On resonant optical excitation and carrier escape in GaInN/GaN quantum wells

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Recently, photoluminescence studies using resonant optical excitation in GaInN layers have been used to investigate the physical origin of efficiency droop in GaInN/GaN light-emitting diodes. In these studies, it has been assumed that in the case of resonant excitation, where electron-hole pairs are generated in the GaInN layers only, carrier transport effects play no role. We report that in contrast to this assumption, carrier escape from quantum wells does take place and shows strong dependence upon the duration of excitation and bias conditions. We also discuss the time scales required to reach steady-state conditions under pulsed optical excitation. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3089691]

The efficiency droop in GaInN/GaN light-emitting diodes (LEDs) is the well-known and intensely studied decrease in efficiency as injection current density surpasses relatively low values, typically less than 10 A cm^{-2}. The physical origin of the efficiency droop remains controversial and several mechanisms have been suggested as explanations, including electron leakage enabled by sheet charges at heterointerfaces,[1–3] poor hole injection efficiency,[4–7] Auger recombination,[8,9] and carrier delocalization from In-rich low-defect-density regions at high carrier densities.[10]

Characterization of GaInN layers by photoluminescence (PL) using resonant optical excitation at varying excitation power is a popular approach to investigating the efficiency droop; studies have been performed on both GaInN/GaN multiquantum well (MQW) LEDs[1,6] and double heterostructures.[8] Resonant optical excitation ensures that the pump laser is absorbed and therefore, electrons and holes are generated in the GaInN layers only. In this case, the generation rate for electrons and holes will be identical. By contrast, under electrical bias, the injection rates for electrons and holes into a GaInN/GaN quantum well or double heterostructure will be different if carrier leakage takes place. This fundamental distinction motivates use of resonant optical excitation to study the efficiency droop.

Commonly in resonant excitation experiments, it has been assumed that carrier-transport-related mechanisms can be neglected—specifically, that the escape rates for electrons and holes from GaInN quantum wells are both equal to zero.[1,6,8,11] If this is true, electron-hole pairs are created and must recombine in the GaInN active layer only and the dependence of PL intensity upon pump power can be used to determine the true radiative efficiency of the GaInN active layer. This assumption, together with occurrence of a reduction in efficiency at very high PL excitation has been used to argue that Auger recombination is the cause of efficiency droop in GaInN/GaN LEDs.[8,9] However, here we report measurements on GaInN/GaN MQW LEDs, which demonstrate that carriers actually do escape from the quantum wells and that carrier transport cannot be neglected even for resonant optical excitation experiments. This result indicates that radiative efficiency cannot be determined directly from the ratio of PL intensity to pump power and raises questions about the argument that the efficiency droop is caused by Auger recombination.

The LEDs used in our experiments are grown on (0001) oriented sapphire substrates by metal-organic chemical vapor deposition, and consist of a 2.8 μm thick *n*-type GaN lower cladding layer, a five-period GaInN/GaN MQW active region that emits at approximately 460 nm with 3 nm GaInN quantum wells and 12 nm Si-doped GaN quantum barriers, a 50 nm *p*-type AlGaN electron-blocking layer, and a 70 nm *p*-type GaN upper cladding layer. The wafer is processed into lateral LED structures with side-by-side *n*-contact and transparent indium tin oxide *p*-contact. The sapphire is thinned to approximately 80 μm thickness and then diced into individual LED chips 300×300 μm^2 in size. Electroluminescence begins just above 2.2 V forward bias. A 405 nm laser diode is focused on the center of the LED to a spot less than 25 μm in diameter. The laser is operated in pulsed mode with a pulse width of 20 μs and a 1 kHz repetition rate unless otherwise noted. The minimum pulse width is limited by the current rise time of our laser driver, which is approximately 4 μs. Output power of the laser can be continuously varied by sweeping the injection current of the laser diode; peak optical power density in excess of 8 kW cm^{-2} is achievable. The LED is characterized under open circuit conditions, short circuit conditions, and with an applied voltage.

