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"U-turn" feature in the efficiency-versus-current curve of GaInN/GaN light-emitting diodes

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The onset of the efficiency droop in GaInN/GaN blue light-emitting diodes (LEDs), i.e., the maximum-efficiency point, typically occurs at current densities of 1–10 A/cm^2 and the efficiency decreases monotonically beyond the onset. At typical operating current densities (10–100 A/cm^2), LEDs are strongly affected by the droop. At cryogenic temperatures, an increase in the efficiency, i.e., a "U-turn" feature, is found in the droop regime of the efficiency-versus-current curve. The occurrence of the U-turn feature coincides with a distinct increase in device conductivity, which is attributed to an enhancement in p-type conductivity that in turn increases the injection efficiency. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4903518]

The droop in the external-quantum-efficiency-versus-current curve of GaInN/GaN light-emitting diodes (LEDs) is a well-known phenomenon that includes a peak-efficiency point.[1] The peak-efficiency point occurs at typical current densities of 1–10 A/cm^2 which are lower than typical LED operating current densities of 10–100 A/cm^2. Because LEDs are operated in the droop regime, the performance of GaInN/GaN LEDs is strongly compromised by the droop phenomenon. Indeed, the efficiency droop has been identified as one of the major efficiency-loss mechanisms in GaInN/GaN LEDs, and, for typical operating conditions, is the dominant loss mechanism.[2]

The efficiency has been presumed to monotonically decrease beyond the onset of the droop (i.e., the peak-efficiency point).[1,2] However, at temperatures ranging from 10–150 K, an unusual phenomenon is found in high-quality GaInN/GaN blue LEDs: When operated in the droop regime (10–100 A/cm^2), the efficiency reaches a minimum and then, unexpectedly, increases again. A family of experimental internal-quantum-efficiency-versus-current curves for GaInN/GaN LEDs is shown in Figure 1. The peak internal quantum efficiency (IQE) at 10 K is assumed to be 100% where the IQE is the mathematical product of injection efficiency and radiative efficiency. Measurement temperatures include 10 K, 25 K, and then increase to 350 K with 25 K increments. Detailed information on the measured LED (Cree EZ900 chip) and the measurement setup was given by Wang *et al.*[3] Inspection of the figure reveals a minimum in the efficiency followed by a subsequent increase, giving the curve a "U-turn" appearance. To understand and overcome the efficiency droop, it would be beneficial to understand the cause of the U-turn.

In this paper, we investigate the U-turn in the efficiency-versus-current curve of GaInN/GaN LEDs as well as the electrical conductance of the LED. We show that the unexpected increase in efficiency (U-turn) is correlated to a distinct increase in diode conductance that is particularly pronounced at low temperatures. The distinct increase in conductivity is attributed to an enhancement in p-type conductivity (additional holes), thereby increasing the injection efficiency.[4] The results contribute to the understanding of the efficiency droop and give guidance for strategies in overcoming the droop, several of which will be proposed.

Recently, the onset of the efficiency droop has been correlated with the onset of high injection.[3,5] It was shown that the onset of high injection consistently precedes the onset of the efficiency droop. Figure 2, which is consistent with this finding, shows the current-voltage characteristic for a range of temperatures with the (i) onset of high injection, (ii) onset of droop, and (iii) minimum of U-turn, marked by circle, square, and rhombus symbols, respectively. The difference in voltage between the two onsets (droop and high injection) was found to be a few 100 mV, i.e., 100–600 mV, among a large group of measured devices. At cryogenic temperatures, acceptors freeze out due to the high Mg acceptor ionization energy in GaN. Accordingly, the carrier asymmetry (between electron and hole concentration) is exacerbated.[6] A stronger

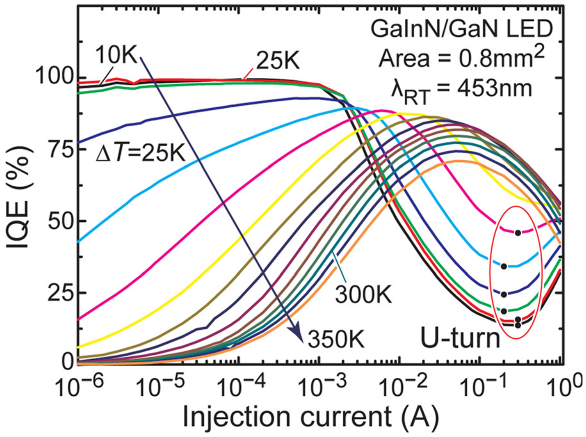

FIG. 1. Internal-quantum-efficiency-versus-current curves of GaInN/GaN LEDs showing a U-turn behavior at high current densities and cryogenic temperatures. The current range of the measurement instrument is limited to 1.0 A.

