APPLIED PHYSICS LETTERS **100**, 081106 (2012)

Temperature dependent efficiency droop in GaInN light-emitting diodes with different current densities

David S. Meyaard,[1] Qifeng Shan,[2] Jaehee Cho,[1,a)] E. Fred Schubert,[1,2] Sang-Heon Han,[3] Min-Ho Kim,[3] Cheolsoo Sone,[3] Seung Jae Oh,[4] and Jong Kyu Kim[4,b)]
[1]*Future Chips Constellation, Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA*
[2]*Future Chips Constellation, Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York 12180, USA*
[3]*R&D Institute, Samsung LED, Suwon 443-743, Korea*
[4]*Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang 790-784, Korea*

(Received 15 December 2011; accepted 6 February 2012; published online 22 February 2012)

The effect of chip area on the temperature-dependent light-output power (LOP) in GaInN-based light-emitting diodes (LEDs) is investigated. The larger the chip size, the faster the reduction in LOP with increasing temperature becomes, indicating that increasing the size of LED chips, a technology trend for reducing the efficiency droop at high currents, is detrimental for high temperature-tolerant LEDs. In addition, it is found that regardless of chip size, the temperature-dependent LOP is identical for the LEDs operating at the same current density. © *2012 American Institute of Physics*. [doi:10.1063/1.3688041]

GaN-based high-power light-emitting diodes (LEDs) have become increasingly prevalent in illumination applications such as interior/exterior lighting and automotive headlights. However, a long standing problem called "efficiency droop" has been dimming the future prospects of LEDs as the ultimate illumination sources. The efficiency droop can be categorized using two classifications: current-density droop and temperature droop. First, the conventional definition of efficiency droop describes the decrease in radiative efficiency with increasing operating current, which we call the current-density droop, *J*-droop, in this study. Several explanations have been proposed for the causes of the *J*-droop, including electron leakage due to polarization mismatch[1] and poor hole injection caused by asymmetry of carrier-transport properties,[2] delocalization of carriers,[3,4] density-activated defect recombination,[5,6] and Auger recombination.[7] These have led to possible solutions such as polarization matched multiple quantum well (MQW) structures, double heterostructure designs, and large-size (large junction area) devices for reducing the current density. Second, GaN-based LEDs also suffer from a strong decrease in radiative efficiency with increasing temperature,[8,9] which we call the temperature droop, *T*-droop, in this study.

Figure 1 shows the external quantum efficiency (EQE) of a commercial high-power LED as a function of driving current measured at several ambient temperatures. The EQE peaks at a low forward current and then drops with increasing current, showing typical *J*-droop behavior. In addition, the EQE decreases significantly as the ambient temperature increases; increasing temperature from 300 to 450 K results in the reduction of the EQE by about 30% of its peak value, indicating that the *T*-droop can be more detrimental than the *J*-droop. High temperature-tolerant LEDs are becoming increasingly important in applications where a weak-temperature-dependence of the EQE is highly desirable, for example, automotive headlights for which the ambient temperatures can be as high as 90 °C. Until now, however, *T*-droop has been less focused on than the *J*-droop.

There has been a great deal of research to understand the mechanisms of efficiency droop caused by high current densities; however, the understanding of *T*-droop, originating from high temperature, is not comprehensive. One of the technology trends in current state-of-the-art LEDs is to increase the chip size, thus decreasing the current density to minimize the *J*-droop. However, the effect of the chip size on the temperature dependent efficiency droop is often overlooked, and systematic studies have not been reported. In this article, we report the fabrication of LED chips with different sizes, and we compare the effect of current density on temperature-dependent performance. We find that increasing the size of LED chips reduces the *J*-droop at a certain temperature (e.g., 300 K) as expected, but degrades the temperature-dependent performance of the LEDs.

