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The effect of stair case electron injector design on electron overflow in InGaN light emitting diodes

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Effect of two-layer ($In_{0.04}Ga_{0.96}N$ and $In_{0.08}Ga_{0.92}N$) staircase electron injector (SEI) on quantum efficiency of light-emitting-diodes (LEDs) in the context of active regions composed of single and quad 3 nm double heterostructures (DHs) is reported. The experiments were augmented with the first order model calculations of electron overflow percentile. Increasing the two-layer SEI thickness from $4+4$ nm up to $20+20$ nm substantially reduced, if not totally eliminated, the electron overflow in single DH LEDs at low injections without degrading the material quality evidenced by the high optical efficiency observed at 15 K and room temperature. The improvement in quad 3 nm DH LEDs with increasing SEI thickness is not so pronounced as the influence of SEI is less for thicker active regions, which in and of themselves necessarily thermalize the carriers. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4817387]

High efficiency InGaN based light emitting diodes (LEDs) are gaining increasing interest for general lighting,[1] but they still suffer from loss of efficiency at high electrical injection which hampers their implementation.[2–5] Although the genesis of the efficiency roll off still remains to be debatable, a large body of experimental data suggest electron overflow and doping asymmetry to be the most important causalities.[6] We have already demonstrated that with an InGaN staircase electron injector (SEI), the droop could be significantly reduced and the electron blocking layer (EBL), which is used as a standard in most LED designs to keep electrons in the active region but in turn hampers hole transfer, is not imperative.[7] SEI acting as an electron cooler reduces the kinetic energy of injected electrons through longitudinal optical (LO) phonon emission sufficiently to significantly reduce the probability of ballistic and quasi-ballistic transport.[8] In addition, the LED efficiency also depends strongly on the active region design and double heterostructure (DH) active regions have been shown to be more promising than conventional quantum wells (thickness < 2 nm) due to their 3D density of states.[9,10] Moreover, it has been shown that multiple thin (3 nm) DH active regions separated by low energy barriers are more promising for high material quality and high efficiency light emitters than quantum well based and also thick (more than 6 nm) DH layers.[11] Therefore, investigation of SEI effects in multi-3 nm DHs LEDs is warranted which is the subject matter of this manuscript.

In this work, the impacts of the two-layer SEI design on electron overflow, and thus the overall LED efficiency, are explored using both optical and electrical injection. A first order model calculation for electron transport through the active region was also employed to support experimental results.

The *c*-plane InGaN LED structures, emitting at $\sim$430 nm, were grown on $\sim$3.7 μm-thick *n*-type GaN templates on sapphire in a vertical low-pressure metalorganic chemical vapor deposition (MOCVD) system. The structures feature either single or quad 3 nm $In_{0.15}Ga_{0.85}N$ DH active regions separated by 3 nm $In_{0.06}Ga_{0.94}N$ low energy barriers to help reduce adverse effects on hole transport [Figure 1(a)]. Situated below the active region is a two-layer varied thickness SEI consisting of $In_{0.04}GaN$ and $In_{0.08}GaN$ layers of the same thickness grown in the given order on a 60-nm $In_{0.01}Ga_{0.99}N$ underlying layer intended for improving materials quality. Both the underlying $In_{0.01}Ga_{0.99}N$ and the SEI were doped with Si to 2×10^{18} cm^{-3}. The LED structures were completed with 100 nm-thick Mg-doped *p*-GaN layers having 6×10^{17} cm^{-3} hole density, determined from Hall measurements in separate samples. Square mesa patterns (400×400 μm^2) were then formed by conventional photolithography and chlorine based Inductively Coupled Plasma (ICP) 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 electrodes served as the semi-transparent *p*-contacts with 40/50-nm Ni/Au electrodes deposited for *p*-contact pads, which completed the LED fabrication.