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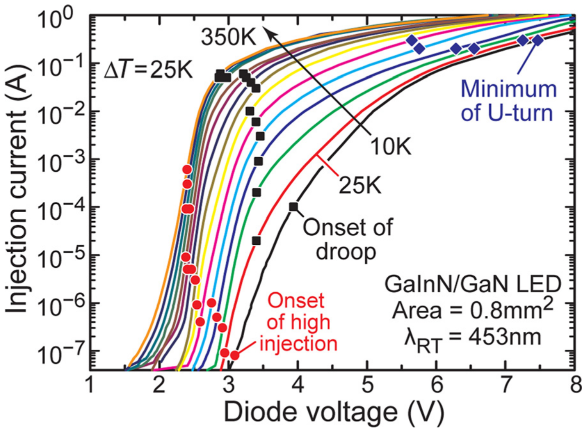

FIG. 2. Current-versus-voltage curve at temperatures ranging from 10 K to 350 K. Shown are the onset of high injection (circle), onset of droop (square), and the minimum point of the U-turn (rhombus).

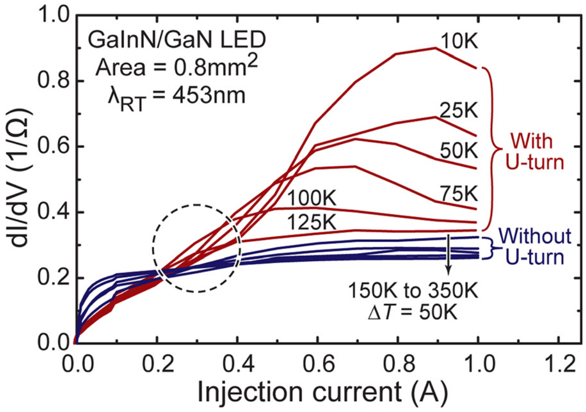

FIG. 3. Diode differential conductance of the GaInN/GaN LED as a function of the injection current.

carrier asymmetry leads to an earlier onset of high injection. It is well known that in the high-injection regime, the incremental voltage applied to the device drops only in part across the pn-junction region with the other part dropping across one of the neutral regions.[4,7–9] Given that p-type GaN is more resistive than n-type GaN, it can be assumed that, in the high-injection regime, the incremental voltage drops, to a significant extent, across the p-type region. In a common GaInN/GaN LED, this includes the p-type electron-blocking layer (EBL) and the p-type GaN layer.

An analytic model has been developed to explain the efficiency droop based on a reduction in the injection efficiency.[4] The injection efficiency is defined as the fraction of the electron current that is injected into the active region for recombination. The drift-leakage term is given by $C_{\mathrm{DL}}\, n_{\mathrm{QW}}$,[3] with $C_{\mathrm{DL}} = \delta\, \mu_{\mathrm{n}}/(\mu_{\mathrm{p}}\, p_{\mathrm{p0}})$, where δ is the ratio of electron concentration in the EBL to the electron concentration in the quantum well (QW), p_{p0} is the hole concentration in the p-type layer, and the remaining symbols have their usual meaning.[4] The model shows that the efficiency droop depends sensitively on the hole concentration (p_{p0}). A higher hole concentration leads to a higher droop-onset current and a smaller efficiency droop. The freeze-out of holes at cryogenic temperatures therefore exacerbates the efficiency droop and the electric field caused by the voltage dropping across the p-type region is inherently larger at cryogenic temperatures. The analytic model elucidates that (i) lack of hole injection and (ii) electron leakage are two sides of the same coin.

Next, we investigate the correlation of the U-turn with the electrical properties of the LED. Specifically, we analyze the differential conductance of the LED, i.e., the first derivative of the injection current (I) with respect to the diode voltage (V), i.e., ($\mathrm{d}I/\mathrm{d}V$). The result ($\mathrm{d}I/\mathrm{d}V$) is shown in Figure 3 as a function of current. For temperatures ranging from 10 K to 125 K, a U-turn is found (see Figure 1) and, concomitantly, the diode conductance shows a marked increase (see Figure 3). In contrast, for temperatures ranging from 150 K to 350 K, no U-turn is found and the diode conductance remains almost the same.

