2008

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Xie, J., Ni, X., Fan, Q., et al. On the efficiency droop in InGaN multiple quantum well blue light emitting diodes and its reduction with p-doped quantum well barriers. Applied Physics Letters, 93, 121107 (2008). Copyright © 2008 AIP Publishing LLC.

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APPLIED PHYSICS LETTERS **93**, 121107 (2008)

On the efficiency droop in InGaN multiple quantum well blue light emitting diodes and its reduction with *p*-doped quantum well barriers

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(Received 16 July 2008; accepted 29 August 2008; published online 23 September 2008)

Multiple quantum well (MQW) InGaN light emitting diodes with and without electron blocking layers, with relatively small and large barriers, with and without *p*-type doping in the MQW region emitting at ~420 nm were used to determine the genesis of efficiency droop observed at injection levels of approximately $\geqslant 50\ A/cm^2$. Pulsed electroluminescence measurements, to avoid heating effects, revealed that the efficiency peak occurs at $\sim 900\ A/cm^2$ current density for the Mg-doped barrier, near $550\ A/cm^2$ for the lightly doped *n*-GaN injection layer, meant to bring the electron injection level closer to that of holes, and below $220\ A/cm^2$ for the undoped InGaN barrier cases. For samples with GaN barriers (larger band discontinuity) or without *p*-AlGaN electron blocking layers the droop occurred at much lower current densities ($\leqslant 110\ A/cm^2$). In contrast, photoluminescence measurements revealed no efficiency droop for optical carrier generation rates corresponding to the maximum current density employed in pulsed injection measurements. All the data are consistent with heavy effective mass of holes, low hole injection efficiency (due to relatively lower *p*-doping) leading to severe electron leakage being responsible for efficiency droop. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2988324]

Although InGaN based light emitting diodes (LEDs) have been commercialized for indoor and outdoor lighting and displays they suffer from reduction in efficiency at high injection current levels which has been dubbed as the "efficiency droop."[1] The external quantum efficiency (EQE) reaches its peak at current densities as low as $50\ A/cm^2$ and monotonically decreases with further increase in current.[2] It is imperative that LEDs produce high luminous flux which necessitates high efficiency at high current densities. Contrary to what may appear at an instant glance, dislocations have been shown to reduce the overall efficiency but not affect the efficiency droop.[3] Other mechanisms, such as "current rollover,"[4] carrier injection efficiency,[5] and polarization field,[6] have also been proposed, but the genesis of the efficiency droop is still the topic of an active debate. Although Auger recombination was proposed for the efficiency droop,[7] the Auger losses in such a wide bandgap semiconductor are expected to be very small,[8] which has also been verified using fully microscopic many body models.[9] In addition, if an inherent process such as Auger recombination were solely responsible for the efficiency degradation, this would have undoubtedly prevented laser action, which requires high injection levels, in InGaN which is not the case.

The efficiency droop was also noted to be related to the quantum well (QW) thickness in the form of peak efficiency shifting to higher injection currents with increasing well thickness.[10] It was suggested that the effect of polarization field may be playing a role.[10] The observations, however, are consistent with large effective mass of holes because of which it is very likely that only the first QW next to the *p*-barrier substantially contributes to radiative recombination. Making the well wider, therefore, increases the emission intensity providing that the layer quality can be maintained. It has also been suggested that in wider QWs the carrier density is reduced for the same injection level and thus reduced Auger recombination.[11] What is very revealing is that in below barrier photoexcitation experiments (photons absorbed only in the QWs), where carriers are excited and recombined in the QWs only, the efficiency droop was not observed at carrier generation rates comparable to electrical injection (confirmed in our experiments as well) which indicates that efficiency droop is related to the carrier injection, transport, and leakage processes.[6]

The relatively low hole transport through barriers caused by large hole effective mass and low hole injection caused by relatively low hole concentration adversely affect the efficiency at high injection levels. As a remedy, embedding the *p*-InGaN QW active layer into the *p*-(Al)GaN region has been proposed.[5] However, there is no experimental report incorporating this concept as yet, most likely due to Mg doping acting as luminance "killer" and resulting in very low quantum efficiency.

In the present work, we doped only the barriers to circumvent the detrimental effect of Mg in the wells, and therefore, holes are supplied to the QWs without injection and transport being the sole supplier. For comparison we also investigated undoped InGaN and GaN barriers. The latter, owing to its larger barrier height, accentuates the detrimental effect of the large hole mass. For a comprehensive analysis, the effects of the electron blocking layer (EBL) and the doping level of the *n*-GaN electron injection layer have also been explored.

