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Identifying the cause of the efficiency droop in GaInN light-emitting diodes by correlating the onset of high injection with the onset of the efficiency droop

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An unequivocal correlation between the onset of high injection and the onset of the efficiency droop is demonstrated in GaInN light-emitting diodes over a wide range of temperatures. The diode voltage at the onset of high injection and the voltage at the onset of the efficiency droop are correlated by the equation $V_{\text{High-injection onset}} + \Delta V \approx V_{\text{Droop onset}}$. The excess voltage, ΔV, determined to be 0.3 V, drops partially over the p-type neutral region. The resulting electric field sweeps electrons out of the active region and results in substantial electron leakage despite high barriers that confine the carriers to the active region. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4811558]

Light-emitting diodes (LEDs) in the GaInN/GaN material system suffer from a loss of external quantum efficiency at high current densities, a phenomenon known as efficiency droop. The physical mechanism causing the efficiency droop has been highly debated.[1,2] The mechanisms that have been proposed to explain efficiency droop include electron leakage due to polarization mismatch,[3] poor hole injection,[4] delocalization of carriers,[5,6] and Auger recombination.[7,8] Recently, a drift-leakage model has been developed to explain efficiency droop, caused by the asymmetry of carrier concentrations and mobilities, which was shown to lead to electron leakage from the active region.[9,10] In the present work, we demonstrate a strong correlation between the onset of the high-injection regime and the onset of the efficiency droop. Once the LED violates the low-injection condition, an electric field begins to develop in the p-type region, sweeping electrons away from the active region. Furthermore, the results show how electron leakage is made possible despite the strong confinement of electrons to the multi-quantum-well (MQW) active region.

The LED used in our experiments is grown by metalorganic chemical vapor deposition and has five GaInN/GaN QWs which emit at a peak wavelength of 440 nm. The LED structure employs an $Al_{0.15}Ga_{0.85}N$ electron-blocking layer (EBL) grown after the last-grown GaInN QW and the immediately following 6 nm thick undoped GaN spacer layer. Thin-film LEDs are fabricated by bonding the LED wafer to a silicon wafer and utilizing laser-lift-off to remove the sapphire substrate. The exposed N-face GaN is then surface roughened to enhance light extraction. The LED wafer is diced into $1 \times 1\ \text{mm}^2$ chips that are left unpackaged.

Figure 1 shows the GaInN LED current–voltage (I–V) characteristics for the temperature range 200 K to 450 K, plotted on a semi-log scale. For each temperature and for sufficiently small voltages, the diode meets the low-level injection condition: That is, the conductivity due to minority carriers (electrons) injected into the p-side is much lower than the conductivity due to holes, i.e., $\Delta n\ \mu_n \ll p_{p0}\ \mu_p$.[9] However, for a sufficiently large applied bias, the low-level injection condition is no longer satisfied, and an incremental voltage begins to drop over the p-type EBL and p-type GaN quasi-neutral region. This is known as the high-level injection regime. As illustrated in Fig. 1(a), as the temperature is increased, the high-injection point shifts to higher current levels. To determine the onset of the high-injection point in the I–V characteristic, shown in Fig. 1(a), we determine the point at which the I–V characteristics transitions from the exponential to the linear regime. This is easily done by the procedure illustrated in Fig. 1(b); the figure reveals a clear demarcation between the low-injection and the high-injection regime.

For the same temperature range, i.e., 200 K to 450 K, we study the current value at which the LED reaches its peak efficiency. We denote this point as the onset-of-droop point. There are multiple mechanisms of carrier recombination including Shockley-Read-Hall (SRH) recombination, radiative recombination, and drift-induced carrier leakage from the active region.[10] These mechanisms each exhibit strong temperature dependencies. For example, at low temperatures, SRH recombination is significantly reduced.[11] The probability of radiative recombination (i.e., the B coefficient), however, is greater at cryogenic temperatures.[12,13] Electron leakage has a more complicated temperature dependence; it has been shown that at cryogenic temperatures, such as 200 K, electron leakage is higher than at room temperature.[9] These multiple factors result in the behavior shown in Fig. 2, where the LED's external quantum efficiency (EQE) is shown as a function of injection current for different temperatures. The peak efficiency decreases as temperature is increased, mainly due to increased SRH recombination and reduced radiative efficiency.[9,14] The current at which the peak-efficiency point occurs also increases strongly as temperature is increased. In addition to this, Fig. 2 shows a strongly increased droop near 200 K where the