The correlation between U-turn and conductance is further investigated by evaluating the second derivative of the injection current with respect to diode voltage ($\mathrm{d}^2I/\mathrm{d}V^2$), i.e., the change in differential conductance. Figure 4 shows the second derivative, $\mathrm{d}^2I/\mathrm{d}V^2$, as well as the efficiency as a function of voltage for the temperatures 10 K, 50 K, and 100 K. Inspection of the figure reveals a strong increase in diode conductance occurring simultaneously with the

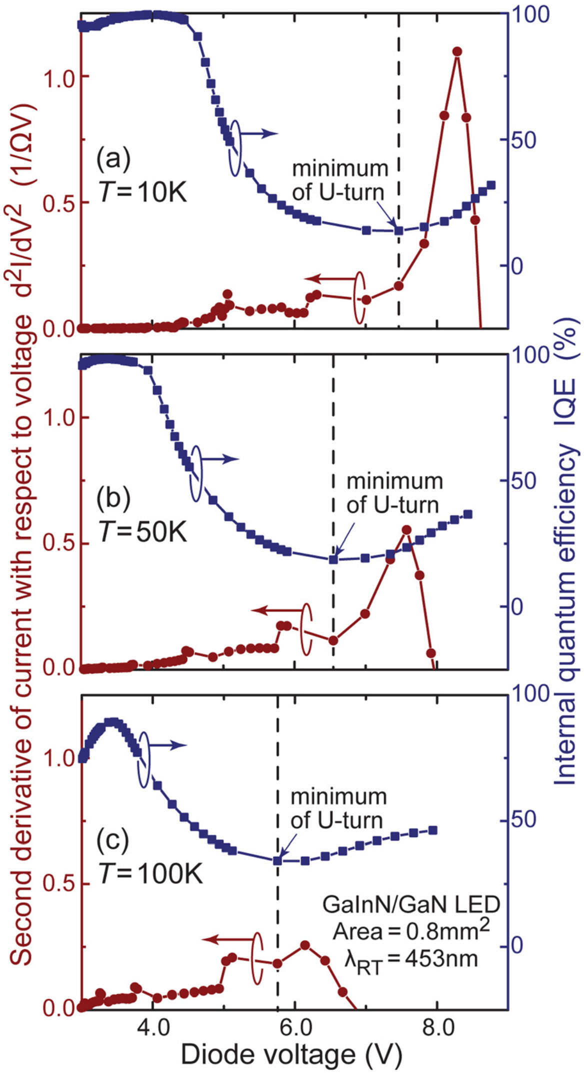

FIG. 4. Second derivative of the current with respect to the voltage ($\mathrm{d}^2I/\mathrm{d}V^2$, left-hand ordinate) as well as the IQE (right-hand ordinate) versus voltage for temperatures of (a) 10 K, (b) 50 K, and (c) 100 K.

increasing efficiency (i.e., beyond the minimum point of the U-turn). The increasing strength of the U-turn is positively related to the peak value of d^2I/dV^2. That is, a larger peak value of d^2I/dV^2 corresponds to a stronger U-turn. An abrupt increase of diode conductance is not found for the efficiency curves without the U-turn feature ($T \geq 150\,\mathrm{K}$).

Similarly, in Figure 5, the second derivative of current with respect to voltage, d^2I/dV^2, is shown as a function of diode voltage for temperatures ranging from 10 K to 150 K. We find that the increase in p-type conductivity becomes continuously smaller as temperatures increases. The peak in d^2I/dV^2 vanishes as temperatures exceed 150 K.

Under very high injection conditions, an electric field occurs in the LED's p-type region, specifically its most resistive part. Two scenarios can be envisioned: First, the electric field causes field-ionization of acceptors by means of the Poole-Frenkel effect.[10,11] At cryogenic temperatures, acceptors are mostly neutral. However, if the semiconductor is subjected to a sufficiently large electric field, acceptors become ionized.[12–14] Estimates for the threshold electric field for acceptor-field ionization vary from 10 to 100 kV/cm.[9,11] For a p-type layer thickness of 200 nm and a voltage drop of 4.0 V, i.e., the voltage difference between onset of high injection and minimum of U-turn shown in Figure 2, the calculated average electric field indeed exceeds 100 kV/cm. Second, if the electric field occurs mostly in the EBL, its natural effect is to reduce the injection barrier for holes. That is, in both cases, the electric field enhances hole injection into the active region so that the efficiency increases.