The InGaN/(In)GaN multiple QW (MQW) LED samples, emitting at ~410–420 nm, were grown on (0001) sapphire substrates in a vertical low-pressure metal-organic chemical vapor deposition system. Trimethylgallium, trimethylaluminum, trimethylindium, silane (SiH_4), Cp_2Mg, and ammonia (NH_3) were used as sources for Ga, Al, In, Si, Mg, and N, respectively. The GaN templates having $\sim 2 \times 10^8\ cm^{-2}$ dislocation density prepared with *in situ* SiN_x served as templates for this study.[12] The schematic of the

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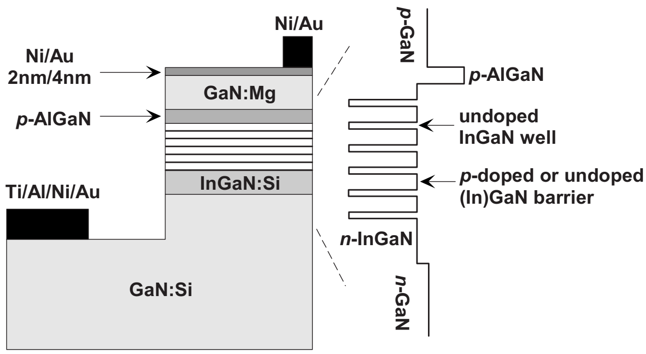

FIG. 1. Schematic of LED structures investigated. In all the samples, the 2 nm InGaN QWs were undoped, and the 12 nm (In)GaN barriers were either left undoped, or *p*-doped with Mg. An ~10 nm *p*-AlGaN was also included as an electron barrier in all the samples. The peak of EL spectrum is at ~420 nm.

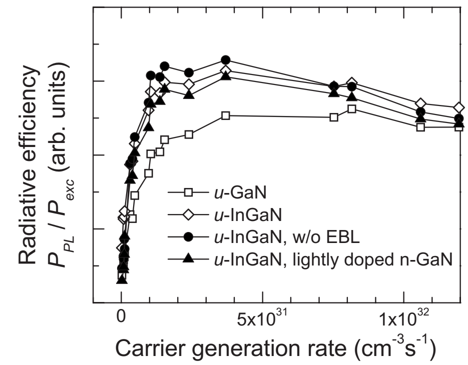

FIG. 2. Radiative efficiency, integrated PL intensity (P_{PL}) divided by the excitation density (P_{exc}) of the MQW active regions of the LED structures vs the optical carrier generation rate for the samples with undoped barriers.

typical LED structures used is shown in Fig. 1. The top layers of the templates are 1-μm-thick *n*-GaN with 2×10^{18} cm^{-3} doping (5×10^{17} cm^{-3} in one of the samples, see below). The active regions in all samples are composed of six 2-nm-thick undoped $In_{0.20}Ga_{0.80}N$ QWs separated by 12-nm-thick barriers grown on ~60-nm-thick Si-doped (~2×10^{18} cm^{-3}) $In_{0.01}Ga_{0.99}N$ interlayer (compliance layer) used for strain relaxation. An ~10 nm *p*-$Al_{0.15}Ga_{0.85}N$ electron barrier layer was incorporated on top of the active region. The *p*-GaN layer that followed is about 120 nm thick with 8×10^{17} cm^{-3} doping, which was determined by Hall measurements on a calibration sample. The barriers were either undoped GaN (*u*-GaN), undoped $In_{0.01}Ga_{0.99}N$ (*u*-InGaN), or Mg-doped (~5×10^{17} cm^{-3}) $In_{0.01}Ga_{0.99}N$ (*p*-InGaN) to help delineate the genesis of efficiency degradation. Having *p*-doped QWs would be ideal but the degradation of luminescence with Mg doping necessitated doping the barriers only. Furthermore, two additional samples, one with undoped $In_{0.01}Ga_{0.99}N$ barriers but without the EBL (*u*-InGaN w/o EBL), and the other with $In_{0.01}Ga_{0.99}N$ barriers and the EBL but with lightly doped (5×10^{17} cm^{-3}) *n*-GaN and compliance layers (*u*-InGaN, *LD*-*n*-GaN), were prepared. The thicknesses of the QWs were determined by high resolution x-ray diffraction with the aid of satellite peaks up to fourth order. After mesa (250 μm diameter) etching, Ti/Al/Ni/Au (30/100/30/30 nm) metallization annealed at 850 °C for 30 s was used for *n*-Ohmic contacts, and 2 nm/4 nm Ni/Au contacts annealed in air ambient (550 °C 15 min) were used for the semitransparent *p*-contacts. Finally, 30/30 nm Ni/Au contact pads were deposited on part of the top of the mesa (although with opacity).

