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InGaN staircase electron injector for reduction of electron overflow in InGaN light emitting diodes

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Ballistic and quasiballistic electron transport across the active InGaN layer are shown to be responsible for electron overflow and electroluminescence efficiency droop at high current levels in InGaN light emitting diodes both experimentally and by first-order calculations. An InGaN staircase electron injector with step-like increased In composition, an "*electron cooler*," is proposed for an enhanced thermalization of the injected hot electrons to reduce the overflow and mitigate the efficiency droop. The experimental data show that the staircase electron injector results in essentially the same electroluminescence performance for the diodes with and without an electron blocking layer, confirming substantial electron thermalization. On the other hand, if no InGaN staircase electron injector is employed, the diodes without the electron blocking layer have shown significantly lower (three to five times) electroluminescence intensity than the diodes with the blocking layer. These results demonstrate a feasible method for the elimination of electron overflow across the active region, and therefore, the efficiency droop in InGaN light emitting diodes. *© 2010 American Institute of Physics*. [doi:10.1063/1.3465658]

InGaN light emitting diodes (LEDs) are destined to become a key component of the lighting technology owing to significant improvements in their efficiencies. However, they still exhibit peak external quantum efficiency (EQE) at current densities as low as 50 A/cm^2 and a monotonic decrease thereafter even under short pulsed operation.[1] This loss of electroluminescence (EL) efficiency at high injection currents, the genesis of which is still controversial, should be understood and solved before InGaN LEDs could be widely used in general lighting. Auger nonradiative recombination has been proposed to explain the efficiency loss.[2–4] However, there is a large discrepancy (some six orders of magnitude) among the reported Auger recombination coefficient for InGaN layers,[2,4–7] and unreasonably large Auger coefficients, in the range of 10^{-27}–10^{-24} $cm^6\ s^{-1}$, were needed for fitting the EL efficiency data from commercial LEDs considering loss due only to Auger recombination.[5] These results imply that Auger recombination alone (if any) is not enough to explain the EL efficiency loss. Also not consistent with the Auger model is the fact that in below-the-barrier resonant photo excitation experiments (photons absorbed only in the InGaN active region with ensuing generation of equal number of electrons and holes), the efficiency loss has not been observed at carrier photogeneration rates comparable to if not beyond the electrical injection level. This indicates that the loss under discussion is more likely related to the carrier injection, transport, and leakage processes.[8,9]

Our previous experiments show that electron overflow (or spillover) results in a substantial EL efficiency loss, by 70%–80% more, for LEDs in both polar c-plane and nonpolar m-plane orientations when no electron blocking layer (EBL) is employed.[10] Simple calculations indicate that electron density in equilibrium with the lattice even at unreasonably high junction temperatures and injection currents would not support sufficiently high thermionic emission to account for the notable carrier spillover due to large barrier height.[11] Therefore, a nonequilibrium process must be considered to explain the electron leakage problem, such as that reported by Ni *et al.*[12] In this realm, upon injection from the n-GaN layer into the InGaN active region the electrons gain additional kinetic energy equal to the conduction band offset between n-GaN and InGaN. These "*hot electrons*" either lose their excess energy through scattering with longitudinal optical (LO) phonons or avoid thermalization. The thermalized electrons participate in radiative or nonradiative recombination processes in the active region,[13] while the rest of the electrons can cross the active region and leave it for the p-GaN layer if they undergo either no scattering (ballistic transport) or only a few scattering events (quasiballistic transport). In order to reduce the electron overflow-induced loss of efficiency, the injected hot electrons need to be sufficiently thermalized, or "cooled," before being captured by the InGaN active region for recombination with the injected holes (the latter are heavier, and therefore, are thermalized easier). The present work shows that an InGaN staircase electron injector (SEI), which has step-like increased In composition and used as an "*electron cooler*," helps to eliminate the overflow current due to ballistic and quasiballistic electrons for efficiency retention at high injection without the need for an EBL, which would somewhat impede the hole injection due to the valence band offset between the EBL and p-GaN ($\sim$0.08 eV for the case of EBL with 15% Al).

