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Auger-generated hot carrier current in photo-excited forward biased single quantum well blue light emitting diodes

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We report on measurements of the photo-modulated current-voltage and electroluminescence characteristics of forward biased single quantum well, blue InGaN/GaN light emitting diodes with and without electron blocking layers. Low intensity resonant optical excitation of the quantum well was observed to induce an additional forward current at constant forward diode bias, in contrast to the usual sense of the photocurrent in photodiodes and solar cells, as well as an increased electroluminescence intensity. The presence of an electron blocking layer only slightly decreased the magnitude of the photo-induced current at constant forward bias. Photo-modulation at constant forward diode current resulted in a reduced diode bias under optical excitation. We argue that this decrease in diode bias at constant current and the increase in forward diode current at constant applied bias can only be due to additional hot carriers being ejected from the quantum well as a result of an increased Auger recombination rate within the quantum well. *Published by AIP Publishing.*
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Blue InGaN/GaN light emitting diodes (LEDs) form the basis of efficient solid-state white lighting. One mechanism limiting LED bulb efficiency is the "efficiency droop" phenomenon, where the efficiency of an LED decreases above a certain operating current density. Therefore, to achieve a given light output power efficiently, large area devices, or several small area devices, are used to reduce the operating current density.

Several mechanisms for LED efficiency droop have been proposed (reviewed elsewhere[1–4]), including carrier overshoot of the quantum well (QW) active region, thermionic escape of carriers out of the QW(s), and non-radiative Auger recombination in the QW(s). Recently, high-energy electron emission into ultra-high vacuum (UHV) from the surface of an operating blue LED has been reported,[5] confirming the presence of Auger recombination. These electroemission spectroscopy experiments require a UHV environment, a custom large area device and contact geometry, and a clean cesiated surface. The technique is also only sensitive to hot electrons although both hot electrons and hot holes may be produced by Auger processes within the LED, via electron-electron-hole (eeh) or electron-hole-hole (ehh) processes, respectively. Therefore, a complementary, and simpler, technique for detecting Auger recombination, sensitive to both types of hot carriers, would be of interest to further study the efficiency droop in InGaN LEDs.

In this letter, we report on a benchtop measurement of the modulation of the current-voltage (IV) characteristic and electroluminescence (EL) intensity of single quantum well (SQW) blue InGaN/GaN LEDs under resonant optical excitation of the QW. A schematic of the observed changes in the IV characteristic is shown in Fig. 1. Additional forward current is observed in forward bias under optical excitation, in LEDs with and without an AlGaN electron blocking layer (EBL). We attribute this additional forward current to a photo-induced increase in the Auger-generated hot carrier current within the device.

The fate of the hot carriers produced by Auger recombination is typically absent from discussions of carrier transport in InGaN/GaN LEDs. However, as early as the 1980s, it was recognized that hot carrier generation in the active region of GaInAsP/InP double-heterostructure LEDs and lasers could lead to additional minority carrier current in those devices.[6] Römer *et al.*[7] made an attempt to account for possible recapture of the ejected hot carriers back into the QW(s) of InGaN/GaN blue LEDs, but the carrier escape direction was not discussed. Also, Vampola *et al.*[8] considered "Auger-assisted electron overflow" as a potential explanation for luminescence from a QW embedded in the p-region of electrically injected blue LEDs.

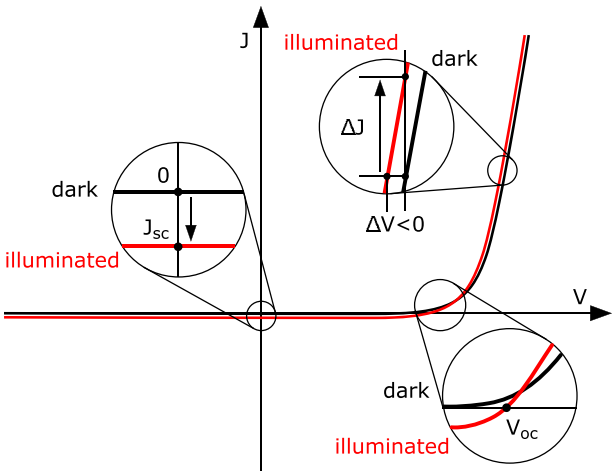

FIG. 1. A schematic showing the observed effect of resonant optical excitation of the QW on the IV characteristic of a SQW c-plane blue InGaN/GaN LED. At voltages below the open-circuit voltage, V_{OC}, the photo-induced current is in the conventional, reverse direction. At higher forward voltages, the photo-induced current is observed to switch the direction.