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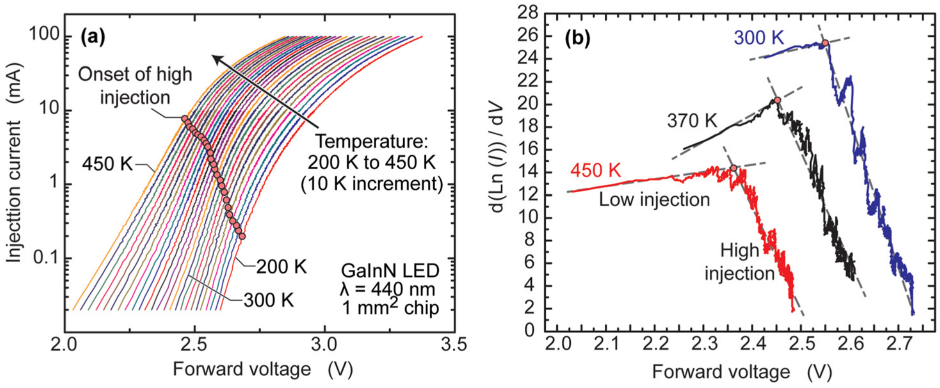

FIG. 1. (a) Current-voltage characteristics of 440 nm GaInN LED measured from 200 K to 450 K. The red-filled circles indicate the onset of high-level injection. (b) Determination of the onset of high-level-injection point as the transition point from an exponential slope to a sub-exponential slope.

efficiency curves cross over the higher-temperature curves. This result is consistent with the increased droop at cryogenic temperatures that has been reported by several research groups.[15,16]

Next, we correlate the current values at the onset of high-injection with the current values at the onset of the efficiency droop. Figure 3 displays these two values for measurements taken in the range 200 K to 450 K. Inspection of the figure shows a strong correlation of these values. A linear fit to the experimental points is shown in Fig. 3 with a correlation coefficient, R^2, value of 0.931, indicating a strong correlation. The figure reveals that the currents at the peak-efficiency points are about one order of magnitude higher than the currents at the high-injection point. We propose that the voltage associated with the current difference is required to build up an electric field in the EBL and p-type GaN region. That is, at the *onset* of high injection, the electric field in the p-type region is negligible; it takes an additional incremental voltage drop over this region to generate an electric field that will initiate the transport of electrons by drift (rather than diffusion).

Next, we correlate the voltage difference associated with the onset of high-injection and the onset of the efficiency droop. The lower group of data points in Fig. 4 shows the voltage at the onset of high injection, as extracted from the forward I–V characteristics, as a function of temperature. The upper group of data points shows the voltage at which peak efficiency occurs. These voltages decrease, together, as temperature increases, with a remarkable constant difference, ΔV, of about 0.3 V. Because the LED has entered high-level injection, it is very reasonable to assume that a portion of this voltage drops over the EBL and p-type GaN quasi-neutral region.

The experimental data of Fig. 4 indeed show an excellent correlation between the onset of high-injection and onset of efficiency-droop. The parallel nature of the two lines constitutes evidence that the efficiency droop is directly linked to the onset of high-injection. As an electric field builds up in the EBL and p-type GaN, electrons are extracted out of the active region, thereby causing the efficiency droop.

GaInN/GaN MQW active regions with AlGaN EBLs are expected to provide excellent carrier confinement due to the wide bandgaps of the constituent semiconductors as well as the large band discontinuities associated with these semiconductors. As a result, the ratio of the electron concentration in the barrier to the electron concentration in the QW, δ, has been estimated to be[10]

$$\delta = \frac{n_{Barrier}}{n_{QW}} \approx 0.1\%. \tag{1}$$

Here, n_{QW} and n_{Barrier} are the concentrations of electrons in the QW and the EBL, respectively. Given that the fraction δ is undoubtedly very small, it is not intuitively obvious how such a small fraction can lead to a large macroscopic effect