The LED structures investigated in this work were grown on $\sim$500 μm-thick freestanding *m*-plane $(1\bar{1}00)$ GaN substrates (sliced from boules grown in the c-direction at Kyma Technologies, Inc. with dislocation density $<5\times10^6$ cm^{-2}) in a vertical low-pressure metalorganic chemical vapor deposition system. Two investigated m-plane

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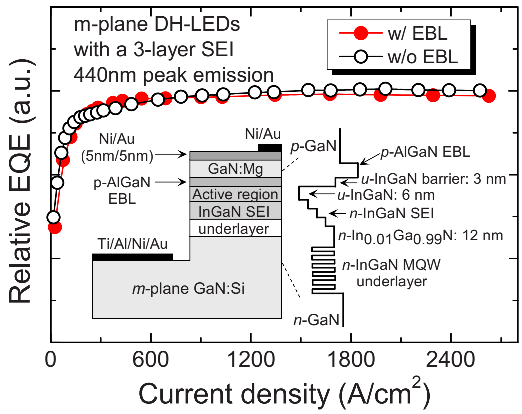

FIG. 1. (Color online) Relative EQE of two m-plane LEDs grown on free-standing m-plane $(1\bar{1}00)$ GaN substrates with a three-layer SEI: one with and one without the EBL. The inset shows the schematic for the LED with a 10 nm EBL (p-$Al_{0.15}Ga_{0.85}N$).

InGaN LEDs, one with and one without a 10 nm p-$Al_{0.15}Ga_{0.85}N$ EBL next to the p-GaN layer, have undoped 6 nm $In_{0.2}Ga_{0.8}N$ active regions followed by a 3 nm undoped $In_{0.01}Ga_{0.99}N$ barrier (Fig. 1). Both LEDs incorporate an InGaN SEI consisting of three 5 nm InGaN layers (three-layer SEI) with In compositions of 3%, 6%, and 10%, in the given order, inserted before the InGaN active region (Fig. 1). The steps having potential energy drop by more than one LO phonon energy contribute to electron thermalization through electron-LO-phonon interaction. For mechanical reasons the first two SEI layers were grown with small In composition difference, and therefore, act as a single step for electron cooling. A six-period $In_{0.01}Ga_{0.99}N$(7 nm)/$In_{0.06}Ga_{0.94}N$(3 nm) multiple quantum well underlayer was employed before the InGaN SEI to improve the active layer material quality. The underlayer and the SEI were n-type doped with Si to an electron density of 2×10^{18} cm^{-3}. The final Mg-doped *p*-GaN layer was about 100 nm thick with a nominal hole density of 7×10^{17} cm^{-3}. The LED devices were fabricated as 250 μm mesas with 30/100/40/50nm Ti/Al/Ni/Au n-type contacts and 5/5 nm Ni/Au p-type contacts, with 30/50 nm Ni/Au contact pads deposited on parts of the mesa tops.[10] EL measurements were performed under pulsed current (1 μs, 0.1% duty cycle) without any special means to enhance light extraction. Both LEDs were found to exhibit the same internal quantum efficiency (50%–55% at 1×10^{18} cm^{-3} carrier density) from excitation power-dependent photoluminescence measurements[14] assuming a radiative recombination coefficient of $B=1\times10^{-11}$ cm^3 s^{-1}.

Figure 1 shows that the relative EQE values of the two m-plane LEDs with the SEI, one with and the other without the EBL, are essentially the same for the same current injection levels. This is substantially different from what we have observed in LEDs without the SEI, where the EL intensity from the LED without an EBL is 20%–30% of that from the LED with the EBL.[10] It is, therefore, reasonable to suggest that the InGaN SEI either reduces or eliminates the electron overflow by efficient thermalization of the injected electrons in the SEI.

