Lateral current transport path, a model for GaN-based light-emitting diodes: Applications to practical device designs

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An advanced model to explain the current spreading phenomenon of a conventional GaN-based light-emitting diode is presented. For this work, an equivalent circuit, consisting of the two lateral resistance components of the p-transparent electrode and the n-type layer is proposed. Theoretical calculations clearly reveal that the current density crowds near the n or p pads according to the device parameters and has an exponential behavior as a function of the lateral length. Based on these results, appropriate device parameters including the critical transparent-electrode thickness were determined, leading to a perfectly uniform current distribution. It was even possible to demonstrate the ideal device geometry without the need for a transparent electrode such as an interdigitated structure. © 2002 American Institute of Physics. [DOI: 10.1063/1.1499994]

A sound physical understanding of distributed series resistance and the current crowding effect in GaN-based light-emitting diodes (LEDs) with a lateral injection geometry is essential in the design of highly efficient devices as well as the extraction of accurate diode quality factors from current–voltage data. In an earlier work, involving mathematical modeling, the p-transparent metal electrode was considered to be equipotential, and the lateral resistance component of the n layer and the vertical resistance components of the p layer and p contact were the main focus of study,1,2 Theoretically and experimentally, an exponential decrease in current density with distance from the mesa edge was successfully demonstrated. However, this model is only valid for a sufficiently bulky thickness of the transparent electrode because the resistivity of thin metal films is strongly dependent on thickness.3 It is also worth noting that the conventional GaN-based LED contains a thin transparent electrode in order to guarantee a high extraction efficiency of the generated light.4 In this regard, we attempted to develop and analyze a more accurate quantitative model by including the resistance component of the p-type transparent electrode. In addition, a method for designing and fabricating a highly efficient LED was also investigated based on the developed model.

Figure 1 shows the schematic LED structure with a lateral injection geometry. In this structure, important distributed components of the total series resistance can be categorized into the lateral resistance component of the n layer (r_n) and the transparent electrode (r_t), and the vertical component of the p layer (r_p) and the p contact (r_c). It should be noted that the lateral resistance component of the transparent electrode (r_t) was considered, which is different from earlier studies. Applying the assumption reported by Guo,1,2 the current continuity equation applied to this advanced circuit leads to two basic equations:

\[ \frac{d^2V_n}{dx^2} = \frac{n}{t_n}J, \]  
(1)

which is calculated from \( J_n = -1/\rho_n dV_n/dx \) combined with \( dJ_n/dx = -J/t_n \) and

\[ \frac{d^2V_t}{dx^2} = \frac{n}{t_t}J, \]  
(2)

which is calculated from \( J_s = -1/\rho_s dV_s/d(l-x) \) combined with \( dJ_s/d(l-x) = -J/t_s \). The parameters \( V_n, V_t, \rho_n \), and \( \rho_t \) are the lateral voltage drops and the electrical resistivities of the n layer and transparent electrode, respectively, and \( J \) is the current density across the p–n junction region. In addition, \( V_n \) and \( V_t \) can be also presented by

\[ V_n = V_j + R_c I_0 \exp \left( \frac{eV_j}{kT} \right) + V_j, \]  
(3)

\[ V_t = V_j + R_t I_0 \exp \left( \frac{eV_j}{kT} \right) + V_n, \]  
(4)

FIG. 1. Equivalent LED circuit with a p pad as a physical ground.

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which holds for the $p$ and $n$ pad as a physical ground, respectively. $V_j$ is the junction voltage drop, $I_0$ is the reverse saturation current, and $R_s$ is the vertical resistance of the area element $w dx$, which can be written

$$R_s = \rho_{p} \frac{t_n}{w dx} + \rho_{n} \frac{1}{w dx},$$

where $\rho_{p}$ is the $p$-layer resistivity. Calculating the second derivative of $V_n$ and $V_j$ with respect to $x$ in Eqs. (3) and (4), and combining the results with Eqs. (1) and (2) leads to

$$\frac{d^2 V_j}{d x^2} = -\frac{e}{kT} \left(1 - \frac{e V_j}{kT}\right)^2 \frac{d V_j}{d x}$$

$$= \frac{\pm 1}{\rho_{p} + \rho_{n} \frac{t_n}{t_j}} \left(\frac{\rho_{n} - \rho_{p}}{t_n \frac{t_n}{t_j}} \frac{kT}{e} \right) \cdot \pm: p \text{ pad}$$

$$- : n \text{ pad}$$

where the (+) sign holds for the $p$ pad and the (−) sign for the $n$ pad as physical grounds, respectively. Solving Eq. (6) for $V_j$ and inserting the $V_j$ into the diode equation $J = J_0 \exp(e V_j/kT)$ leads to

$$J(x) = J(0) \exp$$

$$\left(\frac{\pm x}{\sqrt{(\rho_{p} + \rho_{n} \frac{t_n}{t_j})} \frac{\rho_{n} - \rho_{p}}{t_n \frac{t_n}{t_j}} + \pm: p \text{ pad} + : n \text{ pad}}\right)$$

where $J(0)$ is the reverse saturation current density ($J_0$) at the mesa edge. The current spreading length ($L_s$) is given by

$$\sqrt{(\rho_{p} + \rho_{n} \frac{t_n}{t_j})} \frac{\rho_{n} - \rho_{p}}{t_n \frac{t_n}{t_j}}.$$

