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Asymmetry of carrier transport leading to efficiency droop in GaInN based light-emitting diodes

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The effect of the asymmetry in carrier concentration and mobility is studied in GaInN pn-junction light-emitting diodes (LEDs). We propose and present experimental evidence that the asymmetry in carrier concentration and mobility, and associated high-level injection phenomena, cause efficiency droop in GaInN LEDs. Low temperatures exacerbate the degree of asymmetry of the junction by reducing acceptor ionization, and shift high-injection-phenomena to lower currents. Accordingly, at temperatures near 80 K, we measure a greater droop compared to room temperature. The analysis of temperature-dependent I–V curves shows an excellent correlation between the onset of high-level injection and the onset of droop. © *2011 American Institute of Physics*. [doi:10.1063/1.3671395]

The decrease in efficiency with increasing forward current is a well-known effect for light emitting diodes (LEDs) in the GaInN/GaN material system. The physical mechanism causing this efficiency droop has been a topic highly debated over the last several years, but no general consensus within the technical community has been reached.[1] Several mechanisms have been proposed to explain efficiency droop, including electron leakage due to polarization mismatch,[2] poor hole injection,[3] delocalization of carriers,[4,5] and Auger recombination.[6] It is well accepted that the hole concentration in GaInN/GaN LEDs is much lower than the electron concentration. This is due to the high ionization energy of Mg acceptors in GaN, as well as a self-compensation effect at high dopant levels, both effects limiting the maximum attainable hole concentration.[7] Due to these limitations, only a small percentage of the Mg atoms is ionized and provides holes. At temperatures below 300 K, even fewer acceptors will be ionized (while the electron concentration remains much more constant), thereby enhancing the asymmetry (or mismatch) between the electron and the hole concentration. In addition to the difference in electron and hole concentration, holes have a significantly lower mobility than electrons,[8] further exacerbating the asymmetry of carrier transport. In this paper, we analyze the effects of asymmetry and high-level injection of GaInN LEDs on the efficiency droop. Specifically, we deliberately enhance the given asymmetry in carrier concentration by measuring the light-output power (LOP) of a GaInN/GaN LED at low temperatures. Furthermore, from the electrical characteristics of the GaInN LED, we identify the onset of high-level injection as a function of temperature and find that it strongly correlates with the onset of the droop.

We begin by analyzing a symmetric and an asymmetric GaN pn-homojunction diode. Although a GaInN/GaN LED will have a more complicated structure, analyzing GaN pn-homojunction diodes lets us gain useful insight into the carrier dynamics of an asymmetric junction without overcomplicating the considered device structure. Two GaN pn-homojunction diodes are analyzed using the simulation program APSYS;[9] one is doped to attain symmetry with $n \approx p$, and the other is doped so that $n \gg p$. A field dependent mobility model is utilized, where the mobility of electrons and holes is based on both dopant concentration and electric field.[10] The electron mobility can vary between 100 and 300 cm^2/(V·s); the hole mobility can vary between 1 and 5 cm^2/(V·s), similar to previous reports of that value.[11] It is well-known from Shockley's diode theory that at a voltage near the built-in voltage, V_{bi}, the concentration of injected minority carriers on the lightly doped side approaches the concentration of majority carriers; this is known as high-level injection.[10] Under high-level injection, several things occur: (1) a voltage drop occurs not only in the depletion region but also over one of the quasi-neutral regions, resulting in an electric field in this region. (2) Carrier drift in the neutral region plays a role in transport as well as carrier diffusion. (3) The series resistance of the device causes a deviation from the exponential I–V characteristics which can be easily identified. Figures 1(a) and 1(b) show the average recombination location for the symmetric and asymmetric diode, respectively. The product of electrons and holes ($R = Bnp$) is used to calculate the average recombination location. The change in recombination location for the symmetric junction is only 1.6 nm towards the p-side; the change for the asymmetric junction is significantly larger, 18.3 nm. From this result, it is obvious that the asymmetry between electrons and holes plays a large role in the carrier dynamics of this diode. Regarding the buildup of electric field in the p-type region, we first consider the conductivity in each region of the device. When the conductivity of the depletion region becomes comparable to the conductivity of the p-type region, an electric field will begin to build up in the p-type

