Droop in InGaN light-emitting diodes: A differential carrier lifetime analysis

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To investigate the variation in internal quantum efficiency in InGaN structures, we measure the differential carrier lifetime of an InGaN/GaN double-heterostructure light-emitting diode under varying electroluminescence injection conditions. By coupling this measurement to an internal quantum efficiency measurement, we determine the carrier density and the radiative and nonradiative contributions to the lifetime without making any assumptions on recombination processes. We find that droop is caused by a shortening of the nonradiative lifetime with current. The observed shortening of both radiative and nonradiative lifetimes with current is found to be in excellent agreement with an *ABC* model including phase-space filling. © *2010 American Institute of Physics*. [doi:10.1063/1.3330870]

The internal quantum efficiency η_{int} of GaN-based light-emitting diodes (LEDs) peaks at low current density J, and decreases at the current densities required to operate power LEDs ($\sim 100-1000$ A cm^{-2}), a phenomenon known as droop[1,2] whose origin is a subject of controversy. It was recently suggested that Auger recombination is the cause of this behavior.[3] This is supported by the fact that the efficiency curve of a III-nitride structure can well be fitted by a simple *ABC* theory where A, B, and C represent the Shockley–Read–Hall (SRH), radiative, and Auger contributions. However, there has not been to date any direct experimental evidence of Auger scattering. Other proposed hypotheses include the delocalization of carriers at high injection[4] and carrier overflow induced by the piezo and junction fields.[5] From the theoretical standpoint as well there is some controversy. Early results concluded that Auger scattering should be weak,[6] but this conclusion was questioned when higher-order conduction bands[7] or phonon contributions[8] were considered.

In this article, we study the differential carrier lifetime in a GaN/InGaN LED. By coupling the data with an internal quantum efficiency (η_{int}) measurement, we obtain the evolution of the radiative and nonradiative lifetimes versus carrier density without making any assumption on the recombination processes. We observe a reduction in the nonradiative lifetime with increasing carrier density, which we compare to an *ABC* model.

The studied sample is a (0001) GaN LED whose active region is an InGaN double heterostructure (DH) of thickness $t_{\text{AR}}=15$ nm emitting at $\lambda \sim 430$ nm, similar to the samples of Ref. 2. To evaluate η_{int} for the LED, we measure its external quantum efficiency in a simple planar geometry where extraction efficiency is known, as in Ref. 9. We obtain a peak η_{int} of $\sim 65\%$.

The differential carrier lifetime τ at carrier density n_0 is related to the total recombination rate $G=J/e \times t_{\text{AR}}$ and to the carrier density n by the following:

$$\tau^{-1} = \frac{\partial G}{\partial n}\Big|_{n=n_0}. \tag{1}$$

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To determine τ, we fabricate vertically injected LEDs with a small mesa size (100 μm) probed on-wafer, in order to avoid package and contact parasitics. The LED is injected with 3 μs pulses (to avoid heating), under varying voltage V. A small AC voltage (frequency ω, amplitude $V_{\max}=50$ mV) is added to this pulse and serves as a probe for the lifetime measurement. The light output is collected with a photomultiplier and the current running through the LED is measured with a high-frequency current probe. The phase shift φ between the AC components of the current and the light output is then

$$\tan(\varphi) = \omega\tau. \tag{2}$$

To reduce the measurement noise, φ is measured with varying ω in a range 10–100 MHz and Eq. (2) is fitted to yield τ. In contrast to "large pulse" decay measurements where the bias is switched from V to 0, here τ is measured at a set applied bias V. This is important in III-nitrides where fields influence wave function overlaps, and varying V can considerably alter the lifetime as shown in Ref. 10. In addition, by measuring the phase shift between current and light, we avoid impedance-related artifacts common in optical small-signal measurements.[11]