Li *et al.*[9] reported a photo-induced forward current in a forward biased green multiple quantum well (MQW) InGaN/GaN LED. A very high excitation power density was used (~500× higher that in this work), and the potential role of hot carriers in the photo-induced current was not discussed. Ahn *et al.*[10] reported measurements of the photo-induced forward current in blue MQW LEDs. The photo-induced current was attributed to "carrier spill-over"—escape of carriers from the QWs by thermionic emission in the forward direction—but no alternative mechanisms were discussed. As such, their measurements do not provide more information than the embedded p-side QW experiment reported in the paper by Vampola *et al.*,[8] where it was concluded that "… the mechanism responsible for electron overflow is undetermined and may be different for the two test structures. Both traditional overflow mechanisms and Auger-assisted electron overflow mechanisms are capable of explaining this data."

Complicating the interpretations in the previous reports of forward photo-induced current are that the LEDs analyzed had MQW active regions. It is well known that carriers are not uniformly injected into each of the QWs in a MQW LED.[11] In contrast, the absorption of the optical excitation is nearly uniform across all the QWs, making the photoresponse a weighted average of each of the QWs, all with different carrier densities.

The measurements reported herein were performed on blue SQW c-plane InGaN/GaN LEDs with peak EL emission wavelengths of 450 ± 5 nm from 1 A/cm^2 to over 100 A/cm^2. The epitaxial layers were grown on flat sapphire by metal-organic chemical vapor deposition, at UCSB. The device layers in the LEDs without an EBL were, in the order grown after the buffer layer, 1.1 μm of Si:GaN, a 6 period (8 nm/3 nm) GaN/$In_{0.05}Ga_{0.95}N$ superlattice, 43 nm of Si:GaN, 7 nm of unintentionally doped (UID) GaN, a single 3 nm UID $In_{0.16}Ga_{0.84}N$ QW, 7 nm of UID GaN, 200 nm of Mg:GaN, and a p+ Mg:GaN contact layer, as shown in Fig. 2(b). In the LEDs with an EBL, the first 8 nm of the Mg:GaN layer were instead Mg:AlGaN.

LEDs were fabricated from 1 cm^2 pieces, and the devices were left on-wafer. They had circular etched 0.1 mm^2 mesas, Ti/Au n-contacts completely surrounding the mesas, and ~30% transparent Pt/Au p-contacts for near ideal current spreading. The device was probed with off-mesa contact pads. The p-pad metallization was brought off the mesas with 300 nm of SiO_2 as an insulating underlayer to prevent shorting on the mesa sidewall. The p-contact covered ~75% of the mesa area, and ~87.5% of that injected area was exposed to the laser excitation through the contact.

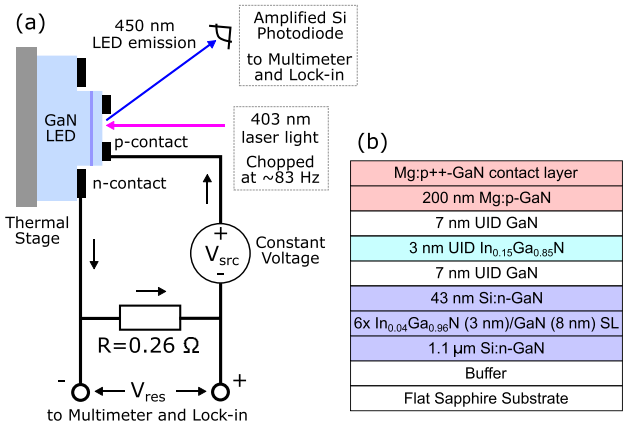

FIG. 2. (a) A schematic of the experimental apparatus, showing the circuit for measuring the photo-induced current at constant voltage. To measure the voltage drop at constant current, the voltage across the LED was measured instead of just the voltage across the resistor network. (b) A schematic of the epitaxial layers in the LEDs measured.

A 100 mW continuous wave (CW) 403 nm Coherent Cube laser was used to resonantly excite carriers selectively into the blue-emitting QW. A series of neutral density filters was used to adjust the incident power. A 1 mm diameter pinhole was placed after the filters to limit the beam area to a known value. A calibrated silicon photodiode was used to measure the beam power after the pinhole. A schematic of the experiment is shown in Fig. 2(a).

The back of the LED die was coated with an absorbing colloidal graphite paint to limit multiple pass reflections of the laser light through the QW of the device. To reduce self-heating under high forward current densities, the LED die was attached with thermally conducting paste to an aluminum heat sink and a thermoelectric stage controlled to 25 °C.