Among the resistances in LEDs, the p-type layer resistance makes a significant contribution. If the acceptors in the p-type layer become ionized due to the electric field arising in the high-injection regime, the p-type layer conductance should increase and along with it the diode conductance. The correlation of (i) the distinct increase in diode conductance and (ii) the U-turn, as shown in Figure 4, indeed confirms that the U-turn is related to an enhancement in hole conductivity for temperatures ranging from 10 K to 150 K. We note that for some studies of GaN-based LEDs, this U-turn feature has not been found under similar measurement conditions.[3,5] Investigating the conductance of those LEDs revealed no distinct increase in conductance. This further strengthens a correlation between increasing diode conductance and U-turn feature.

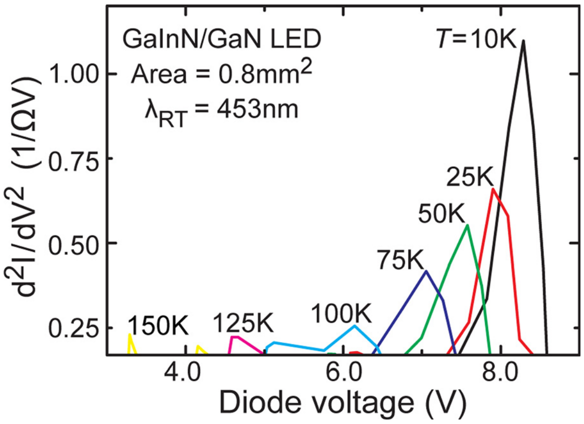

FIG. 5. Second derivative, d^2I/dV^2, of a GaInN/GaN LED as a function of diode voltage for temperatures ranging from 10 K to 150 K. For $150\,\mathrm{K} < T \leq 350\,\mathrm{K}$, the second derivative does not show a significant peak.

The U-turn becomes weaker as temperature increases. This can be understood as follows: First, as temperature rises, neutral acceptors become fewer. As a result, there is less opportunity for field-ionization of acceptors by means of the Poole-Frenkel effect. Second, as temperature rises, the voltage applied to the LED, for a given injection current, becomes smaller (see Figure 2). As a result, the accompanying electric field in the p-type region becomes smaller as well. Third, as temperature rises, the hole concentration increases. As a result, the electric field in the p-type region is reduced by free-carrier screening. The disappearance of the U-turn feature for $T > 150\,\mathrm{K}$ can be attributed to these reasons and, as a result, the abrupt increase of diode conductance is not observed for $T > 150\,\mathrm{K}$.

The results presented here represent an opportunity to address the urgent need for alleviating the efficiency droop by strategies aimed at reducing the asymmetry in electron and hole injection in GaInN/GaN LEDs and laser diodes by enhancing the p-type conductivity. Promising approaches may include: (i) The employment of external-voltage-induced electric fields to ionize neutral acceptors present in the Mg-doped cladding layer of the LED. This can be accomplished by an Al-graded AlGaN p-type region of controlled thickness, instead of a conventional p-type AlGaN EBL and a p-type GaN region. This allows for a more uniform and higher electric field in the Al-graded p-type region so that more field-ionized acceptors and a higher hole concentration are attained. (ii) The use of alternate p-type cladding layer materials that are optically transparent and have high hole concentration and mobility so that the carrier-transport asymmetry is reduced.

In conclusion, we have found a U-turn feature in the efficiency-versus-current curve of GaInN/GaN blue LEDs for temperatures ranging from 10 K to 150 K. We analyzed the diode differential conductance and its derivative with respect to voltage. It is found that the diode conductance shows a distinct increase that is correlated to the minimum point of the U-turn feature. We explain the distinct increase in p-type conductance by (i) field-ionization of acceptors and/or (ii) reduction of the EBL barrier for hole injection. The enhancement in p-type conductance reduces the transport asymmetry and alleviates the efficiency droop. The findings demonstrate that an enhancement in injection efficiency is a promising strategy in overcoming the efficiency droop. To accomplish this goal, we propose several approaches including (i) the employment of external-voltage-induced electric fields to ionize neutral acceptors present in the Mg-doped cladding layer, and (ii) the use of alternate p-type cladding layer materials (other than GaN) that are transparent and have high hole concentration and mobility.

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