In order to verify the need and effectiveness of SEI, we performed first-order calculations of the electron overflow for the multi-3 nm DH LEDs with different SEI thickness (no electron blocking layer involved) as a function of injected current density. These calculations do not take into consideration the effect of electric field inside the active region on the electron velocity and assume a constant phonon scattering rate regardless of the current, which in fact decreases with increasing electron density.[12] As a result, electron overflow values at high injection are underestimated, especially in the case of single-DH active region.[8] Moreover, for simplicity, the electrons are assumed to move in the direction normal to the hetero-interfaces and the total electron overflow is obtained by summing the contributions due to both ballistic (no LO phonon scattering) and quasi-ballistic electrons (limited to one LO-phonon scattering

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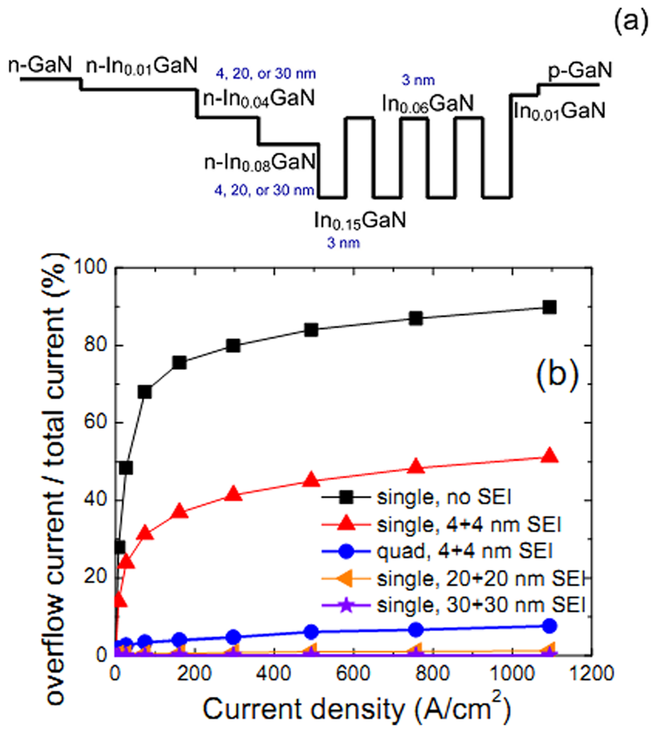

FIG. 1. (a) Conduction band schematic of the quad 3 nm LED structures investigated. (b) Electron overflow percentile in single and quad 3 nm DH LEDs with different SEI thicknesses as a function of injected current density.

event for simplicity without loss of vital accuracy),[7,8] which depend on applied bias. Although a single layer SEI would also help with electron cooling, we use a more effective two-layer SEI as it provides smaller conduction band energy steps, equal to or larger than the LO phonon energy, reducing the kinetic energy gained by the electrons at each interface upon injection.[8] Thus, lower velocity enhances electron cooling via LO-phonon emission, reducing the overflow.[13] The electrons that emit multiple LO-phonons in the SEI region have negligible effect on overflow as they have a very low probability to escape the active region due to the ~0.25 eV barrier between the final step in the SEI and the bottom of the *p*-GaN conduction band. The dependence of the voltage drop across the active region on the injected current density was obtained using a commercial simulator, SILVACO ATLAS, with simulation parameters appropriate for nitride materials.[13]

As shown in Figure 1, in the absence of an SEI, the overflow percentile for the 3 nm DH is ~85% at 500 A/cm^2 current injection. This value is reduced to 45% when a 4 + 4 nm-thick $In_{0.04}GaN + In_{0.08}GaN$ SEI is incorporated and further to 1% and 0.1% with 20 + 20 and 30 + 30 nm thick SEIs, respectively. The quad 3 nm DH with 4 + 4 nm-thick SEI exhibits also a low 6% overflow at 500 A/cm^2 as the thick cumulative active region naturally provides efficient electron cooling. At a higher current injection of 1100 A/cm^2, the difference between the overflow percentiles of single and quad 3 nm DH LEDs with 4 + 4 nm SEI increases (e.g., 51% and 7.6%, respectively). These results show that a thicker SEI efficiently reduces the electron overflow for single 3 nm DH LEDs. However, it should be noted that for optimum SEI design, particulars of the active region structure and the effect of SEI composition and thickness on the active region, material quality and strain should be taken into consideration.