The LED was driven with a Keithley 2400 sourcemeter, in a 4-wire configuration. A 0.26 Ω resistor network was placed in series with the LED to allow the measurement of the current through the LED (and its modulation) without adding too much to the series resistance of the circuit. The order in which the data were measured was randomized by the computer control program to transform any remaining systematic error from self-heating in the LED into random scatter in the measured data.

A biased silicon photodiode fitted with simple collection optics was used to collect a portion of the LED EL emission. A long wave pass filter prevented scattered laser light from impinging on the detector. The effective blocking of the pump light was confirmed with the LED biased in reverse, where the photoluminescence of the QW is below the noise floor of the detector. The absence of photoluminescence of the diode in reverse bias is indicative of effective carrier sweep out.

Because the photo-induced current in the LED was small compared to the total forward current, lock-in detection was necessary to measure the modulated LED current and relative EL intensity. The laser light was chopped at ~83 Hz, and a lock-in amplifier was used to detect the modulated signals. The response times of the photodiode and the sourcemeter were much shorter than the period of the modulated optical excitation.

During the measurement, the room lights were kept off. The intensity of the laser light was controlled to be low enough (5.7–6.0 W/cm^2) to produce a linear response in the LED with pump power.

Several LEDs, with and without EBLs, were analyzed and found to have very similar optical and electrical characteristics, including the measured photo-induced currents under forward bias. The photo-induced voltage drop, ΔV, and the dynamic resistance (derivative of the IV characteristic) are shown in Fig. 3(a) for representative LEDs, with and without an EBL. The photo-induced current, ΔJ, at constant applied voltage is shown in Fig. 3(b), for the same LEDs. The magnitude of ΔJ was observed to decrease only slightly in the LEDs with an EBL, compared to those without. Also

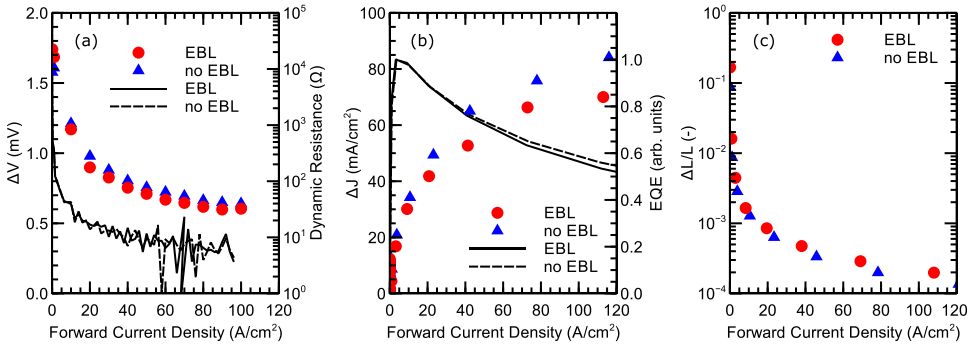

FIG. 3. (a) The absolute value of the voltage drop, ΔV (symbols), obtained from measurements under current control, as well as the dynamic resistance of the diode (lines), for representative LEDs with (circles/full line) and without (triangles/dashed line) an EBL. (b) The photo-induced current density, ΔJ (symbols), obtained from measurements under voltage control, as well as the normalized external quantum efficiency (EQE) (lines), for the same LEDs as in (a). (c) The normalized increase in the EL intensity, ΔL/L, obtained from measurements under voltage control, for the same LEDs as in (a).

shown are the normalized relative external quantum efficiencies (EQEs) of the same LEDs.

The conventional photocurrent at −1 V, which serves as the lower bound on the optical generation rate of carriers in the QW, was measured to be $<20\,\text{mA/cm}^2$ in all devices. This lower bound is exact for a 100% escape probability in reverse bias and is a very good approximation in III-nitride solar cell structures optimized for high escape efficiency.[12,13] The LEDs discussed herein were not optimized. Nonetheless, the measured values of the conventional photocurrent are consistent with an absorption coefficient similar to values reported in the literature (of the order of $\sim 1 \times 10^5\ \text{cm}^{-1}$),[14] assuming 100% escape probability and 30% p-contact transparency. That the photo-induced forward current exceeds the generation rate of carriers in the QW throughout most, if not all, of the droop regime of the diode (current densities $\gtrsim$5–10 A/cm^2) suggests that the increase in current results from a nonlinear process.

Figure 3(c) shows the normalized increase in the relative EL intensity of the LEDs under forward bias, in voltage control. That the EL increases implies that the carrier density in the QW is increasing. Additionally, the relative EL increase provides an approximation of the relative increase in the carrier density in the QW, which is small at current densities higher than where the external quantum efficiency (EQE) peaks. Thus, the photo-excitation is only a small positive perturbation to the QW carrier densities.