In order to determine whether the efficiency droop has its genesis in Auger recombination or carrier leakage, the radiative conversion efficiency was measured with a frequency doubled 80 MHz repetition rate Ti:sapphire laser with 100 fs pulses tuned to 385 nm, below the GaN band edge. Absorption saturation was not observed even at the highest excitation density used (1.1 kW/cm^2), as the percent transmission did not change when the incident intensity was reduced by an order of magnitude. As shown in Fig. 2 no efficiency droop was observed for any of the samples with undoped barriers up to 0.34 kW/cm^2 excitation density, which corresponds to a carrier generation rate of 3.7×10^{31} cm^{-3} s^{-1} that is more than four orders of magnitude higher than the maximum electrical injection rate employed here and the optical generation rates used by Kim *et al.*[6] The decrease above this excitation density is partially related to heating effects. Since the generation and recombination of electron-hole pairs in this excitation condition (385 nm) takes place in the wells only, the electron/hole injection process is bypassed and not involved. At the maximum excitation density employed (1.1 kW/cm^2) the carrier density was estimated to be about 10^{19} cm^{-3}, which is much higher than the injection levels in LEDs.

The electroluminescence (EL) spectra of the LEDs were measured using a pulsed current source with 1% duty cycle and 1 kHz frequency to eliminate the heating effect. To further minimize heating, the sample was mounted on a heat sink with fan cooling, and nitrogen gas was blown directly at the sample surface during measurements. Light was collected by an optical fiber placed above the diode and connected to a computer controlled spectrometer equipped with a charge coupled device detector. The integrated EL intensity versus injection current density, together with the calculated EQE for all the five samples under investigation is plotted in Fig. 3.

When the barrier is undoped GaN, the EQE reaches its peak at only ~35 A/cm^2 [Fig. 3(a)], and decreases at higher injection currents as reported in literature.[13] However, when undoped InGaN barriers are used instead, the saturation current density increased to as high as 220 A/cm^2, as shown in Fig. 3(b). This is consistent with impeded hole transport model and subsequent electron leakage as GaN presents a relatively larger barrier height compared to InGaN. As mentioned before, the increase in QW width is also expected to have a similar effect, as the main contribution to the optical emission is from the first QW next to the *p*-type region. In fact, Li *et al.*[10] reported a shift of EQE peak position from 5 A/cm^2 to over 200 A/cm^2, but with a trade-off for the IQE, by widening QWs from 0.6 to 1.5 nm while keeping the barrier thickness fixed. This observation, not the interpretation, is actually consistent with the report by Gardner *et al.*[11] in which case EQE reached its peak above 200 A/cm^2 when the MQW active layer was replaced by a double heterostructure with a 13 nm InGaN layer. This was, however, interpreted by authors as avoiding/minimizing Auger recombination by reducing the carrier density in the wells.[11]