Figure 1(a) shows the result of the lifetime measurement. The corresponding η_{int} is shown in Fig. 1(b). The carrier density can then be determined exactly, assuming perfect injection efficiency, from the knowledge of τ (Ref. 12)

$$n = \int_0^G \tau \times dG. \tag{3}$$

In Eq. (3) the integral runs from $G=0$, whereas τ can only be measured down to a finite value of $J_{\min}$ (in practice until there is no optical signal). The usual procedure to deal with this is to interpolate τ to obtain its limit value τ_{SRH} at low J.[12] Here since η_{int} is known, we make the more accurate approximation[13]

$$\tau_{\text{SRH}} = \tau \times \frac{1+\eta_{\text{int}}}{1-\eta_{\text{int}}} \tag{4}$$

With this value of τ_{SRH} we can evaluate Eq. (3), as shown on Fig. 2. With the knowledge of τ, n, and η_{int}, we

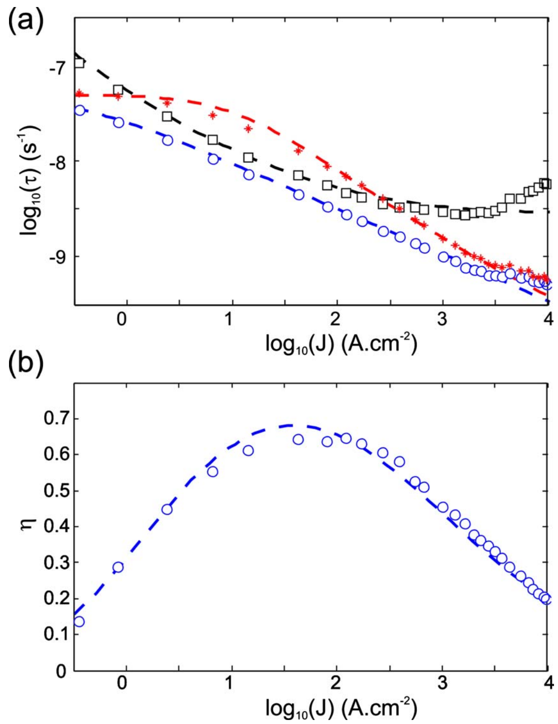

FIG. 1. (Color online) (a) Symbols: experimental differential lifetimes vs current density-total (circles), radiative (squares), and nonradiative (stars). Dashed lines: fit by an *ABC* model. (b) Circles: experimental η_{int} of the LED. Dashed line: fit by an *ABC* model.

can now determine the radiative (R) and nonradiative (NR) contributions to the lifetime owing to

$$\tau_{\mathrm{R}}^{-1} = \frac{dG_{\mathrm{R}}}{dn} = \eta_{\mathrm{int}}\tau^{-1} + G \times \frac{d\eta_{\mathrm{int}}}{dn},$$

$$\tau_{\mathrm{NR}}^{-1} = \frac{dG_{\mathrm{NR}}}{dn} = (1-\eta_{\mathrm{int}})\tau^{-1} - G \times \frac{d\eta_{\mathrm{int}}}{dn}. \tag{5}$$

These are shown in Fig. 1(a). At low J, τ_{NR} reaches a constant value $\tau_{\mathrm{SRH}} \sim 45$ ns. Meanwhile τ_{R} decreases as the radiative rate increases. At higher J, in the droop regime, τ_{NR} decreases, indicating the onset of an additional nonradiative process. At very high J, τ_{R} reaches a limit value ~ 3 ns: the saturated radiative lifetime, which we attribute to phase-space filling as explained below.

