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Promotion of hole injection enabled by GaInN/GaN light-emitting triodes and its effect on the efficiency droop

Sunyong Hwang,[1] Woo Jin Ha,[1] Jong Kyu Kim,[1,a)] Jiuru Xu,[2] Jaehee Cho,[2]
and E. Fred Schubert[2]
[1]*Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang 790-784, Korea*
[2]*Future Chips Constellation, Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA*

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GaInN/GaN light-emitting triodes having two anodes for promoting the injection of holes into the active region were fabricated and characterized. It was found that the anode-to-anode bias modulates not only the hole-injection efficiency but also the effective light-emitting area and hence the current density through the active region. As the anode-to-anode bias increases, the efficiency at the same current density increases, whereas the efficiency droop decreases substantially, indicating that the limited hole-injection efficiency is one of the dominant mechanisms responsible for the efficiency droop in GaN-based light-emitting diodes. © *2011 American Institute of Physics*. [doi:10.1063/1.3658388]

The hole-injection efficiency into the active region of GaN-based light-emitting diodes (LEDs) is known to be much lower than the electron-injection efficiency due to a low hole concentration, a low hole mobility, potential barriers for hole transport, and a reduced quantum-mechanical dwell time of carriers originating from the polarization-induced sheet charges at hetero-interfaces of GaN-based epilayers grown in the *c*-direction.[1–5] In addition, the commonly used $Al_xGa_{1-x}N$ electron-blocking layer (EBL) creates an additional undesired potential barrier for holes. Consequently, the slow moving holes are confronted with an overwhelming flow of electrons as well as barriers at the hetero-interfaces, resulting in substantial electron leakage out of the active region, which has been considered as one of possible mechanisms responsible for the high-current loss mechanism called efficiency droop.[6–11]

Although many physical origins of the efficiency droop, including device heating,[12] Auger recombination,[13–15] delocalization of carriers from In-rich low-defect-density regions,[16,17] and electron leakage,[6–8] have been proposed, there is still a lack of consensus on the dominant mechanism. These proposed mechanisms are based on different physical processes, thus, have different dependences on the hole-injection efficiency. Therefore, it is worthwhile to examine in a systematic way how the hole-injection efficiency affects the efficiency droop behavior, which can be carried out using a "probing" device, the light-emitting *triode* (LET).

An LET is a three terminal p-n junction device having one cathode and two anodes.[18] By applying a bias between the two anodes, holes are laterally accelerated, raising their temperature above the lattice temperature so that the hot holes are more likely to overcome the barriers and be injected into the active region.[19] The unique property of an LET, the ability to manipulate the hole injection by adjusting the anode-to-anode bias, makes it a promising device for investigating the relation between the hole injection, the efficiency, and the efficiency droop.

In this study, GaN-based LETs were fabricated and characterized in order to uncover the mystery behind the efficiency droop. A theoretical model considering the modulation of the effective light-emitting area in the LETs is proposed to interpret the measured efficiency versus cathode current, and consequently, to investigate the dependence of hole-injection efficiency on the efficiency droop behavior.

A typical LED structure ($\lambda_{peak} = 450$ nm) grown by metal organic chemical vapor deposition on a *c*-plane sapphire substrate comprises a 2 μm-thick undoped GaN buffer layer, a 3 μm-thick Si-doped (electron concentration $n = 5 \times 10^{18}$ cm^{-3}) n-type GaN lower cladding layer, a 6 period GaInN (3 nm, undoped)/GaN (9 nm, Si-doped, $n = 5 \times 10^{17}$ cm^{-3}) MQW active region, a 20 nm-thick Mg-doped p-type $Al_{0.15}Ga_{0.85}N$ EBL, and a 300 nm-thick Mg-doped p-type GaN layer ($p = 4 \times 10^{17}$ cm^{-3}). LET mesa structures were obtained by standard photolithographic patterning followed by inductively coupled plasma etching to expose the n-type cladding layer. Ti/Al/Ti/Au n-type ohmic contact was deposited by electron-beam evaporation and annealed at 650 °C for 1 min in N_2 ambient. Ni:Zn/Ag p-type contact was deposited and annealed at 500 °C for 1 min in air, followed by the deposition of Cr/Au pad metal comprises.

A schematic sketch showing the operation principle of the LETs and an optical micrograph of a 300×300 μm^2 LET are shown in Figs. 1(a) and 1(b), respectively. When the two anodes are biased, holes are accelerated laterally, gaining kinetic energy. Thus, the holes in an LET are more likely to overcome the potential barrier posed by the valance band of the EBL and be injected into the active region than those in an LED. As shown in Fig. 1(b), the LET has closely spaced interdigitated p-type contact anode fingers (8 μm) so that an electric field between the fingers is as high as $\sim 10^4$ V/cm enough for lateral-acceleration of holes under moderate applied biases.

The voltages applied to the two anodes and a cathode are noted as V_{A1}, V_{A2}, and V_N, respectively, and corresponding currents through these three terminals are noted as I_{A1}, I_{A2}, and I_N. Anode1-to-cathode current-voltage (*I-V*) characteristics, with

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[a)] Electronic mail: kimjk@postech.ac.kr.