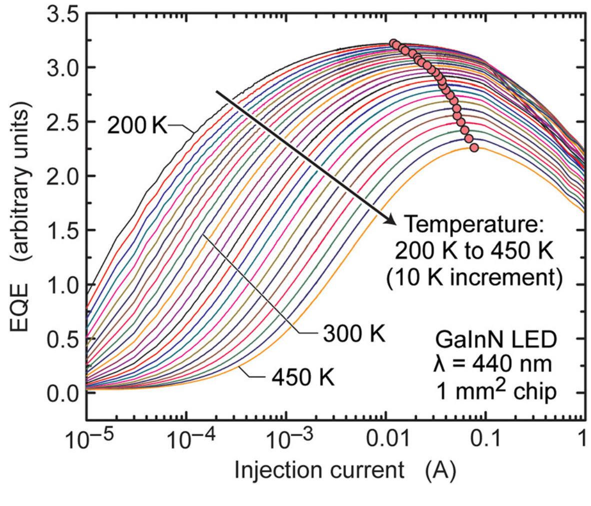

FIG. 2. External quantum efficiency of a 440 nm GaInN LED measured from 200 K to 450 K with 10 K increments. The red circles indicate the peak-efficiency point, i.e., the onset-of-droop point.

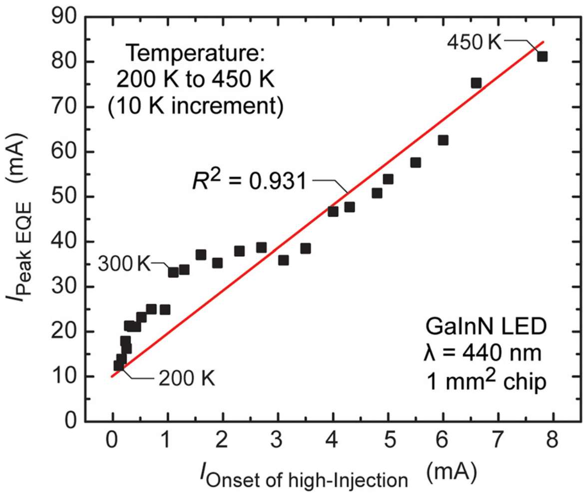

FIG. 3. Current at the onset of high injection, correlated with the current of peak efficiency for a GaInN LED in the temperature range 200 K to 400 K.

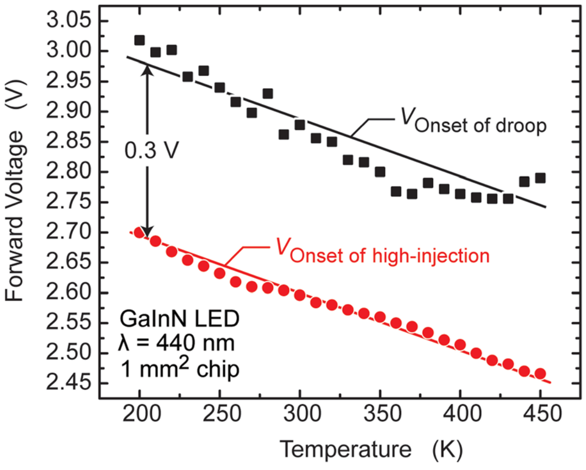

FIG. 4. Voltage at the onset of high injection and voltage at the onset of the efficiency droop (i.e., the peak-efficiency point) as a function of temperature.

such as efficiency droop. Therefore, given that carriers in GaInN/GaN/AlGaN LEDs are confined by high barriers, i.e., δ is very small, how can electron leakage be a significant factor? To answer this intriguing question, we compare the radiative recombination time, $\tau_{\text{Radiative}}$, with the electron sweep-out time, τ_{DL}, as illustrated in Fig. 5.