The occurrence of carrier escape from the quantum wells is verified by measurement of a reverse photocurrent when the pump laser is directed at the LED, and has been reported previously in connection with studies of the piezoelectric field strength in GaInN quantum wells.[12,13] Carriers that escape from the quantum well experience the strong electric field due to the built-in potential of the junction. Electrons accelerate toward the *n*-type region while holes accelerate

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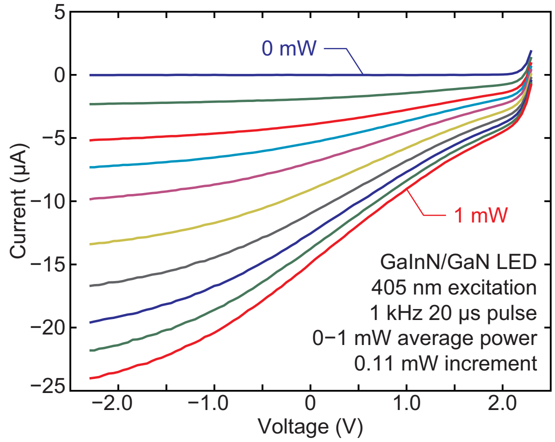

FIG. 1. (Color online) Current-voltage characteristic of the GaInN LED for several incident optical pump power levels.

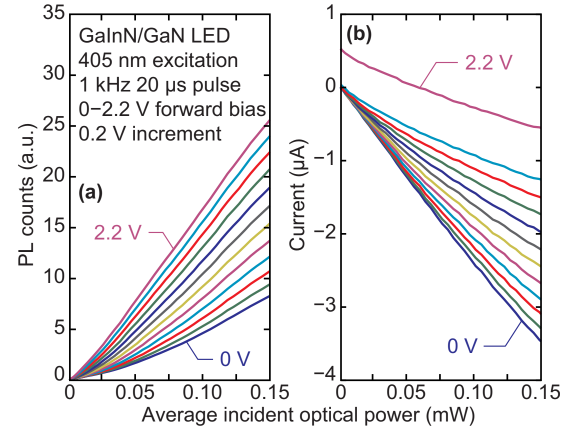

FIG. 2. (Color online) (a) LED PL emission and (b) current as a function of optical pump power for several forward bias voltages.

toward the p-type region, and therefore reverse current flows. Figure 1 shows the current-voltage relationship of the LED with various excitation densities as well as completely without optical excitation. At all bias conditions and pump power levels, significant photocurrent flows through the LED.

The measured photocurrent at 1 mW average pump optical power and 2.3 V reverse bias is 24 μA, which corresponds to 1.5×10^{14} carriers per second, roughly 7% of the incident photon number and approaching the total number of absorbed photons. As the forward voltage is increased, the reverse current decreases; however, this decrease is not necessarily proportional to a decrease in escaping carriers. In a simple homojunction photodetector, photon absorption leads to a photocurrent of magnitude equal to the number of electron-hole pairs generated in the depletion region, plus the number electron-hole-pairs generated in the n-type and p-type regions which diffuse toward the depletion region. Less than half of electron-hole pairs generated outside of the depletion region contribute to the photocurrent. Therefore, as the depletion region width decreases under forward bias, the photocurrent will also decrease. In a GaInN/GaN MQW LED, increasing forward bias will position more quantum wells outside of the depletion region and result in a decrease in the photocurrent even if the carrier escape rate remains the same. We note that even if the measurements are performed in structures having no p-n junctions, the high internal electric fields of the nitride material system may lead to similar carrier transport effects.

Of course, carriers forming the photocurrent do not recombine radiatively, and so PL intensity is reduced as the reverse voltage increases. Figure 2(a) shows the PL intensity as a function of the pump laser power for a range of forward voltages. The increase in PL with increasing forward bias is very apparent; at a forward voltage of 2.0 V and average pump power of 0.15 mW, the PL intensity is nearly 2.9 times larger than the short circuit intensity. This increase is attributed to reduced carrier escape and increased carrier recapture; the recombination efficiency of carriers in the quantum well should actually be lower since the quantum-confined Stark effect increases under forward voltages.[13] When reverse voltages are applied, the PL intensity decreases further. Figure 2(b) shows the photocurrent as a function of pump laser power for the same forward voltages as in Fig. 2(a).

If the LED is left in an open circuit configuration, the electrons and holes forming the reverse current accumulate on the n-type and p-type sides, respectively. As in a capacitor, these excess charges induce a forward voltage on the LED. In steady state, the forward voltage is such that the photocurrent and forward current are equal and opposite; in this way, the requirement of zero net current for an open circuit device is satisfied. In general, since the forward current is exponentially related to the bias voltage, even a very wide range of laser pump powers will result in similar open circuit voltages.