To investigate the effect of SEI design/thickness on electron overflow, single and quad 3 nm DH LEDs with 4 + 4, 20 + 20, or 30 + 30 nm-thick two-layer SEIs ($In_{0.04}GaN + In_{0.08}GaN$) were fabricated and analyzed. Before focusing on the electron overflow, it is necessary to evaluate the effect of SEI on the optical quality of the LEDs. Excitation density dependence of the resonant photoluminescence (PL) intensity was measured at 15 K and room temperature to gain insight into the internal quantum efficiency (IQE) of single and quad DH LEDs with varying SEI thickness, noting that in resonant excitation carriers are cool already. A frequency-doubled Ti:Sapphire laser (385 nm wavelength) was used with the maximum excitation density corresponding to an average carrier concentration of ~10^{18} cm^{-3} in the single DH LED. As shown in Figure 2(a), PL intensity has a linear dependence on the excitation power for all samples at 15 K, which indicates that radiative recombination is dominant within the entire excitation density range employed.[14] Moreover, the PL intensity scales nearly with the number of 3 nm DH layers in the active region: PL intensity for quad DH LEDs is ~4 times that of single DH LEDs. No change was observed in the emission wavelength with increasing SEI thickness for any of the LEDs, suggesting that there is no discernible difference in strain among the structures investigated.

Room temperature measurements [Figure 2(b)] for the quad 3 nm DH LEDs show that at low injection the slope of PL intensity dependence on excitation density decreases with increasing SEI thickness, indicating reduced nonradiative recombination. At a very low excitation density of 0.001 kW/cm^2, increasing the SEI thickness from 4 + 4 nm to 20 + 20 nm improves the PL intensity by nearly an order

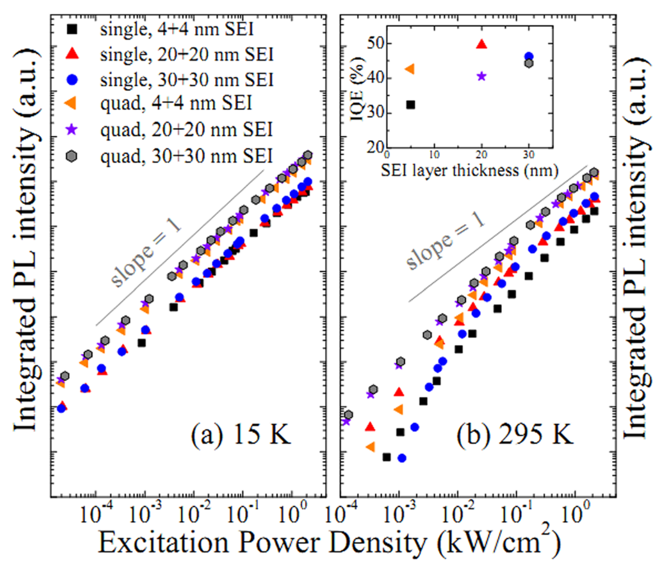

FIG. 2. The integrated PL intensity as a function of excitation power density for single and quad 3 nm DH LEDs with varied SEI thickness at (a) 15 K and (b) 295 K. The inset in (b) shows the IQE values determined, assuming a quantum efficiency of 1 at 15 K, from the ratio of room temperature to low temperature PL intensities at the maximum excitation density employed, which corresponds to a photogenerated carrier density of ~1–2 × 10^{18} cm^{-3}.