The radiative recombination lifetime in the GaInN QW can be estimated by assuming $n_{\text{QW}} = 10^{18}\,\text{cm}^{-3}$ and a radiative coefficient of $B = 10^{-10}\,\text{cm}^3/\text{s}$, which gives a radiative rate of $10^{26}\,\text{cm}^{-3}/\text{s}$ and a radiative lifetime of 10 ns, consistent with experiments on a GaInN LED.[17] The electron sweep-out time can be approximated by the time it takes electrons to drift through the p-type region. The drift-leakage time (electron sweep-out time) is given by

$$\tau_{DL} = \frac{d_{p-GaN}}{v_{drift}} = \frac{d_{p-GaN}}{\mu_e E}, \tag{2}$$

where v_{drift} is the drift velocity, $d_{\text{p-GaN}}$ is the thickness of the p-type GaN layer (≈200 nm), μ_e is the electron mobility in the p-type GaN layer (≈200 cm^2/Vs), and E is the electric field in the p-type region (EBL and p-type GaN), generated by the fraction of ΔV that is dropping across the p-type region. Given the experimental result of a $\Delta V = 0.3$ V, shown in Fig. 4, at least some fraction of this voltage (e.g., 10%–50%) drops across the p-type region. Using these parameters, we estimate the sweep-out time to be, depending on applied voltage, in the range 10–500 ps, i.e., $\ll$1 ns.

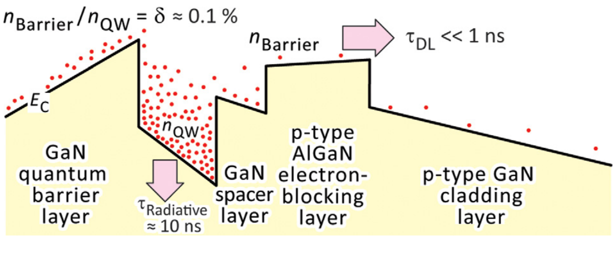

FIG. 5. Schematic conduction band diagram of a GaInN LED structure in the high-level injection regime leading to electron escape from the active region.

Since the energy relaxation time (electron-electron scattering time) in GaN is extremely short (500 fs),[18] electrons in the barrier (EBL) that are swept away from the active region are replaced immediately by new electrons (i.e., within about 500 fs). Therefore in steady-state, the fraction of electrons leaking from the QW can be expressed by the equation

$$\text{Fraction of electrons leaking out} = \frac{n_{\text{Barrier}}/\tau_{\text{DL}}}{n_{\text{QW}}/\tau_{\text{Radiative}}} = \delta\,\frac{\tau_{\text{Radiative}}}{\tau_{\text{DL}}}. \tag{3}$$

This equation is valid near the peak-efficiency point of the efficiency-versus-current curve, where SRH recombination can be neglected. The equation and the numerical values of δ, $\tau_{\text{Radiative}}$, and τ_{DL} show that the fraction of electrons leaking out of the active region can be significant despite the small value of δ. This explains why electrons can leak out of the active region, despite the high barriers confining the electrons.

Electron leakage from the active region has been experimentally demonstrated by resonant photo-excitation of carriers in a forward-biased LED junction, measuring the additional overflow current provided by the photo-excited carriers[19] and by detection of luminescence from a QW grown after the EBL.[20] However, not all experiments detected luminescence from the p-type GaN layer when the LED is operated in the droop regime. This difficulty can be explained: since the carrier drift time across the p-type GaN ($\ll$1 ns) is much shorter than the radiative recombination time ($\gg$1 ns), luminescence in the p-type GaN is unlikely to occur, even at low temperatures.

In order to confirm the correlation between droop and high-level injection, APSYS simulations of a GaInN/GaN LED were performed for a device temperature of 300 K. The simulated LED has three active-region QWs and a 30 nm $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ EBL. $\Delta E_C/\Delta E_g$ is 0.6 for the AlGaN EBL, with acceptor concentration of $1 \times 10^{18}\,\text{cm}^{-3}$ and activation energy 200 meV. The p-type GaN is doped with $1 \times 10^{18}\,\text{cm}^{-3}$ acceptors having activation energy of 170 meV. An Auger coefficient of $10^{-34}\,\text{cm}^6/\text{s}$ is chosen for the simulation. We identify high-level injection by the same method described in Fig. 1(b), at a value of $3\,\text{A/cm}^2$. The simulated current of peak efficiency is $30\,\text{A/cm}^2$. Figure 6(a) shows the simulated band diagram of the last QW and p-type regions. As the diode enters high-level injection, the voltage drops over the p-type regions (EBL and p-GaN) and an electric field builds up, reducing the confinement that the EBL provides and allowing more electrons to leak into the p-type GaN. Figure 6(b) shows the buildup of electric field from low-injection to high-injection. The average electric field in each region is calculated at $0.1\,\text{A/cm}^2$ (still in the low-injection regime) and then the change in average field is calculated for each region at higher current densities. The average electric field in the p-type GaN clearly shows a transition point upon entering high-level injection. In addition, the electric field in the EBL continues to grow with increasing current density. Inspection of the figure reveals that the average electric field in the EBL and p-type GaN increases by about $E = 3$ kV/cm between the onset of high-injection and the onset of the efficiency droop. Using this value, an electron