So far no assumption has been made on recombination processes in determining n, τ_{R}, and τ_{NR} [aside from Eq. (4)

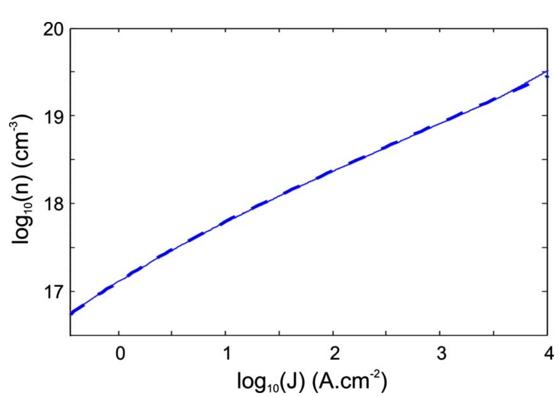

FIG. 2. (Color online) Relationship between current density and carrier density. Full line: experimental data. Dashed line: fit by an *ABC* model.

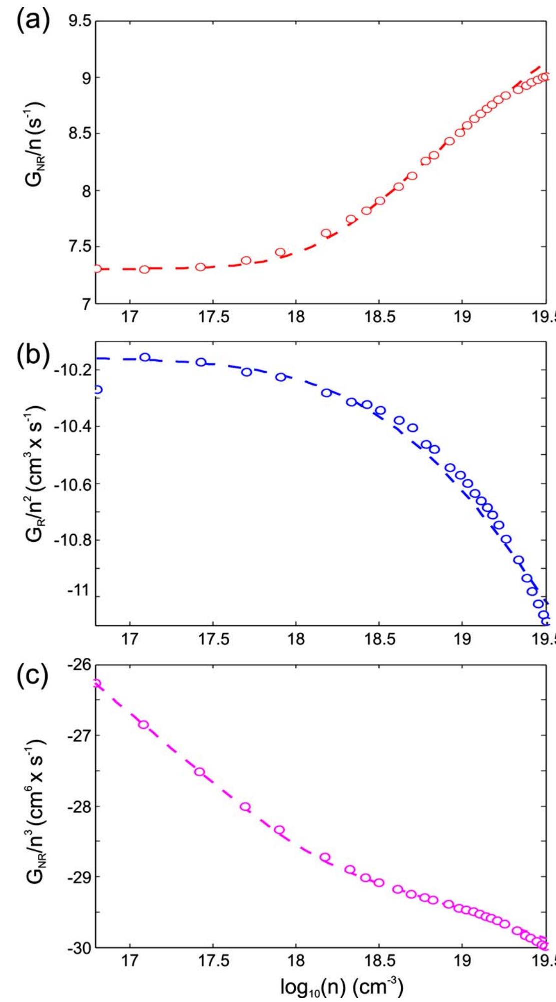

FIG. 3. (Color online) Open circles: experimental radiative and nonradiative coefficients vs n. Dashed lines: fit by an *ABC* model. (a) G_{NR}/n: the value at low n yields the SRH coefficient A. (b) G_{R}/n^2: the value at low n yields the radiative bimolecular coefficient B_0, while the reduction at high n is attributed to phase-space filling. (c) G_{NR}/n^3: the value at high n yields the Auger coefficient C.

which has a minimal impact on the result]. We now compare this data with a model. Figure 3 shows three quantities versus n as follows: (a) G_{NR}/n, (b) G_{R}/n^2, and (c) G_{NR}/n^3. In an *ABC* model $G_{\mathrm{R}}=Bn^2$ and $G_{\mathrm{NR}}=An+Cn^3$. Therefore (a) should be constant for low J and equal to A, (b) should be constant and equal to B, and (c) should be constant for high J and equal to C.

As seen on Fig. 3, (b) is indeed constant at low J but decreases at large J. We attribute this to the influence of Fermi–Dirac carrier statistics on recombination processes, also called phase-space filling.[14] Specifically the form $G_{\mathrm{R}} = Bn^2$ is only valid at low enough carrier density where the electron and hole distributions are Boltzmann-like. At degenerate carrier density, radiative recombinations become monomolecular (e.g., the integral over carrier density in Fermi's Golden rule becomes independent of n): $G_{\mathrm{R}} \sim n$. To quantify this effect, we use a simple two-band model and compute the theoretical spontaneous emission in bulk GaN.[15] The result, shown in Fig. 4, can be very well fitted with an expression of the form $B=B_0/(1+n/n^*)$ with the fitting parameter $n^*=2\times 10^{19}$. Although the model is crude it can be used to get a rough estimate of n^*. Likewise, the Auger term is expected to