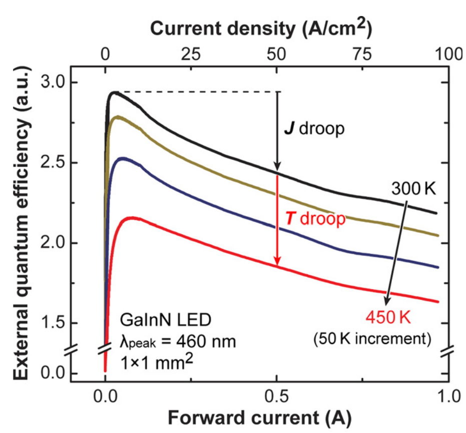

FIG. 1. (Color online) Measured external quantum efficiency of a commercial LED emitting at $\lambda_{peak} = 460$ nm at various ambient temperatures as a function of forward current.

a)Electronic mail: cho.jaehee@gmail.com.
b)Electronic mail: kimjk@postech.ac.kr.

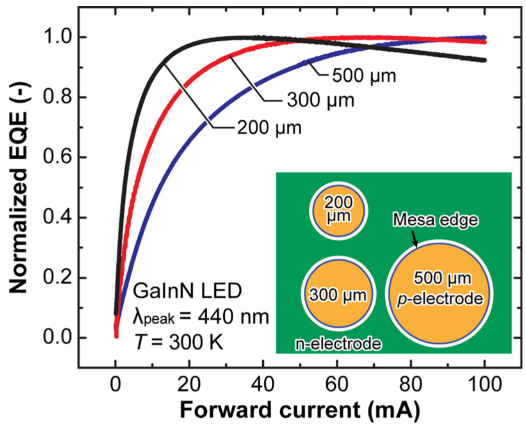

FIG. 2. (Color online) Normalized external quantum efficiency versus forward current of LED chips with different diameters. Schematic description of circular-shape LEDs with different contact-diameter sizes are shown in the inset.

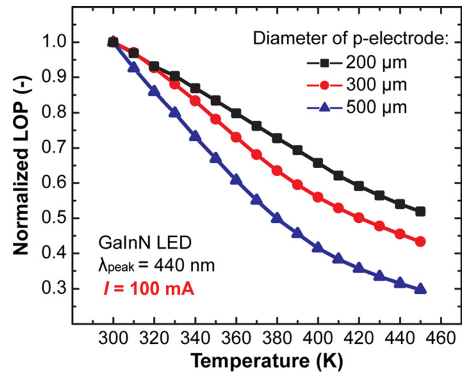

FIG. 3. (Color online) Normalized light-output power versus temperature measured at the constant current of 100 mA for chips with different sizes.

The LED wafer used in this study was commercially grown by metal-organic chemical vapor deposition and has five GaInN/GaN QWs which emit at a peak wavelength of 440 nm. Circular-shaped LED chips with the conventional epi-up geometry were fabricated in order to avoid possible artifacts caused by current crowding that could play a role in the actual current density.[10] Circular mesa structures with diameters of 200, 300, and 500 μm were obtained by standard photolithographic patterning followed by inductively coupled plasma etching to expose the n-type GaN cladding layer. In this article, "chip size" refers to this mesa area for each device. Then, Ti/Al-based n-type ohmic contacts were deposited by electron-beam evaporation and annealed at 650 °C for 1 min in N_2 ambient. ITO-based p-type contacts were deposited and annealed at 500 °C for 1 min in O_2 ambient. The temperature dependent light-output power (LOP) of these chips is then measured from 300 to 450 K. A semiconductor parameter analyzer was used for the measurements, using 500 μs pulse width and 1% duty cycle to minimize self-heating effects.

First, we investigate the effect of chip size on the EQE as a function of driving current. Figure 2 shows normalized EQE versus driving current for each of the three fabricated chips. The LED chip with 200 μm circular contact diameter reaches its efficiency peak earliest, at roughly 35 mA. As the size of the LED chip increases, the peak efficiency shifts towards higher currents; the 300-μm-diameter chip reaches its peak efficiency at around 70 mA, whereas the largest chip with 500 μm diameter does not reach the peak efficiency point in this measurement range. It is clear from this result that in order to operate an LED at high current levels, it is advantageous to increase the chip size, which reduces the *J*-droop. Although increasing the chip size may cause scaling penalties such as the reduction in the total yield from a wafer and reduced extraction efficiency, it has in fact been a trend in commercial LEDs for high-power operation.