of magnitude, while no further improvement is apparent with the 30 + 30 nm-thick SEI. As the excitation density is increased, the slope gradually approaches 1, indicating a strong competition between nonradiative and radiative processes, with the latter becoming more prominent with increasing injection. The improvement observed at low excitation densities with increased SEI thickness suggests improvement of the active region material quality manifested as a reduction of nonradiative recombination centers although particulars of the genesis of this improvement is unclear at this instant. Similar trends are observed for the single 3 nm DH LEDs at room temperature except lower PL intensities due to their smaller active region thickness. Significant improvement is apparent in PL efficiency at low excitation for the single 3 nm DH LED with increasing SEI thickness from 4 + 4 nm to 20 + 20 nm. However, single 3 nm DH LED with 30 + 30 nm SEI exhibits the lowest PL efficiency at low excitation densities (higher slope in Figure 2(b)) but the highest intensity at the highest excitation density employed. This is indicative of the presence of low density of certain type of nonradiative centers that can be saturated faster with increasing excitation compared to those in other LED structures. They may possibly originate from strain driven diffusion of Mg from the p-GaN layer, the detrimental effect of which will be much weaker in the quad LEDs, and/or generation of threading dislocations and related point defects within the active region resulting from partial relaxation due to accumulation of strain energy with increasing SEI thickness. Note that the detrimental effects of dislocations and point defects acting as nonradiative centers can be stronger in the single DH LEDs, which is consistent with the observations by Armstrong *et al.*,[15] who reported reduction in density of deep centers towards the LED surface, i.e., with increasing active region thickness, within multi-QW LEDs. This unusual behavior for the single DH LED with 30 + 30 nm SEI is still under investigation; however, it does not affect the premise of this paper as of particular importance is the LED operation at high excitation densities, where the single 3 nm DH LEDs with 20 + 20 nm and 30 + 30 nm SEIs have comparable performance. Moreover, it should be noted that the higher efficiencies (lower slopes) at low excitation densities for the quad DH LEDs compared to the single DH LEDs result in part from the improvement of material quality with further growth of InGaN active regions in multi-DH LEDs.

The IQE values deduced from ratios of PL intensities at room temperature and 15 K (assuming unity IQE at 15 K) at the highest excitation density employed are also shown in the inset of Figure 2(b). The single 3 nm DH LED with 4 + 4 nm-thick SEI exhibits a room temperature IQE of ~33% whereas increasing the SEI thickness to 20 + 20 nm results in significant enhancement to 49%, in part due to higher absorption within the thicker SEI layers and subsequent carrier relaxation into the active region. The bandgap of the $In_{0.08}Ga_{0.92}N$ SEI layer, 3.08 eV, is lower than the excitation energy of 3.22 eV. The corresponding effect is not as pronounced in quad DH LEDs as most absorption occurs in the thicker active region (4 × 3 nm) before excitation light can reach the SEI. Quad 3 nm DH LEDs with SEI thickness either 4 + 4 nm or 20 + 20 nm exhibit comparable IQE values of 43% and 40%, respectively. It is clear that increasing the SEI thickness to 30 + 30 nm, which results in significant reduction in electron overflow as illustrated in Figure 1, does not cause any noticeable degradation of optical performance of single and quad 3 nm DH LEDs at high injection.

To demonstrate the effect of SEI thickness on carrier overflow, integrated electroluminescence (EL) intensities *vs.* current injection for single and quad 3 nm DH LEDs with varied SEI thickness were measured under pulsed excitation with 0.1% duty cycle to eliminate heating effects. As shown in Figure 3(a), for the LEDs containing 4 + 4 nm SEI, the EL efficiency of quad 3 nm DH LED is ~3.5 times higher than that of single 3 nm DH LED. As for the factor of 3.5 difference being much larger than the difference in IQE values [33% and 43% for the single and quad 3 nm DH LEDs, respectively, Figure 2(b) inset], it can be concluded that the electron overflow in the single 3 nm DH LED is significantly higher due to the thinner active layer thickness allowing ballistic and/or quasi-ballistic electron transport across the active layer without recombination.[13] To reduce the electron overflow in the single 3 nm DH LED, the SEI thickness should be increased to provide hot electrons more time to sufficiently thermalize before being injected into the active region. However, for a given active region thickness and design, the total SEI thickness should be kept below the critical thickness above which the active region material quality would degrade noticeably due to strain relaxation. It should also be noted that the agreement between the simulation results of Figure 1 and the data in Figure 2(a) is satisfactory considering that the calculations do not take into consideration the effect of acceleration of electrons under the electrical field within the active region due to the lack of any hot electron model in SILVACO ATLAS. Besides, a constant phonon scattering rate is assumed in these first-order calculations, which results in underestimation of the overflow percentiles as the phonon lifetime has been reported to decrease with increasing current injection.[12]

As stated increasing the SEI thickness from 4 + 4 nm to 20 + 20 nm for the single 3 nm DH LED resulted in an