In order to justify the reduced electron overflow in the InGaN-based LEDs with a SEI, we performed first-order calculations of the electron overflow under different applied forward voltages across the active region. For simplicity of calculation and a more transparent demonstration of the SEI effect, a 1-layer SEI with one intermediate layer of

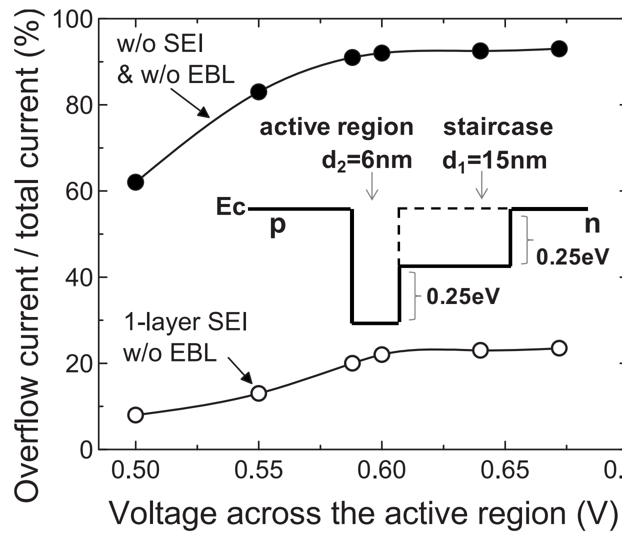

FIG. 2. Calculated overflow electron current/total electron current as a function of applied forward voltage across the 6 nm thick $In_{0.20}Ga_{0.80}N$ active region for the LED without a SEI and without an EBL, and the other LED with a one-layer $In_{0.10}Ga_{0.90}N$ SEI and without an EBL. Solid lines are guides to the eye. The inset shows the band diagrams for the LEDs with and without (dashed line) the SEI.

$In_{0.10}Ga_{0.90}N$ was employed (see Fig. 2 inset). The SEI has a total thickness of 15 nm, the same as the total thickness of the three-layer SEI of the LEDs investigated experimentally.

The probability of ballistic transit (i.e., no scattering) has dependence, $\exp(-t/\tau_{sc})$, where t is the transit time, and $\tau_{sc}=1/(1/\tau_{abs}+1/\tau_{em})$ is the electron-LO-phonon scattering time in terms of the phonon emission (τ_{em}) and absorption (τ_{abs}) times.[12] The percentage of overflow electrons due to ballistic transport in an LED with the SEI is then given by the following:

$$p_0=\frac{\int_{\max\{0,(\phi_{EBL}-qV)\}}^{+\infty} f(E)N(E)\times\exp\left[-\frac{d_1/v_1(E)}{\tau_{sc}}\right]\times\exp\left[-\frac{d_2/v_2(E)}{\tau_{sc}}\right]dE}{\int_0^{+\infty} f(E)N(E)dE}, \qquad (1)$$

where E is the excess electron energy with respect to the bottom of the conduction band of *n*-GaN, $d_1=15$ nm and $d_2=6$ nm are the thicknesses, and $v_1(E)=\sqrt{2(E+0.25\ \text{eV})/m_e}$ and $v_2(E)=\sqrt{2(E+0.5\ \text{eV})/m_e}$ are the electron velocities in the SEI ($In_{0.10}Ga_{0.90}N$) and the active region under flat band conditions, respectively, V is the net potential drop across the active region (applied voltage compensated by the built-in voltage), ϕ_{EBL} is the EBL barrier height (i.e., the conduction band offset between the EBL and the GaN, and is 0 for the LEDs without EBL), m_e is the electron effective mass, $N(E)$ is the conduction-band density of states, and $f(E)$ is the Fermi-Dirac distribution function. The energies, 0.25 and 0.5 eV, in the velocity expressions represent the excess energy gained by electrons from the conduction band discontinuities upon injection into the $In_{0.10}Ga_{0.90}N$ SEI layer and into the $In_{0.20}Ga_{0.80}N$ active layer, respectively. For simplicity, we assume that the electrons transport in the normal direction to the heterointerfaces.