The calculated current distribution of the LED is shown in Fig. 2. In order to compare these findings with those in previous studies, the same LED parameters reported by Guo ($\rho_n = 0.01 \ \Omega \ cm$, $t_n = 2 \ \mu m$, $\rho_p / t_p = 0 \ \Omega$, and $L_s = 400 \ \mu m$) were used in the calculation. Compared to the current distribution calculated under the $p$-transparent electrode as equipotential ($\rho_p / t_p = 0 \ \Omega$), it can be seen that current crowding can be alleviated via the use of a transparent electrode. It is interesting to note that it is even possible to achieve a perfectly uniform current distribution at the critical condition of $\rho_p / t_p = \rho_n / t_n$. This result is in good agreement with previous reports,4,5 which indicates that the advanced model is very reasonable. On the other hand, current crowding can occur at the opposite $p$-pad region for the case of $\rho_p / t_p > \rho_n / t_n$. Due to an infinite increase in transparent-electrode resistivity ($\rho_p$) with decreasing film thickness ($t_p$), it can be seen that the lower limit of the current spreading length ($L_s$) for $\rho_p / t_p > \rho_n / t_n$ cannot be determined, while that for $\rho_p / t_p < \rho_n / t_n$ is 400 $\mu m$. This indicates that the use of device parameters with a $\rho_p / t_p < \rho_n / t_n$ relation is essentially more favorable for a rough LED process.

Experimental $\rho_p / t_p$ data for a Ni/Au film as a function of film thickness ($t_p$) is shown in Fig. 3. The resistivity was measured using a four-point probe system. The drastic increase in $\rho_p / t_p$ with decreasing $t_p$ is due to the enhanced reflection of conduction electrons, arising from defects which are trapped in the film and on internal surfaces during the deposition.3 Based on this experimental behavior, in the case of the LED wafer reported by Guo ($\rho_p / t_p = 50 \ \Omega$), it is predicted that the critical transparent-electrode thickness for perfectly uniform current spreading is approximately 60 $\AA$.

In order to verify these theoretical predictions, several LEDs with different device parameters were fabricated as shown in Table I. The epilayer structures of the LED wafer studied here consist of a 1.5-$\mu m$-thick layer of $n$-GaIn, a GaN/InGaN multiple quantum well with five periods, and 0.25-$\mu m$-thick p-GaN. For the device fabrication, the $p$ layer was selectively etched to expose the $n$ layer using an inductively coupled plasma etching system. For a $p$- and $n$-ohmic

![Fig. 2. Calculated current distribution vs the lateral length $x$ in a LED.](image)

![Fig. 3. Resistivity of the Ni/Au film with a 1:1 thickness ratio as a function of film thickness ($t_p$). The inset shows a microscopic top view of the fabricated LED.](image)
contact, Ni/Au and Ti/Al schemes were evaporated using an electron beam evaporator. The inset in Fig. 3 shows a photograph of the completely fabricated LED designed from the model. In Table I, it is important to note that the approximate critical transparent-electrode thickness of a 55 Ω·μm·/p-n wafer is 60 Å, which exhibits a ρl/t of 49 Ω. It can be seen that the output power (P_{out}) has a maximum around ρl/t = 49 Ω and drops for either ρl/t > 49 Ω or ρl/t < 49 Ω. This result is in good agreement with the largest calculated current spreading length (L_{sp}) of 290 μm for LED C applied to the actual mesa length (l) of 320 μm. The significantly degraded output power for LED D can be attributed to the combined effects of nonuniform current spreading and degraded light transmittance. In addition, it is also worth noting that discussing electrical and optical characteristics of LED D for ρl/t < 49 Ω requires more considerations such as a modeling assumption that neglects lateral p-layer resistance and measurement errors between the transparent electrode and n-layer resistances induced by a different measurement system. More detailed discussions will be presented elsewhere.

As shown in Fig. 2, the current density versus lateral length x shows an exponential behavior. This indicates that the reduction in the lateral mesa length l is extremely favorable in terms of improving the current injection efficiency. With respect to this point, interdigitated LED structures\(^7\) can be proposed as having an ideal geometry as shown in the inset of Fig. 4(a). Figure 4(a) shows the I–V characteristics of the conventional and the interdigitated LED with the same overall dimension of 350×260 μm\(^2\). It should be noted that the interdigitated structures did not employ a transparent electrode. It is clear that the electrical characteristics of the interdigitated type LEDs are superior to the conventional LED. This result is very surprising considering that the junction area of the interdigitated type LEDs is even smaller than the conventional LED by about 30%.

Figure 4(b) also shows the improved output power for the interdigitated type LEDs under the injected current, indicating that the interdigitated structure is very effective in extracting generated light. Interestingly, a more prominent increase in output power was observed for a measurement angle of 0° compared to 90°. This can be attributed to the increase in the mesa sidewall area of the interdigitated structures, which acts as an efficient light-extracting region. However, it should be noted that an absolute comparison of the LED output power for each measurement angle of 0° and 90° is impossible because of the different solid angles of π/100 and π/64 steradian for each direction. In addition, while the interdigitated type A showed superior electrical properties to type B, type B showed a superior optical efficiency compared to type A. Compared to type B, this can be attributed to the larger junction area of type B by a factor of 5.3% and the smaller mesa surface area by 8.7%. This significant pattern influence on device performance suggests that more geometrical LED design and additional testing must be undertaken, to realize a wide range of applications.

In summary, considering the main lateral current transport paths of the p-transparent electrode and the n layer, advanced theoretical modeling was performed and the results were analyzed. Based on the calculated current distribution, the important device parameters and a design rule for uniform current spreading could be extracted. Using these results, it was possible to determine the appropriate device parameters and even to realize the ideal LED geometry without the need for a transparent electrode. With respect to practical applications, it appears that the ideal geometrical design such as an interdigitated structure holds considerable promise for a large-size LED, which exceeds the current spreading length.

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