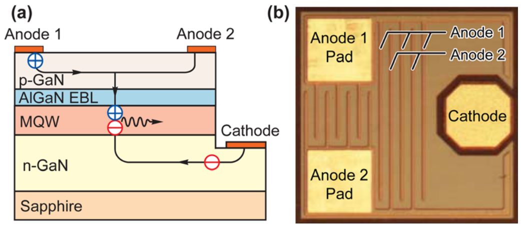

FIG. 1. (Color online) (a) Schematic drawing of the operation of an LET showing enhanced hole injection into active region by an anode-to-anode bias. (b) Photo of an LET with interdigitated anode fingers.

50 mA compliance, and the electroluminescence from the LETs were measured at several different anode-to-anode voltage $V_{A1A2} = V_{A1} - V_{A2}$ (0 to 10 V with 1 V step). The efficiency of the LET is obtained from the optical power divided by the summation of electrical power dissipated via the Anode1-Cathode junction and the Anode2-Cathode junction. Figure 2 shows the efficiency-versus-current curves under various V_{A1A2} conditions. For each curve, the efficiency reaches the peak value at a low current and then decreases, exhibiting the typical efficiency droop behavior. Although the efficiency droop decreases with increasing V_{A1A2}, the peak efficiency decreases also. This result is counter-intuitive and against the previous result,[19] which will be elucidated later.

It is reasonable to assume that the voltage in the p-type layer varies linearly between V_{A1} and V_{A2} and thus periodically under the alternating interdigitated anode fingers, while the voltage of the n-type layer V_N is pinned to the cathode. When the V_{A1A2} is larger than the threshold voltage V_T of the active region, defined as the voltage needed for the I_N of 1 mA ($V_T = 2.86$ V for the LET in this study), the lateral voltage variation inside the p-type GaN layer will also modulate the effective light-emitting area of the active region, that is, only a certain area of the active region near the Anode1 will be the light "ON" state, as schematically shown in Fig. 3(a). Note that the effective light-emitting area of the active region is modulated by V_{A1A2}, which we call the effective-area modulation (EAM) effect. As an evidence of the EAM effect, the device is photographed under different V_{A1A2}'s. Figures 3(b) and 3(c) show the photographs of the lit-up LET at the same cathode current but different V_{A1A2} conditions. The whole LET chip lights up under the zero V_{A1A2}, as shown in Fig. 3(b). However, when the V_{A1A2} is higher than the V_T, only the area close to the Anode1 lights up, as shown in Fig. 3(c). This indicates that the same cathode current does not necessarily result in the same drive current density in LETs. Thus, for an efficiency droop study, the efficiency of the LETs shown in Fig. 2 should be re-evaluated with respect to the current density in the active region instead of the current by taking into account the EAM effect in the LETs.

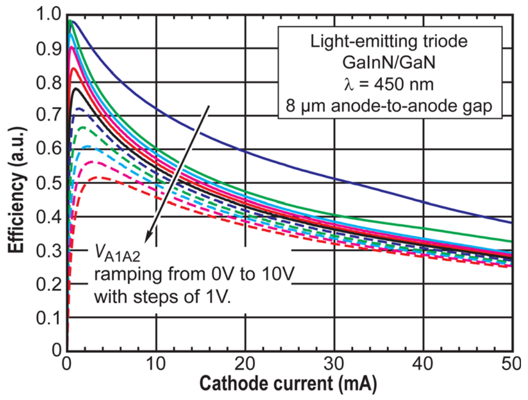

FIG. 2. (Color online) Efficiency versus cathode current for LETs under various anode-to-anode biases.

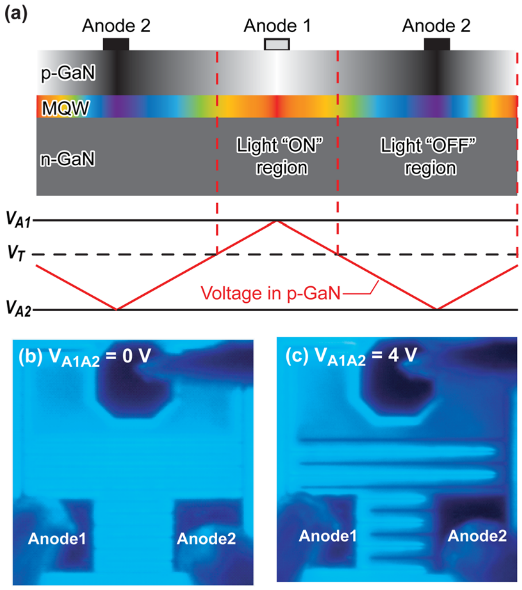

FIG. 3. (Color online) (a) Illustration of effective area modulation of the active region of an LET with the linear voltage variation approximation. Top view of the lit-up LETs under different anode-to-anode voltages: (b) 0 V and (c) 4 V.