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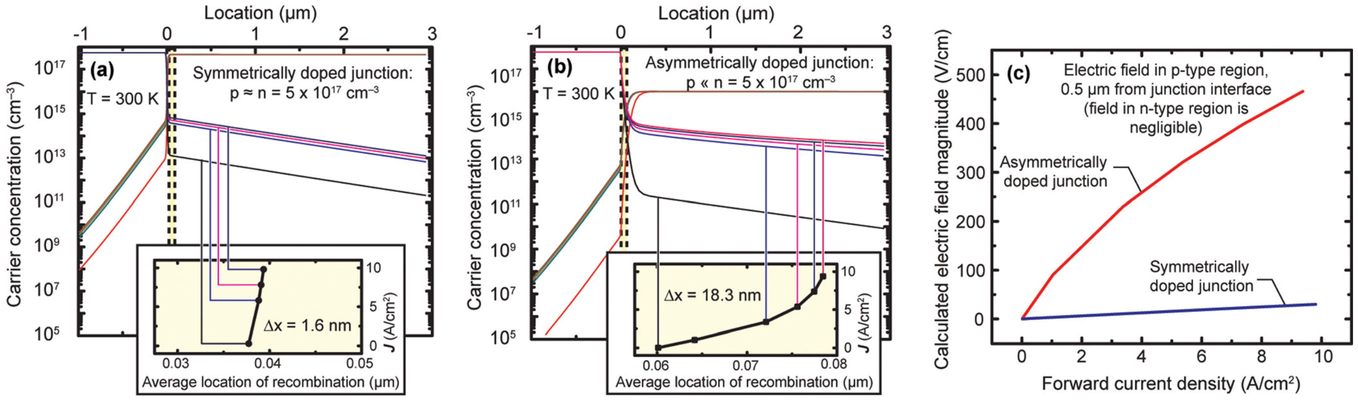

FIG. 1. (Color online) Simulated carrier concentration at several current densities for: (a) symmetrically doped and (b) asymmetrically doped GaN pn-homojunction diodes. The insets of each plot show the average location of carrier recombination. (c) Calculated electric field in p-type quasi-neutral region under different bias conditions.

region. The buildup occurs when $\mu_n \Delta n_p(0) \geq \mu_p p_{p0}$, where $\Delta n_p(0)$ is the concentration of injected electrons at the edge of the p-type neutral region. We note that this condition is equal to the high-injection condition weighted by the carrier mobilities. Figure 1(c) shows the simulated electric field in the p-type region for both doping conditions. The electric field 0.5 μm away from the junction is shown, in the p-type layer, which is outside the depletion region. In the symmetric device, the electric field in the p-type region is relatively small, leading to a small shift in recombination center. In contrast, the asymmetric device shows a large electric field; this will result in a significant change in carrier transport. As the mobility of electrons is significantly greater than holes, electron drift is more strongly affected than hole drift, explaining the shift in average recombination location as shown in Figure 1(a) and 1(b). Suggesting an analogy of the pn-homojunction with an LED pn-heterojunction, this analysis implies a general trend of recombination into the p-side of the device (as the current density increases), which is equivalent to increased electron leakage out of the multi-quantum wells (MQWs) of the LED.

Next, we discuss experimental results on high-quality GaInN/GaN LEDs. The LED used in our experiments is grown by metalorganic chemical vapor deposition and has five GaInN/GaN QWs which emit at a peak wavelength of 440 nm. The LED structure employs a typical AlGaN electron-blocking layer (EBL) with 15% Al mole fraction after the MQW region. Thin-film LEDs are fabricated by bonding the LED wafer to a silicon wafer and utilizing laser-lift-off to remove the sapphire substrate. The exposed N-face GaN is then surface roughened to enhance light extraction. The measured sample wafer is diced into 1×1 mm^2 chips that are left unpackaged. A chip is mounted with thermal grease in a liquid-nitrogen-cooled cryostat to ensure a good thermal conductivity to the active region of the device. By cooling the LEDs to near liquid nitrogen temperatures, we can enhance hole freeze-out, leading to a very asymmetric junction with $n \gg p$. The light-output power is then measured as a function of temperature using pulsed operating conditions, with a 5 μs pulse-duration and a 1% duty cycle used at high currents in order to minimize self-heating.