When the pump laser is pulsed, of concern is the time to reach the steady-state open circuit voltage. This time is determined by the magnitude of photocurrent—which changes as the bias voltage increases, but is related to the incident optical power—and the area of the LED, which affects its capacitance. Unprocessed wafer samples, due to large current spreading resistance in p-type GaN, may have an effective active area smaller than the physical size of the sample. Figure 3 shows the open circuit voltage as a function of time for several pump laser power levels; note that the steady-state open circuit voltage can be above the threshold for electroluminescence. The voltage is measured using an oscilloscope with 1 MΩ input impedance. For low laser pump powers, the rise time can be significant and is in excess of 10 μs for an average pump power of 0.1 mW. This transient

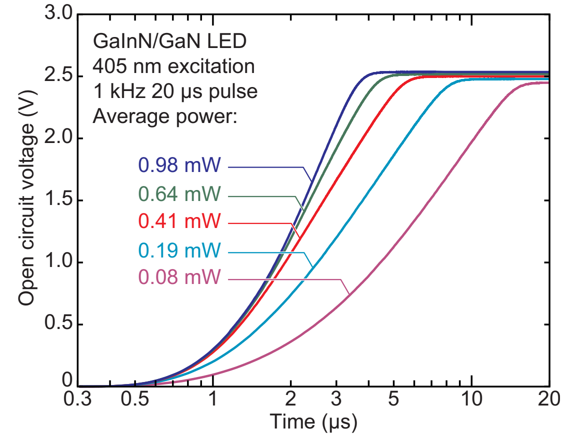

FIG. 3. (Color online) Open circuit voltage as a function of time measured across a 1 MΩ resistor for several optical pump power levels.

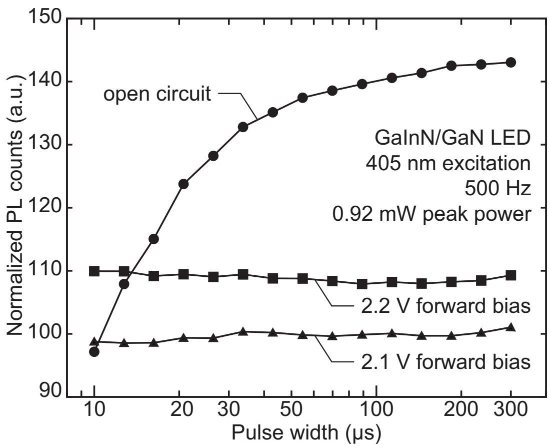

FIG. 4. LED PL emission normalized to the number of photons in the pump laser pulse as a function of pulse width for open circuit configuration and applied bias.

is much longer than any recombination or scattering lifetime for carriers in the quantum wells.

When the laser pulse is shorter than the rise time of the forward voltage, the PL power is greatly affected. In the case of such a short pulse, the open circuit voltage never builds up to its steady-state value; as seen in Fig. 2, PL power is significantly decreased at lower forward voltages. As a result, when the pulse width is decreased, the PL power is also reduced. This effect is demonstrated in Fig. 4, which shows the normalized PL power as a function of pulse width for a true open circuit configuration as well as with fixed 2.1 and 2.2 V forward biases. In contrast to the open circuit configuration, when the LED has a fixed voltage applied, the current in the external circuit flows only while the carriers are moving through the depletion region[14,15] and pulse-width dependence of PL power is avoided. In the case of the open circuit configuration, what truly matters is the total number of photons in each pump laser pulse and the area of the LED; a higher intensity laser pulse will give a faster rise in the open circuit voltage but the total number of photons will determine the peak voltage that is reached. The LED area determines the amount of charge—that is, optically generated electrons and holes—required to induce the steady-state voltage.

In conclusion, we report measurements of substantial photocurrent in GaInN/GaN MQW LEDs under resonant optical excitation for zero bias and bias voltages up to the electroluminescence threshold. As the forward bias is increased, PL intensity increases and photocurrent decreases. These measurements indicate that carrier escape does take place and cannot be neglected in the case of resonant optical excitation. Further, we show that open circuit PL measurements are very sensitive to the total number of photons in a pulse of the excitation source—that is, both pulse width and duration—due to the long-time transients associated with the buildup of an open circuit voltage. These results shed considerable doubt on the ability of basic resonant excitation experiments to assess radiative efficiency and the individual contributions of monomolecular nonradiative, bimolecular radiative, and Auger recombination to total carrier loss from GaInN/GaN quantum wells.

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