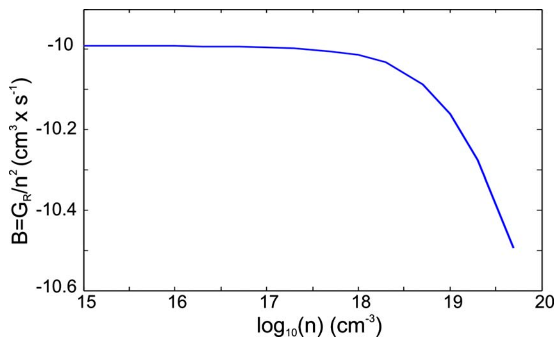

FIG. 4. (Color online) Calculated B coefficient in a two-band model. The observed effect of phase-space filling is integrated in the *ABC* model.

become subcubic, and we assume a heuristic form $C = C_0/(1+n/n^*)$ following Ref. 14.

We now integrate the effect of phase-space filling in the expressions for B and C. We obtain an excellent fit to the experimental data, as shown by the dashed lines in Fig. 3. The fitting parameters are $A=2\times10^7$ s^{-1}, $B_0=7\times10^{-11}$ cm^3 s^{-1}, $C_0=10^{-29}$ cm^6 s^{-1}, and $n^*=0.5\times10^{19}$ cm^{-3} (this adjustment to n^* improves the fit). We note that the value obtained for B_0 is similar to the theoretical bulk value obtained from the two-band model shown in Fig. 4 ($B_0=10^{10}$ cm^3 s^{-1}). This suggests that the DH studied here has a behavior which is rather close to bulklike. Note that we should not expect a better quantitative agreement because (i) the theoretical model used here is simplistic (it notably ignores many-body effects which should significantly increase B_0 for low carrier density[15]) and (ii) some wave function-overlap effects are still expected as the DH is not really flat-band (some potential kinks at its edges are expected as shown in Ref. 3). The values of A, B, and C can now be used to fit Figs. 1 and 2. Again, the various lifetimes, η_{int} and n are very well reproduced by the model. Importantly, phase-space filling alone does not account for droop: in the absence of the C term, η_{int} would saturate at a constant value at high J. The main contribution to droop is the shortening of the nonradiative lifetime, with variations in the radiative term playing a secondary role.

The present data is therefore in quantitative agreement with the hypothesis of Auger scattering. In principle, other mechanisms can be considered. Interband absorption (IBA) is another nonradiative process with n^3 behavior. However, it is related to optical reabsorption so that it should be strongly influenced by geometric factors (sample shape and design, electroluminescence versus photoluminescence). Droop appears to have a universal, geometry-independent behavior, which is compatible with Auger scattering but not with IBA. Regarding transport-related effects, energetic carriers flying over the active region would not influence the lifetime of carriers trapped in the active region and cannot account for the observed lifetime reduction. The present data cannot rule out a scenario of carrier capture-and-escape, although we are not aware of a theoretical basis for such a process being n^3. Finally, stimulated emission effects (as seen in Refs. 16 and 17) are not expected to be strong here since there is less than one photon per mode in this LED structure up to high current densities. Although our data only pertains to a sample emitting at 430 nm, our conclusions are in good agreement with those of Ref. 3 where a wider range of In contents is studied.

In conclusion, we performed a differential carrier lifetime measurement. The carrier density is obtained without assuming a recombination model. The data can be closely matched by an *ABC* model including phase-space filling. In particular, droop is caused by a shortening of the nonradiative lifetime at high current density which is in quantitative agreement with Auger scattering. Phase-space filling is also revealed to reduce the radiative and nonradiative rates at high carrier density.

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