Next, we investigate the effect of chip size on the LOP reduction caused by elevated temperatures. Figure 3 shows the normalized LOP of each chip at 100 mA constant operating current. The larger the diameter of the circular shape LED chips, the faster the reduction in LOP with increasing temperature becomes. The LED chip with 500 μm diameter, which shows the best EQE at high driving currents, performs worst at high temperature. The reduction in LOP for the 500-μm-diameter LED is as high as 70.2% when the temperature is increased from 300 to 450 K. Such a large LOP reduction would not be acceptable in applications where high temperature-tolerance and stable performance with temperature are required. The LOP in the device with 200 μm diameter drops by 48.1% at 450 K, showing much less degradation in LOP than the larger devices. This experimental result indicates that a smaller chip size, i.e., higher current density operation, would be a better choice to minimize the *T*-droop.

With increased temperature, electrons acquire higher thermal energy and therefore LEDs may suffer more strongly from high-current loss mechanisms. These may include increased leakage over a quantum barrier or an electron blocking layer, increased Auger recombination, or greater delocalization from indium clusters. On the other hand, hole ionization is greater at high temperatures, leading to the alleviation of the asymmetry in the junction.[2] Therefore, it is not intuitively obvious which loss mechanism is dominant for an LED in the high temperature, high current regime. However, note again that the trend is occurring in state-of-the-art commercial LEDs: larger chips for improved optical performance (i.e., less *J*-droop). The experimental results of Fig. 3 show that a high-temperature LOP penalty is incurred for large chip sizes.

In order to fully understand our experimental results, we take the recombination rate equation into account. Shockley-Read-Hall (SRH) non-radiative recombination is proportional to carrier concentration in the light-emitting quantum well (n), while radiative recombination is proportional to the square of carrier concentration (n^2).[10] Considering SRH and bimolecular radiative recombination coefficients (A and B coefficients, respectively, in the *ABC* model commonly used to explain the recombination in LEDs), the SRH recombination plays a relatively large role in the total recombination at low current densities. Thus, most of the *T*-droop that takes place at low driving current can be attributed to the temperature-dependent behavior of SRH recombination. As the current density increases, SRH recombination becomes weaker than other high-current loss mechanisms. In an intrinsic material such as an undoped quantum well, the rate of SRH recombination may be expressed as[11]

$$R_{SRH} = \frac{\Delta n}{\tau_{NR}} = \frac{\Delta n}{\tau_0\left(1 + \cosh\frac{E_T - E_{Fi}}{kT}\right)}, \quad (1)$$

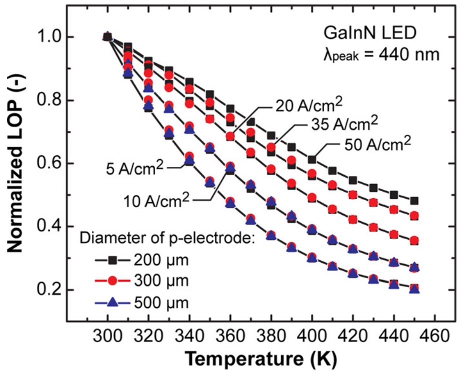

FIG. 4. (Color online) Normalized light-output power versus temperature measured at the current densities of 5 to 50 A/cm^2 for chips with different sizes.

where Δn is the concentration of excess electrons, τ_{NR} is the non-radiative recombination lifetime, E_T and E_{Fi} are the trap energy and the intrinsic Fermi level, respectively, and τ_0 is based on the capture cross section and trap concentration. Based on Eq. (1), we expect SRH recombination to have a hyperbolic cosine-like dependence on temperature, thus the non-radiative recombination lifetime decreases with increasing temperature. The drop in LOP caused by SRH recombination, with increasing temperature, would be dominant at low currents but becomes minimal at high currents where the effect of SRH recombination becomes negligible in comparison with other high-current loss mechanisms. This explains why the results in Fig. 3 show that the smallest chip (200 μm), with higher current density at a same current, displays better performance in terms of T-droop than those of the larger chips (300 and 500 μm).