Figure 2 shows the measured external quantum efficiency vs. current at several temperatures. At 80 K, the LED shows the greatest efficiency droop. As the temperature increases to 200 K, the efficiency droop is reduced, but still greater than the droop observed at room temperature. We propose that this behavior can be explained by the asymmetry in the transport properties of electrons and holes in GaN-based pn-junction diodes. As the temperature decreases, fewer acceptors are ionized. This leads to a large asymmetry in carrier concentration, and therefore an onset of high-level injection conditions at lower currents. At the lowest temperature, 80 K, the onset of droop occurs at the smallest current density. Two trends are apparent from these curves: at low temperatures, the peak efficiency point is higher and occurs at a smaller current density. This agrees with expectations that Shockley Read Hall (SRH) recombination is minimized at low temperatures.[12,13] Enhanced droop at low temperature has been reported on several occasions in GaInN based LEDs.[14,15] Previous explanations for the enhanced droop include tunneling through the EBL,[14] electron leakage,[15] and saturation of the radiative recombination coefficient in In-rich regions.[16]

In order to further investigate the high-level injection, the current–voltage characteristic (I–V) of the LED was measured as a function of temperature. High-level injection manifests itself as a deviation from an exponential I–V, i.e., the emergence of a measured series resistance. Figure 3(a) shows the I–V of a GaInN LED at different temperatures. At low temperatures, the turn-on voltage increases significantly. This large shift, between 1 and 2 V, can in part be explained

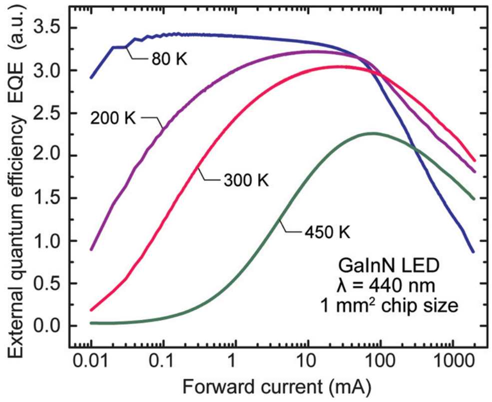

FIG. 2. (Color online) Measured external quantum efficiency of a GaInN LED for several temperatures ranging from 80 K to 450 K.

by the temperature dependence of junction voltage, dV_j/dT.[17] Figure 3(b) correlates the onset of high-level injection with the peak-efficiency point, i.e., the onset of droop. For each measurement temperature, there is an exponential region (linear on a logarithmic scale) consistent with the Shockley equation (see Fig. 3(b)). When the I–V characteristics deviate from this exponential regime, this marks the onset of high-level injection. Inspection of the figure reveals that the onset of high-level injection is followed by the efficiency droop as marked by the peak-efficiency point. For all temperatures, the efficiency droop clearly occurs in the high-level injection regime. Therefore, we propose that the onset of high-level injection results in the buildup of an electric field in the p-type region resulting in stronger electron leakage and a shift of the recombination location into the p-side. As the temperature increases, the concentration of available holes increases so that the onset of high-level injection occurs at higher current, resulting in less electron spillover and lower series resistance, consistent with the results shown in Fig. 3.

The results presented here also may shed light on other mechanisms that were proposed to cause efficiency droop. With respect to polarization fields on the efficiency droop,[2,18] they likely compound the problem of electron leakage, making it easier for electrons to escape the MQW region. With respect to Auger recombination, we point out that both the extremely low current densities at which the droop occurs at low temperatures (80 K) and the temperature dependence of the droop reported here are not consistent with Auger recombination; it is a high-carrier-concentration phenomenon that would not be expected to increase at low temperatures.

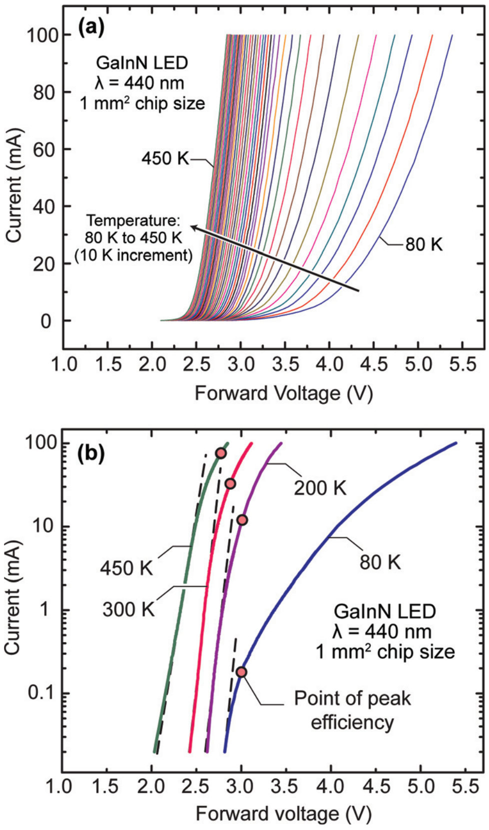

FIG. 3. (Color online) (a) Measured I-V characteristics of the GaInN LED at different temperatures. (b) Measured I-V on a logarithmic scale, showing the onset of high-level injection and series resistance as well as the current at which the efficiency is maximal.

