Modeling of a GaN-based light-emitting diode for uniform current spreading

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The characteristics of the GaN/InGaN multiquantum-well light-emitting diode (LED) have been examined from the viewpoint of uniform current spreading. By means of simple modeling, it was found that the current density and the length of the lateral current path through the transparent layer represent dominant parameters in determining uniform current spreading. In this regard, we studied the effect of current density on the reliability characteristics of the LED. We were able to significantly improve the electrical, optical, and reliability characteristics of the LED in terms of reducing the length of the lateral current path through the transparent layer. © 2000 American Institute of Physics. [S0003-6951(00)05238-4]

To date, a considerable body of data has been published relative to III–V nitride light-emitting diodes (LEDs),1–4 These diodes typically employ a lateral carrier injection type due to an insulating sapphire substrate. The use of a lateral carrier injection type, however, can lead to a nonuniform current spreading due to difficulties in growing a high quality material. Eliashevich et al. demonstrated, both experimentally and theoretically, that the conductivity of an n-type GaN layer has a profound effect on uniform current spreading.5 For the purpose of theoretical modeling, they assumed that the transparent layer represents a perfect current spreader. However, the resistivity of the p-type transparent layer should not be ignored in the development of a more accurate model. In this letter, we report on an attempt to develop a model for uniform current spreading by including the resistivity of the p-type transparent layer. Based on this model, we report some important parameters, which have significant influence on LED performance.

A multiquantum-well GaN/InGaN was grown by metal-organic chemical vapor deposition (MOCVD) on an insulating sapphire ($\alpha$-Al$_2$O$_3$) substrate. The thickness of the n type, the multiquantum-well (MQW), and the n-type layer were 0.25, 0.05, and 1.5 $\mu$m, respectively. The surface of the p-type GaN layer was partially etched until the n-type layer was exposed by the inductively coupled plasma (ICP) etching system. The formation of the Ni/Au (2 nm/6 nm) transparent layer, followed by the deposition of the Ni/Au (30 nm/80 nm) contact was performed for a p-type pad. A Ti/Al (30 nm/80 nm) scheme was adopted as an n-type pad. The overall dimension of the LED chip was $300 \times 300 \mu$m$^2$. The LED performance was evaluated without packaging. The lifetime of the LED chip was determined from a complete turn-off of the optical output power.

Figure 1 shows the cross-section of the LED structure, which shows the possible current paths from the p to n pad. For simplification, the resistance of the ohmic contacts was ignored. The total voltage drop $V_T$ across an arbitrary current path between the two pads can be given by the sum of voltage drops across the transparent layer $V_j$, the p-type layer $V_p$, the p–n junction $V_j$, and the n-type layer $V_n$. The voltage drops of transparent layer $V_j$ can be explained as

$$V_j = (V_j)_{\text{vertical}} + (V_j)_{\text{lateral}} = (I \cdot R)_{\text{vertical}} + (I \cdot R)_{\text{lateral}} = (J_l)_{\text{w}} \left( \frac{p_t l_j}{J_l w} \right) + (J_l)_w \left( \frac{p_l l}{J_l w} \right) = J_p t_j + J_p l = J_p (l_j + l),$$

where $J$ is the current density, $\rho_j$ is resistivity of the transparent layer. The geometrical parameters $l$ represent the length of the lateral current path through the transparent layer, $t_j$ is the thickness of the transparent layer, and $w$ is the device width. Using the same method as shown above, the total voltage drop across the two pads also can be derived as shown below.

$$V_T = V_i + V_p + V_j + V_n = J_p (l + t_j) + J_p (l + t_p) + V_j + J_p (L + t_n),$$

where $\rho_l$, $\rho_p$, and $\rho_n$, are the resistivity of the transparent layer, p-type layer, and n-type layer, respectively. In this

![FIG. 1. A cross-sectional view of the GaN-based LED, which shows the possible current paths from the p to n pad.](image-url)
condition A is equal to the voltage drop across path B which gives a LED can be achieved when the total voltage drop across path effect perfectly uniform current spreading across the active area of the lifetime of the device. In this case, a severe joule heating can degrade the which leads to current crowding in a localized area of the LED lifetime decreases significantly with increasing values statistics as a function of performance, we investigated the LED reliability character-
istics as a function of a material quality. Basically, this is a function of a material quality. Our interest for satisfying condition identical. This work was supported by the Korea energy management cooperation, Brain Korea 21 project, the Ministry of Commerce, Industry, and Energy, and the Ministry of Science and Technology.

\[ (V_T)_A = J(p_l + J(p_l + V_j + J(p_n(L - l)), \quad (3) \]

\[ (V_T)_B = J(p_l + V_j + J(p_nL. \quad (4) \]

In Eq. (3), since \( p_l \) is much larger than \( p_n \), the lateral current path through the \( p \)-type layer \( (J p_l) \) was ignored. A perfectly uniform current spreading across the active area of the LED can be achieved when the total voltage drop across path A is equal to the voltage drop across path B which gives a condition

\[ J(p_l - p_n)l \approx 0. \quad (5) \]

To meet condition (5), the values for \( p_l \) and \( p_n \) must be identical. Basically, this is a function of a material quality. Our interest for satisfying condition (5) is to reduce the parameters of \( J \) and \( l \).

From the point of view of the \( J \) with respect to LED performance, we investigated the LED reliability characteristics as a function of \( J \) as shown in Fig. 2. It can be seen that LED lifetime decreases significantly with increasing values of \( J \). This can be attributed to nonuniform current spreading, which leads to current crowding in a localized area of the device. In this case, a severe joule heating can degrade the lifetime of the device.6

Based on condition (5), we attempted to reduce the geometrical parameter \( l \) in order to obtain a uniform current spreading during LED performance. In Fig. 3(a), the inset on the left side shows the plane view of a typical LED. Conceptually, the parameter \( l \) can be reduced by adding an extra \( p \)-type pad as shown in the inset on the right side of Fig. 3(a). In this case, we were able to observe improved current–voltage \((I-V)\) and power–current \((P-I)\) characteristics as shown in Figs. 3(a) and 3(b). It should be noted that the output power \((P)\) characteristic was improved, although the additional \( p \)-type pad can reduce the light emitting area. This can be attributed to uniform current spreading by a reduction in the value of parameter \( l \). A significant difference in the performance of the modified LED can be found in its LED reliability characteristics shown in Fig. 3(c). It is clear that the lifetime of the modified LED increased by an order of magnitude.

In summary, we report on a modeling of the conditions for uniform current spreading during LED performance. Based on these conditions, a significant dependence in the current density on the LED reliability characteristics are evident. In addition, we were able to improve LED performance by adding an extra \( p \)-type pad, which plays an important role in reducing the length of the lateral current path through the transparent layer.