In calculating the overflow current due to the electrons that experience one scattering event we considered a total of four different cases corresponding to emission or absorption of only one LO phonon in the SEI and the active regions. The probability of only one phonon emission in the SEI is given by the following:

$$p_{11} = \frac{\int_{\max\{0,(\phi_{EBL}-qV+\hbar\omega_{LO})\}}^{+\infty} f(E)N(E)\int_0^{d_1}\exp\left[-\frac{x/v_1(E)}{\tau_{sc}}\right]\times\frac{1}{v_1(E)\times\tau_{em}}\times\exp\left[-\frac{(d_1-x)/v_1(E-\hbar\omega_{LO})}{\tau_{sc}}\right]\times\exp\left[-\frac{d_2/v_2(E-\hbar\omega_{LO})}{\tau_{sc}}\right]dxdE}{\int_0^{+\infty} f(E)N(E)dE}, \quad (2)$$

where $\hbar\omega_{LO}$ is the LO phonon energy. Equation (2) takes into account the probabilities for a suitable electron (e.g., with energy $\hbar\omega_{LO}$ higher than the bottom of conduction band of n-GaN for the case of no EBL and flat-bands) to reach position x ($0 \leq x \leq d_1 = 15$ nm) without being scattered, to emit a phonon near x, and to exit the active region without being scattered between x and d_2. The probability of only one phonon emission in the active region is given by the following:

$$p_{12} = \frac{\int_{\max\{0,(\phi_{EBL}-qV+\hbar\omega_{LO})\}}^{+\infty} f(E)N(E)\int_0^{d_1}\exp\left[-\frac{d_1/v_1(E)}{\tau_{sc}}\right]\times\exp\left[-\frac{(x-d_1)/v_2(E)}{\tau_{sc}}\right]\times\frac{1}{v_2(E)\times\tau_{em}}\times\exp\left[-\frac{(d_1+d_2-x)/v_2(E-\hbar\omega_{LO})}{\tau_{sc}}\right]dxdE}{\int_0^{+\infty} f(E)N(E)dE}. \quad (3)$$

Similarly, we can obtain the probabilities for one phonon absorption events. The contribution of two scattering events to the overflow electrons was found to be negligible for this SEI (<1%). The total electron overflow is then obtained by summing the ballistic and quasiballistic contributions.

Figure 2 shows the percentile overflow electron current for the two LEDs without EBL ($\phi_{EBL}=0$): one with and the other without the SEI, calculated using $\tau_{em}=10$ fs, $\tau_{abs}=100$ fs, and $\tau_{sc}=9$ fs.[15] For the flatband case (voltage drop across the active region=0.5 V) obtained through compensation of the built-in electric field of the p-n junction by the applied voltage, a significant portion (~62%) of the total electron current is the overflow electron current for the LED without a SEI. However, for the LED with the SEI, the electron overflow is substantially reduced to ~8%. This reduction in electron overflow is mainly attributable to reduced conduction band discontinuity steps due to the SEI instead of an increase of the effective width of the active region: a wider active region (15+6=21 nm) without a SEI still has ~18% of electron overflow percentile (not shown). In addition, the thermionic emission in the SEI even in the absence of an EBL was found to be negligible (<1%). The results with the SEI suggest that the electrons have a longer transit time due to a lower velocity because of the lower kinetic energy gained from the band discontinuity. Correspondingly, the longer time helps thermalization through interaction with LO-phonons, dramatically reducing the electron overflow. Obviously, more layers in the SEI (three layers used in our LEDs) provide more freedom for designing the optimal SEI.

In conclusion, we reported on a staircase LED structure where the overflow current due to ballistic and quasiballistic electrons is substantially reduced without any EBL layer, which has the deleterious effect on the hole injection and is not welcome for technological reasons. Specifically, an InGaN SEI with gradually increased In composition was inserted prior to the active region and resulted in essentially the same EL performance for the LEDs with and without EBL. Our calculations confirm that the employment of the SEI in the LEDs nearly eliminates the overflow current due to ballistic and quasiballistic electrons, and almost all injected electrons are efficiently thermalized inside the SEI.

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