Under a simple linear voltage approximation, the effective area emitting light is calculated as

$$A_{eff} = A \times \frac{V_{A1N} - V_T}{V_{A1A2}}, \tag{1}$$

where A represents the physical area of the device. Since the current density J is I/A_{eff}, the drive current can be converted into the current density as plotted in Fig. 4. When the V_{A1A2} is smaller than the V_T, the current density is almost the same as I/A, and the whole area between the anodes will lights up. However, as the V_{A1A2} becomes larger than the V_T, the effective area decreases, so the actual current density in the effective active region increases. Note that this current density difference at the same drive current can be as high as a factor of 5.

The singularity at small forward currents, as shown in Fig. 4, could be possibly due to the oversimplified assumption regarding the validity of the linear voltage approximation of the EAM model. The model can be refined by reassessing the valid region to be where the effective area covers a finite portion of the active region, and also forward voltage is well beyond the turn-on voltage. Based on the reasoning described below, the target valid region turns out to be the linear J versus I region. Let us denote the forward voltage $V = V_{A1N}$, and define $x = I/I_s$. From Eq. (1) and the Shockley equation, $I = I_s\exp[q(V - V_T)/kT]$ where I_s is the saturation current, and the current density can be expressed as

$$J = \frac{I}{A_{eff}} = \frac{I}{A \times \frac{V_{A1N}-V_T}{V_{A1A2}}} = \frac{qI_s V_{A1A2}}{AkT} \times \frac{x}{\ln x}. \tag{2}$$

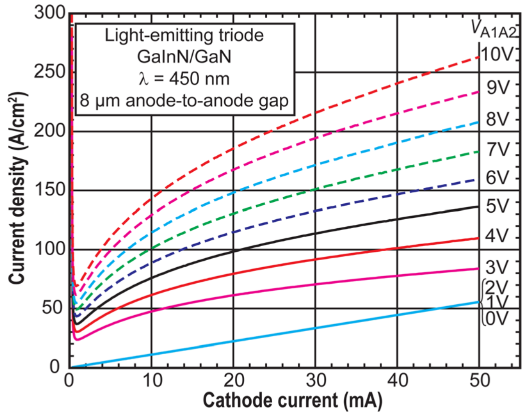

FIG. 4. (Color online) Current density as a function of cathode current with various anode-to-anode biases, calculated under the linear voltage approximation.

The slope of the current to current density conversion curve now can be expressed as,

$$\left.\frac{dJ}{dx}\right|_{V_{A1A2}} \propto \frac{1}{\ln x} - \frac{1}{(\ln x)^2}. \tag{3}$$

When x is large, the slope is a slow changing function. Hence, the quasi-linear portion of the current to current density conversion curve is the valid region where we can evaluate the efficiency of the devices using the current density rather than the current.

Figure 5 shows the LET efficiency versus the current density evaluated from the quasi-linear portion of the current to current density conversion curve in Fig. 4. It is clearly shown that as the V_{A1A2} increases, the efficiency of the light emitter dramatically increases, which is attributed to the enhancement of the hole-injection efficiency enabled by the LET structure.[18,19] We believe that the huge change in current density resulting from the EAM effect causes the decrease in overall efficiency with increasing V_{A1A2} shown in Fig. 2 despite the promotion of hole injection. Looking at the overall trend of the efficiency versus current density curves, the efficiency still drops with increasing drive current density. However, as the V_{A1A2} increases, it drops at a slower rate, i.e., the efficiency droop decreases. This trend indicates that the limited hole-injection efficiency is one of the major causes of the efficiency droop in GaN-based LEDs.

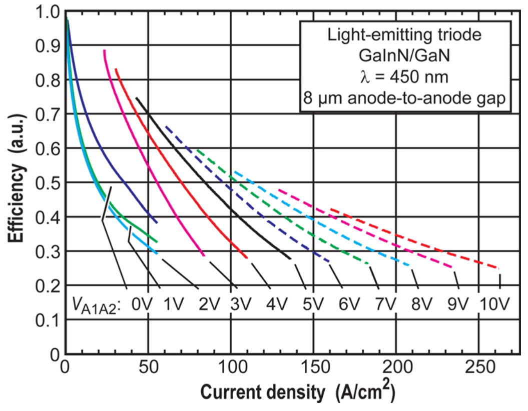

FIG. 5. (Color online) Efficiency versus drive current density for LETs under different anode-to-anode biases.

In summary, GaN-based LETs were fabricated and characterized to investigate the efficiency behavior with increasing current density. It was found that the V_{A1A2} modulates not only the hole injection efficiency but also the effective light-emitting area, and hence the current density. Based on our theoretical model considering the EAM, the cathode current was converted to the current density. As the V_{A1A2} increases, the efficiency increases at the same current density whereas the efficiency droop decreases, which is attributed to the improved hole-injection efficiency enabled by the LET structure. In addition, we believe that this probing device, the LET, gives evidence that the limited hole-injection efficiency into the active region is one of the major mechanisms responsible for the efficiency droop in GaN-based LEDs.

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