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On the temperature dependence of electron leakage from the active region of GaInN/GaN light-emitting diodes

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Reduction in the light-output power in GaN-based light-emitting diodes (LEDs) with increasing temperature is a well-known phenomenon. In this work, temperature dependent external-quantum-efficiency versus current curves are measured, and the mechanisms of recombination are discussed. Shockley-Read-Hall recombination increases with temperature and is found to greatly reduce the light output at low current densities. However, this fails to explain the drop in light-output power at high current densities. At typical current density (35 A/cm^2), as temperature increases, our results are consistent with increased Shockley-Read-Hall recombination and increased electron leakage from the active region. Both of these effects contribute to the reduction in light-output power in GaInN/GaN LEDs at high temperatures. © *2011 American Institute of Physics*.
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Over the last several years, GaInN/GaN based light-emitting diodes (LEDs) have become increasingly prevalent in the lighting industry. One drawback with LEDs compared to conventional light sources is that they exhibit a significant reduction in light-output power (LOP) with increasing temperature. Mechanisms that can cause the LOP reduction with increasing temperature include Shockley-Read-Hall (SRH) recombination and carrier leakage (overflow) from the active region. Electron leakage is caused by strong electric fields in the multiple quantum wells (MQWs) as well as a sheet charge at the spacer/electron blocking layer (EBL) interface caused by material polarization mismatch.[1] The strong asymmetry of transport between electrons and holes in GaN will exacerbate electron overflow.[2] Electron leakage out of the active region has been demonstrated experimentally by detecting luminescence from an additional quantum well grown after the EBL.[3] Recently it has been suggested that with increasing temperatures, more acceptors are ionized leading to less asymmetry between electron and hole transport, thus resulting in less electron leakage.[4] Another possibility is that the higher thermal energy of electrons results in greater probability of escape from the quantum wells. However, there are no systematic studies that identify the dominant causes to explain the LOP reduction at high temperature among the above-mentioned two mechanisms.

Recombination in LEDs is commonly described by the *ABC* model.[5,6] This simplistic model considers *A*, *B*, and *C* to represent the SRH, radiative, and Auger coefficient, respectively. In this article, we utilize the $ABC + f(n)$ model, where $f(n)$ refers to additional non-radiative recombination mechanisms, such as leakage from the active region.[7] We then measure temperature dependent light output from a GaN/GaInN based LED and quantitatively extract the contribution of each carrier loss mechanism.

The LED used in our experiments is grown by metal-organic chemical vapor deposition and has five pairs of GaInN/GaN MQWs which emit at a peak wavelength of 460 nm. 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 of the GaN is then patterned with surface roughening. The measured sample wafer is diced into 1×1 mm^2 chips that are left unpackaged. A chip is mounted with thermal grease in a cryostat to ensure good thermal conductivity to the active region of the device. The light-output power is then measured as a function of temperature using pulsed operating conditions, with 5 μs pulse-width and 1% duty cycle used at high currents in order to minimize self-heating.

It has been shown that the typical *ABC* recombination model commonly used to explain recombination in LEDs cannot appropriately fit experimental data of GaN-based LEDs.[7] For this reason, we extend the *ABC* model by adding another recombination term, $f(n)$, to the model, where $f(n)$ includes carrier leakage and is allowed to contain 2nd and 3rd, as well as higher order terms of n. Because of the ambiguity with respect to C and the 3rd order term of $f(n)$, we will include both of these in $f(n)$.

The basis for the recombination analysis begins with the recombination rate, R, in an LED

$$R = I/qV_{active}, \tag{1}$$

where I is injection current, q is elementary charge, and V_{active} is the active region volume. For this work, an active region volume is assumed based on recombination solely occurring in the last quantum well, consistent with previous experimental reports.[8,9] The internal quantum efficiency (IQE) may be expressed as

$$IQE = Bn^2/R, \tag{2}$$

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leading to an expression for carrier concentration

$$n = \sqrt{\frac{IQE \cdot I}{BqV_{active}}} = \sqrt{\frac{IQE_{peak}}{BqV_{active}}}\sqrt{IQE_{normalized} \cdot I}, \qquad (3)$$