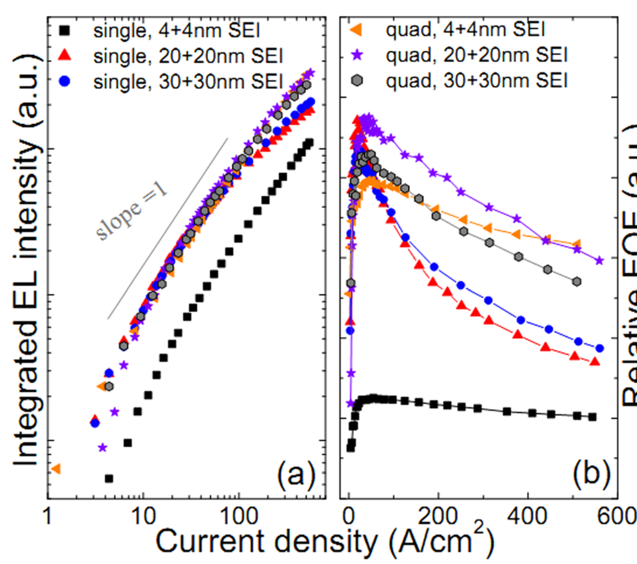

FIG. 3. (a) The integrated EL intensity dependence on current density for single and quad 3 nm DH LEDs with varied SEI thickness. (b) The relative EL efficiency vs. injected current density.

enhancement in the peak EL efficiency by nearly 3.5 times, making it comparable to that of the quad 3 nm DH LEDs [Figure 3(a)]. This significant improvement indicates that the electrically injected hot electrons are cooled efficiently within the thicker SEI, and therefore, the electron overflow is greatly reduced if not totally eliminated. The more visible efficiency roll off in the single DH LED both with 20 + 20 nm-thick SEI compared to the quad 3 nm DH LED [Figure 3(b)] suggests larger electron overflow in the thinner active region, which increases at higher injection levels. Nevertheless, the efficiency for the single 3 nm DH LED with 20 + 20 nm SEI at the highest injection level employed (550 A/cm^2, which corresponds to an average carrier density around 4–6 $\times 10^{18}$ cm^{-3}, estimated using $A = 10^7$ s^{-1} and $B = 5 \times 10^{-11}$ cm^{-3} s^{-1})[11,16] is nearly twice that for the single DH LED with 4 + 4 nm SEI. Moreover, since most of the recombination occurs in the part of the active region closer to *p*-GaN due to the limited hole transport, thicker or multi-DH active region itself would function as an additional electron cooler resulting in less electron overflow as observed for the quad-DH LED in the case of thin 4 + 4 nm SEI layers. It should, however, be noted that a thicker active region, either multiple wells or wider DH, may not provide as efficient electron cooling as an optimally designed SEI region due to large conduction band discontinuities at the interfaces launch electrons at high velocity (reduced transit time) and thus impede electron cooling as discussed earlier and due to impediment of hole transport and possible strain relaxation. The higher peak EL efficiency in the quad LEDs is also consistent with higher IQEs deduced from PL measurements [Figure 2(b) inset].

In conclusion, we have shown that SEI thickness plays an important role in quantum efficiency of LED structures through reduction of electron overflow, particularly those with thin active regions such as in the single 3 nm DH LED. Increasing the two-layer SEI thickness from 4 + 4 nm up to 20 + 20 nm did not degrade the material quality, as suggested by the high optical efficiency observed from 15 K and room temperature PL measurements, but substantially reduced, if not totally eliminated, the electron overflow at low injection as proposed. The improvement in quad 3 nm DH LEDs with increasing SEI thickness is not that obvious, as the influence of SEI is less in effectively thicker active regions, which also naturally thermalize carriers during their transport. Consequently, although the peak EL efficiencies are similar for single and quad 3 nm DH LEDs with thicker SEIs, at high injection, single 3 nm DH LEDs suffer more from electron overflow due to the thinner active region. However, even at the highest excitation density employed (550 A/cm^2), the EL efficiency of the single 3 nm DH LED with 20 + 20 nm or 30 + 30 nm SEI is nearly doubled when compared to that with a much thinner 4 + 4 nm SEI. These results indicate that the two-layer SEI with optimum thickness significantly reduces the electron overflow, and that the optimum SEI design depends on the specifics, such as composition and thickness, of the active region structure employed.

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