In conclusion, we propose and present experimental evidence that the asymmetry of GaN-based pn junctions, specifically the large disparity in carrier concentration and mobility cause the efficiency droop in GaInN LEDs. The measured efficiency droop at 80 K is significantly greater than that at room temperature. Furthermore, the analysis of temperature-dependent I–V characteristics shows an excellent correlation between the onset of droop and the high-level injection. We interpret the strong droop to be a consequence of the strong asymmetry of GaN-based pn junctions that is exacerbated when lowering the temperature. Low temperatures result in less acceptor ionization, leading to increased electron leakage from the MQWs. As the conductivity due to electrons injected into the p-side approaches the conductivity due to holes, the high-level injection condition is met, leading to an electric field on the p-side that further enhances leakage and droop.

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[1] J. Piprek, Phys. Status Solidi A **207**, 2217 (2010).
[2] 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).
[3] I. V. Rozhansky and D. A. Zakheim, Semiconductors **40**, 839 (2006).
[4] T. Mukai, M. Yamada, and S. Nakamura, Jpn. J. Appl. Phys. Part 1 **38**, 3976 (1999).
[5] Y. Yang, X. A. Cao, and C. Yan, IEEE Trans. Electron Devices **55**, 1771 (2008).
[6] Y. C. Shen, G. O. Mueller, S. Watanabe, N. F. Gardner, A. Munkholm, and M. R. Krames, Appl. Phys. Lett. **91**, 141101 (2007).
[7] P. Kozodoy, H. Xing, S. P. Denbaars, U. K. Mishra, A. Saxler, R. Perrin, S. Elhamri, and W. C. Mitchel, J. Appl. Phys. **87**, 1832 (2000).
[8] T. T. Mnatsakanov, M. E. Levinshtein, L. I. Pomortseva, S. N. Yurkov, G. S. Simin, and M. A. Khan, Solid-State Electron. **47**, 111 (2003).
[9] APSYS Device Simulator, Software Package, Crosslight Software, Inc., Canada.
[10] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. (John Wiley and Sons, Hoboken, 2007).
[11] S. Nakamura, M. Senoh, and T. Mukai, Jpn. J. Appl. Phys. Part 2 **30**, L1708 (1991).
[12] D. S. Meyaard, Q. Shan, Q. Dai, J. Cho, E. F. Schubert, M.-H. Kim, and C. Sone, Appl. Phys. Lett. **99**, 041112 (2011).
[13] E. F. Schubert, *Light-Emitting Diodes*, 2nd ed. (Cambridge University Press, Cambridge, 2006).
[14] N. I. Bochkareva, V. V. Voronenkov, R. I. Gorbunov, A. S. Zubrilov, Y. S. Lelikov, P. E. Latyshev, Y. T. Rebane, A. I. Tsyuk, and Y. G. Shreter, Appl. Phys. Lett. **96**, 133502 (2010).
[15] J. Wang, L. Wang, W. Zhao, Z. Hao, and Y. Luo, Appl. Phys. Lett. **96**, 201112 (2010).
[16] J.-I. Shim, H. Kim, D.-S. Shin, and H.-Y. Yoo, J. Korean Phys. Soc. **58**, 503 (2011).
[17] Y. Xi, T. Gessmann, J. Xi, J. K. Kim, J. M. Shah, E. F. Schubert, A. J. Fischer, M. H. Crawford, K. H. A. Bogart, and A. A. Allerman, Jpn. J. Appl. Phys. Part 1 **44**, 7260 (2005).
[18] J. Xu, M. F. Schubert, A. N. Noemaun, D. Zhu, J. K. Kim, E. F. Schubert, M. H. Kim, H. J. Chung, S. Yoon, C. Sone *et al.*, Appl. Phys. Lett. **94**, 011113 (2009).