendicular to the GaN *c*-axis. The polarization degree is $\rho=(I_{\perp c}-I_{\parallel c})/(I_{\perp c}+I_{\parallel c})=0.48$, where $I_{\perp c}$ and $I_{\parallel c}$ correspond to intensities for polarization perpendicular and parallel to the *c*-axis, respectively. This value is comparable to that reported in Ref. 15 (~0.43) for the same emission wavelength (~400 nm) and the same wafer configuration (on-wafer measurement without dicing, no sidewall polishing to reduce light scattering) employed here. The degree of polarization has been reported to increase with increasing emission wavelength,[15] which is attributed to increased valence-band splitting caused by larger compressive strain in quantum wells (QWs) with increasing In composition.[16]

On-wafer pulsed EL measurements (0.1% duty cycle, 1 kHz) were carried out for both *m*-plane and *c*-plane LED samples to determine the external quantum efficiency (EQE) without any special treatment to enhance light extraction, assuring the same extraction efficiency from sample to sample during measurements. The relative EQE values of the two representative LEDs of different crystal orientation are shown in Fig. 3. The *m*-plane LED shows negligible droop, i.e., almost full retention of its efficiency for a current density up to 2500 A cm^{-2}; specifically only 5% degradation as compared to ~25% for that on *c*-plane freestanding GaN having the same structure. This observation is consistent with the premise of relatively higher hole concentration and smaller hole effective mass expected in *m*-plane that would favor the transport of holes throughout the active region and reduce the electron spill over (or overflow) and thereby mitigate the efficiency droop.[12] Furthermore, as also evident from Fig. 3, at relatively lower injection levels the relative EQE for the *m*-plane LED increases more rapidly than that for the *c*-plane LED, reaching its peak value at ~140 A cm^{-2} compared to ~400 A cm^{-2} for the *c*-plane LED, which is indicative of a relatively small Shockley–Reed–Hall nonradiative recombination coefficient for the *m*-plane variety. Among several devices tested for both orientations, *m*-plane LED EQE values are consistently higher by ~35% and even higher at higher injection levels due to better efficiency retention than those of *c*-plane LEDs, which is consistent with the results obtained from the intensity dependent PL measurements. The variation from device to device for each orientation was less than 10%. Experiments on *m*-plane LEDs with longer emission wavelengths (450 nm and larger) are in progress with preliminary data indicating IQE values comparable to those reported here for *m*-plane LEDs emitting at 400 nm and will be discussed in a future paper.

In conclusion, the IQE values deduced from intensity dependent PL measurements for the *m*-plane LEDs are approximately 30% higher than those for the *c*-plane LEDs of the same structure. EL measurements at various injection levels also revealed more than 35% higher EQE for the *m*-plane LEDs than *c*-plane LEDs, a factor which increased with injection. More importantly, the high EQE was retained in *m*-plane LEDs at high injection levels up to 2500 $\mathrm{A\ cm^{-2}}$ (only 5% droop). The LEDs on *c*-plane freestanding GaN exhibited ~25% droop within the same current injection range. The observations are consistent with the predicted increased optical matrix elements and improved hole concentration/transport in *m*-plane orientation, and absence of polarization. Determination of the exact mechanism requires detailed further investigations.

The work at VCU is funded by a grant from the National Science Foundation (No. 0725506) and partial support by ARO under Phase II Contract No. W911NF-07-C-0099 for nonpolar bulk development at Kyma Technologies, Inc., is acknowledged. H.M. would like to thank Dr. C. Tran of SemiLEDs for useful discussions.

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