where $\mathrm{IQE}_{\mathrm{normalized}}$ is 100% when the LED operates with peak efficiency. Using Eqs. (1) and (3), the curve of n-vs.-R is fitted with a polynomial. This method requires knowing the absolute peak IQE of the LED ($\mathrm{IQE}_{\mathrm{peak}}$). Because of the high quality of this device, a 100% $\mathrm{IQE}_{\mathrm{peak}}$ is assumed at low currents and low temperatures; by comparing the LOP at low temperature to the room temperature LOP, a room temperature $\mathrm{IQE}_{\mathrm{peak}}$ of 78% is estimated. A room temperature value for the B is chosen to be 10^{-10} cm^3 s^{-1}, based on previous reports.[7,10] Classically, in quantum wells, B is proportional to the inverse of temperature,[11] which is assumed in our present analysis. However, in more complete models, B may have an even stronger temperature dependence, as well as, due to phase-space filling, a carrier-concentration dependence.[12] Letting B vary with temperature results in different absolute values of the extracted coefficients. However, the calculated fraction of each recombination mechanism over the total recombination remains the same, regardless of the assumed temperature dependence of B. We note that the inclusion of the phase-space-filling effect has negligible impact on our analysis.[7] For our analysis, *ABC* fitting was first performed up to the peak external quantum efficiency (EQE) point. A nearly perfect fit (within the noise margin of the measurement) can be obtained up to this point, even when viewing the EQE vs. n plot with logarithmically scaled abscissa. By extracting the $f(n)$ contribution after the peak EQE point, it is possible to look at each of the $AB+f(n)$ coefficients and discuss the possible recombination mechanisms and how they evolve with temperature and current. Because of the existence of strong 4th and higher order terms in $f(n)$, Auger recombination cannot be the sole cause of the efficiency reduction at high currents and high temperature.

Figure 1(a) shows the measured temperature-dependent EQE as a function of current. With increasing temperature, the peak efficiency point shifts to slightly higher current levels due to increased non-radiative recombination and decreased bimolecular radiative coefficient. The efficiency at high current levels is also reduced. Figure 1(b) shows the normalized LOP at several current levels. At 450 K and 10 mA, the LOP drops to 57.3% of its room-temperature value. As the current level is increased, the drop in LOP is reduced but still shows a drop in LOP of around 25%. SRH recombination is proportional to the carrier concentration (n), so at high current densities it is expected that this recombination is minimal compared to the other recombination mechanisms. This indicates that at current densities above 35 A/cm^2, a different mechanism (not SRH) is primarily responsible for the drop in light-output power with increasing temperature.

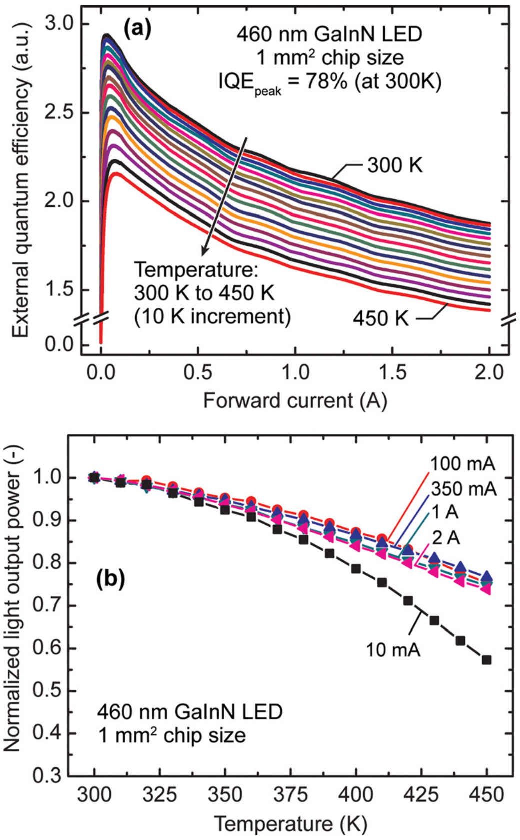

FIG. 1. (Color online) (a) Measured external quantum efficiency vs. forward current at different temperatures, with high frequency noise removed. The temperature was increased from 300 to 450 K in 10 K increments. (b) Normalized light output power as a function of temperature at several operating points.

Using the $AB+f(n)$ method, the SRH recombination coefficient can be calculated as a function of temperature (i.e., An/R, where $R = An + Bn^2 + f(n)$). Figure 2 shows the extracted contribution from SRH recombination at various current levels. At 10 mA, the SRH recombination plays a relatively large role in the total recombination; at room temperature it accounts for 10.0% of the total recombination. At 450 K, this recombination accounts for 47.3% of the total recombination. This contributes to the peak shift in the measured EQE vs. I data, as well as the reduction in peak EQE with increasing temperature. This chart also depicts the SRH contribution at higher current levels. At 2 A and room temperature, SRH contributes only 0.6% of the total recombination. While this contribution increases with temperature, it still contributes only 3.1% at 450 K; therefore, it is too small