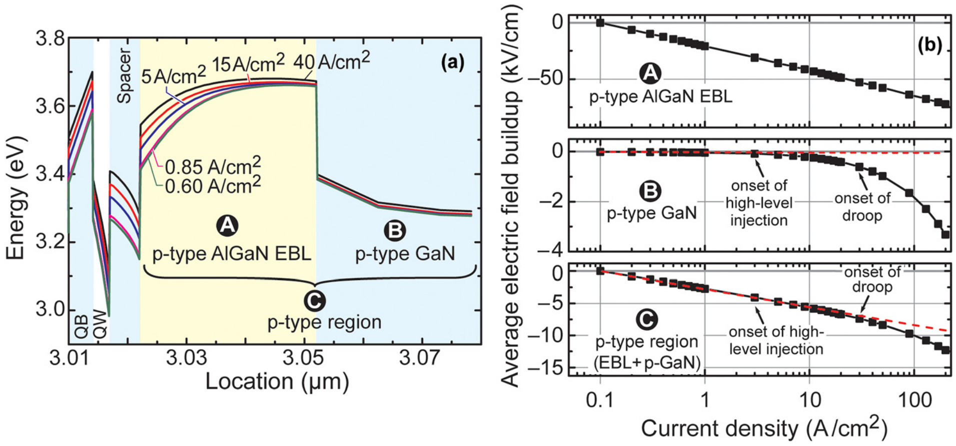

FIG. 6. (a) Simulated band diagram of GaInN LED at 300 K, showing the transition from low-injection to high-injection. (b) Simulated average electric field buildup in the p-type regions from 0.1 A/cm to higher current densities.

mobility of 200 cm^2/Vs and a p-type layer thickness of 200 nm, $\tau_{DL} = d_{\text{p-GaN}}/(\mu_e E)$ can be calculated to be tens of ps consistent with $\tau_{DL} \ll \tau_{\text{Radiative}}$.

We note that the efficiency droop exhibits several key characteristics including (i) a C coefficient on the order of 10^{-29} cm^6/s,[18,21] (ii) the droop becoming more pronounced at cryogenic temperatures,[9,15,16] (iii) an asymmetric EQE-versus-n curve that cannot be adequately described by the ABC model,[22] and (iv) the occurrence of the efficiency droop in LEDs made of multiple material systems, including AlGaInP and GaInN.[23] These key characteristics are not readily explained by Auger recombination. However, these key characteristics can be explained, qualitatively as well as quantitatively, by the drift-leakage model.

In conclusion, we have presented an unequivocal correlation between the onset of high-level injection and the onset of efficiency droop in GaInN LEDs. Within a wide range of temperatures, the onset of the efficiency droop occurs at a forward voltage that is about 0.3 V higher than the onset of high injection. As an electric field builds up in the p-type region, electrons are swept out of the active region. It is shown that because the electron sweep-out time ($\tau_{DL} \ll 1$ ns) is much shorter than the radiative recombination time in QWs ($\tau_{\text{Radiative}} \gg 1$ ns), substantial electron leakage can occur despite the high barriers that confine carriers to the active region. APSYS simulations show the emergence of an electric field in the p-type region upon entering the high-injection regime, consistent with the propensity of GaInN LEDs to high-injection phenomena such as drift leakage. The (i) unequivocal correlation between the onset of high injection and the onset of the efficiency droop, and (ii) fact that Auger recombination is completely unrelated to the onset of high injection, are both consistent with the drift-leakage mechanism being the dominant cause of the efficiency droop.

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