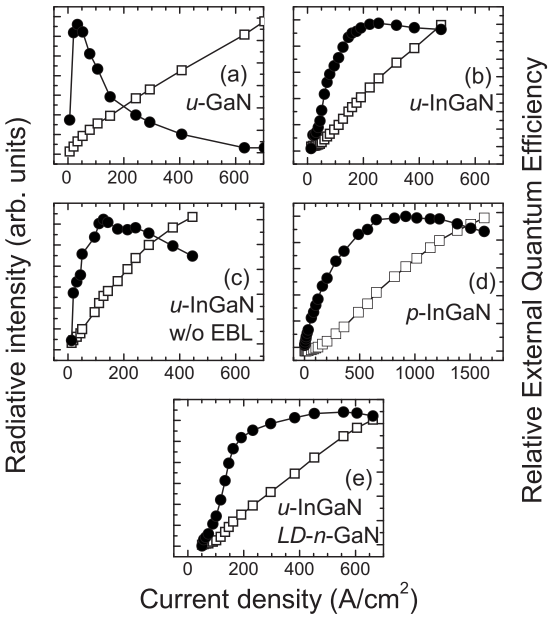

FIG. 3. Integrated EL intensity (open squares) and relative EQE (solid circles) vs injection current density measured under pulsed conditions (1% duty cycle, 1 KHz) for LED structures with (a) undoped GaN barriers, (b) undoped InGaN barriers, (c) undoped InGaN barriers and without the EBL, (d) with Mg-doped *p*-InGaN barriers, and (e) undoped InGaN barriers and lightly doped *n*-GaN (LD-*n*-GaN) layer. The shift of EQE peaks to higher current densities with the inclusion of an EBL or *p*-InGaN barriers or LD-*n*-GaN layer supports the argument that electron leakage is the cause for efficiency droop.

Furthermore, for the samples with undoped InGaN barriers, when the EBL was removed, the EQE peak was observed at a lower current density ($\sim 110\ \mathrm{A/cm^2}$), as seen from Fig. 3(c), due to increased electron leakage. On the other hand, in our sample with the *p*-doped barriers, the efficiency droop occurs above $900\ \mathrm{A/cm^2}$ [Fig. 3(d)], which is more than four times higher than that for the double heterostructure in Ref. 11. It should be noted that despite the pulsed measurements and pushing of the efficiency peak to higher currents, the droop is still affected by heating since a redshift (not shown) of the EL peak position beyond $900\ \mathrm{A/cm^2}$ is observed. Practically, the best structure to alleviate hole transport through barriers is to have no barriers in the MQW region and replace the wells with one *p*-InGaN layer. However, Mg that is required adversely affects radiative recombination. Even when only the barriers are doped with Mg, expected Mg diffusion into the wells reduces the efficiency in our sample with *p*-InGaN barriers.

The hole impediment model can be tested further by reducing the doping level in the *n*-GaN electron injection layer below the active region, while keeping the doping level in the top *p*-GaN layer at the same high level. In this case the injected electron concentration in the active region can be lowered to be closer to that of the injected holes, reducing the limiting factor of hole transport and consequent electron leakage. In fact, doing so increased the current at which the peak efficiency occurs near $550\ \mathrm{A/cm^2}$, as shown in Fig. 3(e).

In summary, we have investigated the genesis of efficiency droop in InGaN based LEDs. The results presented, that there is no efficiency drop with increased optical excitation in photoluminescence (PL) experiments at carrier generation rates much higher than that can be achieved by electrical injection and that the current at which efficiency droop increases with use of *p*-doped barrier or a lightly doped *n*-GaN electron injection layer, are indicative of the fact that hole transport impediment and consequent electron leakage is most likely the cause of the droop phenomenon. The cumulative results tabulated in Table I show that *p*-doping InGaN barriers or reducing the doping in the *n*-GaN below the QW region increase the current density where the peak efficiency occurs to 900 and $550\ \mathrm{A/cm^2}$, respectively, when compared to $220\ \mathrm{A/cm^2}$ for samples with undoped InGaN barriers. Further impeding hole transport with higher GaN barriers reduces the current where efficiency peaks to a dismal $35\ \mathrm{A/cm^2}$. Additionally, inclusion of an EBL is essential regardless of the structure and was observed to increase the current density at which the EQE peaks due to reduced electron leakage. Combination of electrical injection experiments in structures designed to interrogate hole transport and PL experiments provides sufficient evidence that droop in InGaN MQW LEDs is due to heavy effective mass of holes which impedes hole transport in MQW and consequent electron leakage. Therefore providing holes in addition to injection, favoring hole injection over electron injection, and providing an EBL all increase the current where the efficiency begins to droop.

TABLE I. Tabulation of current density at which efficiency peaks for various structures investigated.

Barrier	Doping in *n*-GaN injection layer ($\mathrm{cm^{-3}}$)	EBL	Peak efficiency current density ($\mathrm{A/cm^2}$)
Undoped GaN	2×10^{18}	Yes	35
Undoped InGaN	2×10^{18}	Yes	220
Undoped InGaN	2×10^{18}	No	110
Undoped InGaN	5×10^{17}	Yes	550
p-type InGaN	2×10^{18}	Yes	900

This work was funded by a grant from the Air Force Office of Scientific Research (Dr. Kitt Reinhardt and Dr. Don Silversmith). Very useful discussions with Dr. C. Tran of SemiLEDs and help from Mr. J. H. Leach for *p*-type Ohmic contact optimization are greatly appreciated.

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