The measured drop in voltage, ΔV, at constant current [Fig. 3(a)] and the increase in current density, ΔJ, at constant voltage [Fig. 3(b)] are consistent with the dynamic resistance of the diode [Fig. 3(a)].

Since the photo-excitation resonantly pumps the QW, photo-induced carriers must escape the QW for there to be any photo-induced current through the device, at constant diode bias. Current which overshoots the QW entirely is not directly affected by the resonant photo-excitation of the QW.

We consider three possible carrier escape mechanisms for the QWs: (1) tunneling, (2) thermionic emission, and (3) hot carrier production by Auger recombination.

As the measured photo-induced current is in the forward direction, it cannot be due to carriers tunneling out of the active region. Tunneling escape, if present, must produce reverse current as there are no available states for carriers to tunnel into in the forward direction [Fig. 4(a)].

Thermionic emission of *electrically injected* carriers out of the QW will contribute to forward current if *any* of the escaping carriers travel in the forward direction (towards the p-side for electrons or the n-side for holes). Electrically injected carriers escaping in the reverse direction do not produce a net current as they just cancel the forward injection current, as shown in Fig. 4(b).

On the other hand, thermionic escape of *photo-excited carriers*, generated within the QW, can only produce a net reverse current as the *majority* of escaping carriers are swept out by the residual built-in field of the junction, as shown in Fig. 4(c). Thus, the photoresponse to optical modulation of the thermionic emission rate of carriers out of the QW can

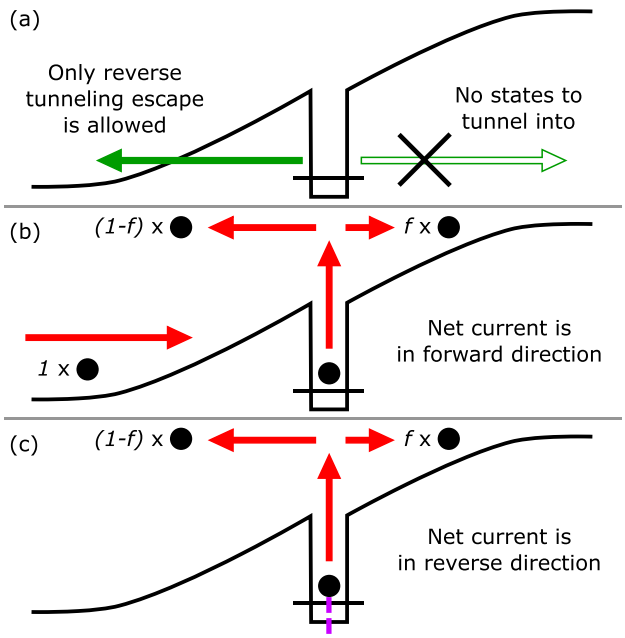

FIG. 4. Schematics depicting (a) tunneling escape and (b) and (c) thermionic emission in the conduction band of a SQW LED, at a sufficient injected carrier density in the QW to screen the built-in and piezoelectric fields. The situation for the valence band is analogous. (a) Tunneling escape out of the QW can only occur in the reverse direction as there are no final states in the forward direction. (b) Thermionic emission of electrically injected carriers produces a net forward current equal to the fraction, f, which escape forward. (c) Thermionic emission of photo-excited carriers produces a net current equal to the net forward escape rate. This current can only ever be in reverse, on net, because $f < 0.5$ due to the higher barrier to escape in the forward direction.

only be a net reverse current and cannot be responsible for the observed increase in forward current.

So, as tunneling and thermionic emission cannot be the source of the observed photo-induced forward current, only escape of Auger-generated hot carriers remains as an explanation. Unlike thermionic escape, Auger-induced escape of photo-excited carriers can cause a net increase in the forward current because it is an inherently multi-body process which can involve both electrically injected and photo-excited carriers.

Increased Auger recombination in the photo-excited state is additionally consistent with the observed increase in EL intensity, as well as with the lack of a significant reduction in the photo-induced current upon insertion of an EBL into the LED. This is because transport of high energy hot carriers should be relatively unaffected by an EBL, which provides a barrier that is smaller than the kinetic energy of Auger-generated hot carriers. The blocking efficiency of an AlGaN EBL for non-hot carriers is controversial however,[15,16] and the lack of a significant reduction is not *on its own* a confirmation that Auger-generated hot carriers are the cause of the photo-induced forward current. It is nonetheless useful information since the opposite result, a significant reduction in photo-induced current, would have ruled out hot carriers as the cause—it is hard to imagine carriers with such high energy being blocked by the AlGaN layer.