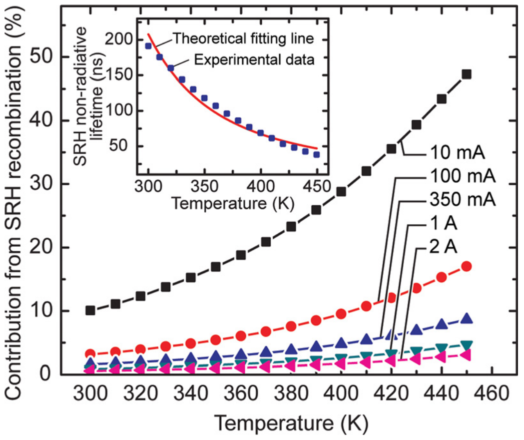

FIG. 2. (Color online) Fraction of SRH non-radiative recombination at different current levels. SRH non-radiative lifetime as a function of temperature and theoretical fit is shown in the inset.

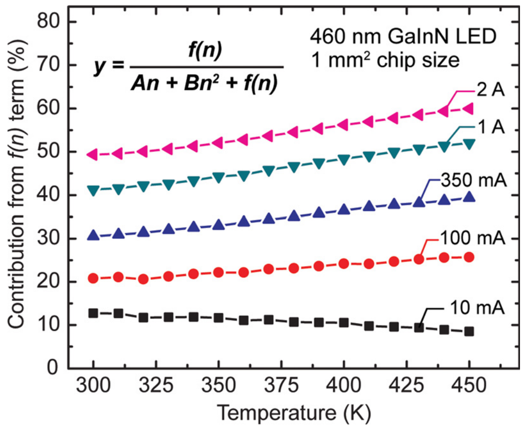

FIG. 3. (Color online) Fraction of $f(n)$ non-radiative recombination at different current levels.

to explain the reduction in LOP at high currents. The inset of Fig. 2 shows the SRH non-radiative lifetime extracted as a function of temperature. The values of the extracted SRH coefficient and the non-radiative recombination lifetime at room temperature, $A = 5.2 \times 10^6\ \text{s}^{-1}$ and 191 ns, respectively, are similar to previous reports.[13,14] The non-radiative recombination lifetime decreases with increasing temperature, finally reaching 38 ns at 450 K (dotted points in the inset of Fig. 2). Based on the theoretical expectations, the relationship between the non-radiative lifetime and temperature can be described by Eq. (4) below, where E_T and E_Fi are the trap energy and intrinsic Fermi level, respectively. τ_0 is a constant that depends on the concentration of traps and the carrier capture rate.[10]

$$\tau_{NR} = \tau_0\left(1 + \cosh\frac{E_T - E_{Fi}}{kT}\right). \tag{4}$$

When the measured data is fitted by Eq. (4), we find that the non-radiative lifetime shows behavior consistent with theoretical expectations.

Figure 3 shows the extracted contribution of $f(n)$ at various current levels (i.e., $f(n)/R$, where $R = An + Bn^2 + f(n)$). It is clear that at all temperatures, the $f(n)$ term contributes more strongly at high currents. For example, at room temperature, the $f(n)$ term accounts for 12.7% of the total recombination at 10 mA and 49.3% at 2 A. Except at 10 mA, the $f(n)$ term increases with increasing temperatures. At 350 mA, the extracted $f(n)$ term increases from 30.5% at room temperature to 39.3% at 450 K. This increase of $f(n)$ contribution may be caused by electrons with increased energy failing to be captured by the active region, more electrons available for overflow due to decreased radiative efficiency, greater thermionic field-assisted emission over the EBL, or increased defect assisted tunneling through the EBL.

Based on this analysis, we can estimate each contribution to the efficiency loss of LEDs at high temperature. At 350 mA, the IQE of this device is 67.8% at room temperature, dropping to 52.0% at 450 K; this corresponds to a measured drop in LOP of 23.4%. This drop can be explained as a combination of both SRH and $f(n)$ contribution. The increase in SRH recombination accounts for 10.4% of this drop in LOP, and the increase in the $f(n)$ term accounts for 13.0%.

In summary, our findings are consistent with the drop in LOP with increasing temperature being attributed to two different mechanisms: the increase in SRH recombination and the increase in the $f(n)$ term. Either of these effects alone cannot explain the downward shifting trends of EQE at both high and low current levels. Under normal operating current densities, a combination of increased SRH recombination and increased $f(n)$ recombination are shown to contribute to reduced light output from the device at high temperatures. In order to improve the high temperature performance of LEDs, two issues must be considered: reducing dislocation density to minimize SRH recombination and eliminating the cause of the $f(n)$ term, which we attribute to electron leakage from the active region.

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