Figure 4 shows the normalized LOP as a function of temperature at various current densities. The parameter analyzer used for this experiment has a maximum output current of 100 mA, so no data points exist at high current density for the larger devices. In the range where data points exist for all three samples (i.e., 5 and 10 A/cm^2), a nearly perfect overlap of data points is observed. The same is true for the two smaller devices at 20 and 35 A/cm^2. Note that regardless of chip sizes, the temperature-dependent LOP of the LEDs is identical if the LEDs are operated in same current density. The LED with lower current-density operation shows worse T-droop than the LED with higher current-density operation, consistent with the results in Fig. 3. Since the LED chips are from a high-quality commercial LED wafer, the dislocation and trap densities, hence the rate of SRH recombination at the same current density, presumably are almost the same for each chip. At low current densities (e.g., 5 and 10 A/cm^2), SRH recombination is strong and therefore plays a significant role in total recombination with temperature. Thus, as the temperature increases, the non-radiative recombination lifetime decreases rapidly, lowering the LOP of the LEDs significantly. With increasing current densities, SRH recombination becomes less dominant, resulting in less temperature-dependence of LED performance.[9]

In summary, this work shows that for the same chip geometry, wafer quality, and active region design, the temperature dependence of the LOP is strongly dependent on current density. That is, regardless of chip size, the temperature-dependent reduction in LOP is identical when injecting the LEDs with the same current density. However, as the current density is decreased by increasing the size of LED chips (keeping the current the same for all LEDs), T-droop is exacerbated. At low current densities, SRH recombination is dominant and the non-radiative recombination lifetime decreases with increasing temperature. With increasing current density, SRH recombination becomes negligible in comparison with other high-current loss mechanisms, resulting in a decrease of the temperature dependence of the LOP. The results indicate that increasing the size of LED chips, a technology trend for reducing the J-droop, makes the LOP of LEDs more temperature sensitive and thus not a desirable solution for high temperature-tolerant LEDs.

The RPI authors gratefully acknowledge support from Samsung LED Co., Sandia National Laboratories, Korean Ministry of Knowledge Economy and Korea Institute for Advancement of Technology through the International Collaborative R&D Program, National Science Foundation, Magnolia Optical Technologies, Inc., and Raydex Technology, Inc. The POSTECH authors gratefully acknowledge support from the Industrial Technology Development Program funded by Korean Ministry of Knowledge Economy, and Priority Research Centers funded by National Research Foundation of Korea (2010-0029711). Authors D.S.M., G.B.L., J.C., and E.F.S. were supported by Sandia's Solid-State Lighting Sciences Center, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Basic Energy Sciences.

[1]M.-H. Kim, M. F. Schubert, Q. Dai, J. K. Kim, E. F. Schubert, J. Piprek, and Y. Park, Appl. Phys. Lett. **91**, 183507 (2007).
[2]D. S. Meyaard, G.-B. Lin, Q. Shan, J. Cho, E. F. Schubert, H. Shim, M.-H. Kim, and C. Sone, Appl. Phys. Lett. **99**, 251115 (2011).
[3]T. Mukai, M. Yamada, and S. Nakamura, Jpn. J. Appl. Phys. **38**, 3976 (1999).
[4]Y. Yang, X. A. Cao, and C. Yan, IEEE Trans. Electron Devices **55**, 1771 (2008).
[5]J. Hader, J. V. Moloney, and S. W. Koch, Appl. Phys. Lett. **96**, 221106 (2010).
[6]J. Hader, J. V. Moloney, and S. W. Koch, Appl. Phys. Lett. **99**, 181127 (2011).
[7]Y. C. Shen, G. O. Mueller, S. Watanabe, N. F. Gardner, A. Munkholm, and M. R. Krames, Appl. Phys. Lett. **91**, 141101 (2007).
[8]S. Chhajed, J. Cho, E. F. Schubert, J. K. Kim, D. D. Koleske, and M. H. Crawford, Phys. Status Solidi A **208**, 947 (2011).
[9]D. S. Meyaard, Q. Shan, Q. Dai, J. Cho, E. F. Schubert. M.-H. Kim, and C. Sone, Appl. Phys. Lett. **99**, 041112 (2011).
[10]X. Guo and E. F. Schubert, Appl. Phys. Lett. **78**, 3337 (2001).
[11]E. F. Schubert, *Light-Emitting Diodes*, 2nd ed. (Cambridge University Press, Cambridge, 2006).