The way in which Auger-generated hot carriers produce forward current in an LED will now be discussed in more detail. Figure 5 shows how the different types of recombination in the QW affect the net forward current through the LED, in the steady state. Figures 5(a)–5(c) depict recombination of electron-hole pairs which have been electrically injected, and Figs. 5(d)–5(f) depict recombination of optically injected electron-hole pairs. For Shockley-Read-Hall (SRH) and radiative recombination, there is only the forward current required to inject the recombining carriers. For

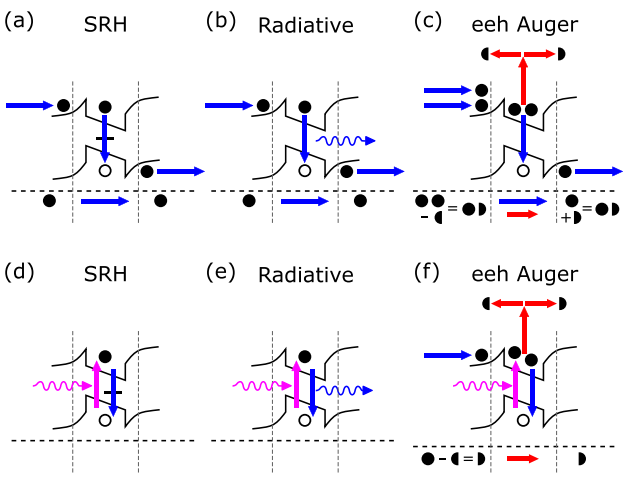

FIG. 5. (a), (b), and (c) show the average current flow per recombination event, in the steady state, with only electrical injection of carriers into the QW, for Shockley-Read-Hall (SRH), radiative, and eeh Auger, respectively. (d), (e), and (f) show the average current flow per recombination event, in the steady state, for an optically injected electron-hole pair, for SRH, radiative, and eeh Auger, respectively. It is assumed for definiteness that the fraction of forward escaping hot carriers is exactly half, though this need not be the case. The band diagrams are not to scale and are for illustration purposes only. Filled disks: electrons; empty circles: holes.

electrically injected electron-hole pairs, this is one electron of current through the circuit per recombination event (full, filled circles in the figure). For optically injected electron-hole pairs, no current needs flow for SRH or radiative recombination.

The situation is different for Auger recombination. For brevity, only eeh Auger recombination is depicted [in Figs. 5(d) and 5(f)] although the situation is analogous for ehh Auger recombination. For purely electrical carrier injection, not only does the recombining pair of carriers need to be injected from the contacts but also the eventual hot carrier (an electron for eeh and a hole for ehh Auger). This leads to a higher net forward current per recombination event [Fig. 5(c)].

It is difficult to assess the fraction of hot carriers which will travel in the forward direction. However, if the simple approximation is made that half of the hot carriers travel in each direction, as in Fig. 5, then it is easy to see that the net forward current will be one half electron more per recombination event than for either SRH or radiative recombination. A fraction different from one half will produce a proportionally different net forward current per Auger recombination event.

In the case of photo-excitation of carriers into the QW, because Auger recombination is a multi-body process unlike thermionic emission, forward current will still be induced in the device if Auger recombination is occurring in the QW. This current, due to the hot carriers produced by Auger recombination involving both electrically injected and photo-excited carriers, as shown in Fig. 5(f), corresponds to the photo-induced forward current that has been measured.

The observed photo-induced current is a measure of the sum of the eeh and ehh Auger rates in the QW because both hot electrons and hot holes will produce forward current. This sets the present measurement apart from the electro-emission measurements of high energy carriers reported by Iveland *et al.*,[5] which were only sensitive to eeh Auger processes and only measured the small fraction of hot carriers that survived to be emitted from a cesiated p-GaN surfaced.

In summary, we have described measurements of changes in the IV characteristic and EL intensity under resonant optical excitation of the QW layer in a blue SQW c-plane InGaN/GaN LED under forward bias. The photo-induced current was in the forward direction when the LED was forward biased—opposite to the usual direction of the reverse bias photocurrent in solar cells and photodiodes. The EL intensity of the LED increased upon optical excitation, indicating that the carrier density in the QW layer increased, as well as all recombination rates, including the Auger rates.

The magnitude of the photo-induced forward current was not observed to decrease significantly upon inserting an AlGaN EBL into the LED structure, indicating that the photo-induced current was not due to carrier escape by tunneling or thermionic escape but instead due to hot carriers generated by Auger recombination in the QW active region of the LEDs.

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