On a relationship among optical power, current density, and junction temperature for InGaN-based light-emitting diodes

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Theories of spontaneous emission rates and carrier recombination mechanisms for multiple-quantum-well InGaN-based blue light-emitting diodes (LEDs) have been carefully studied. A relationship among the optical power, the current density, and the temperature (heat-sink temperature or p-n junction temperature) is identified, and an optical-electrical-thermal model (OETM) is proposed. Thereafter, spectral measurements have been carried out to confirm the validity of this OETM. Results show that measured optical powers under various current densities and heat-sink temperatures agree satisfactorily with those determined by the OETM. Furthermore, the traditional forward-voltage method (FVM) has also been carried out for comparison. Junction temperatures determined by this OETM is in accordance with those measured by the FVM. Therefore, this model can serve as an alternative tool for fast estimating junction temperatures after relevant fitting coefficients having been determined. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). [http://dx.doi.org/10.1063/1.4974877]

I. INTRODUCTION

Light-emitting diodes (LEDs) based on nitride (InGaN/GaN) compounds have recently become popular electronic components that serve lighting communities. In evaluation of LEDs' performances, quantum efficiencies and temperatures \( T \) (heat-sink temperatures, \( T_s \); or p-n junction temperatures, \( T_j \)) at a certain electrical current are deemed as two critical criterions. In general, there are interactions among these photometric, electrical, and thermal aspects. In their works, the photo-electro-thermal theory has been presented by linking the luminous flux, thermal resistance, electrical current, junction temperature, heat dissipation coefficient, etc. Here, by studying theories of spontaneous emission rates and carrier recombination mechanisms, we derive a simple and useful model only linking the optical powers, junction temperatures or heat-sink temperatures, and current densities. Correlations among these parameters have been considered as powerful tools for evaluating some key factors of optoelectronic devices, such as the optical power and the junction temperature among others.

In this present study, we have developed an empirical model, in which experimental optical powers \( (P) \), temperatures, and current densities \( (J) \) for InGaN-based LEDs are interrelated. First, it is noted that the integral of the theoretical spontaneous emission rate (SER) of LEDs \( (R_{spon}) \), called as the theoretical optical power) is proportional to the well-known radiative recombination

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coefficient ($B$) as well as to the square of the free carrier concentration ($n$). Second, the carrier recombination inside quantum wells by means of $J/\rho = An + Bn^2 + Cn^3$ \textsuperscript{14} (the simple traditional ABC model in consideration of the Auger recombination) or other proposed complicated models like $J/\rho = An + Bn^2 + Cn^3 + f(n)$ (polynomial formula) in consideration of carrier losses and other “efficiency droop” mechanisms\textsuperscript{15} implies that $n$ is a function of $J$. Therefore, theoretical $R_{\text{spon}}$ can be logically expressed in terms of $J$. Then, we infer that the electroluminescent (EL) optical power can also be described as a function of $J$. But coefficients of $A$, $B$, $C$, or others are all functions of temperatures.\textsuperscript{16} For purposes of separating temperatures from electrical currents, a reference state is introduced such that all coefficients can be expressed by an exponential term containing temperatures and their respective referenced values. Under such arrangements, we obtain the modeling equation for determining optical powers in terms of current densities and temperatures. Finally, spectral measurements are conducted to confirm the validity of this model.

II. THEORY

Our analysis starts from the theoretical SER of multiple-quantum-well (MQW) LEDs\textsuperscript{17,18} namely,

$$\gamma(h\nu) = \frac{1}{\tau} \rho(h\nu)f_e(h\nu)[1 - f_e(h\nu)],$$

(1)

where $\tau$, is the lifetime of the electron-hole radiative recombination; $h\nu$ the photon energy; $\rho(h\nu)$ the optical joint density of states; and $f_e(h\nu)[1 - f_e(h\nu)]$ occupation probabilities of electron and hole states in conduction and valence bands. When this SER is integrated from the energy band-gap ($E_g$) to the infinity, we obtain

$$R_{\text{spon}} = \int_{E_g}^{+\infty} \gamma(h\nu)d(h\nu),$$

(2)

which is known to be equal to $Bn^2$.\textsuperscript{19} Eventually, we wish to derive an equation expressing $R_{\text{spon}}$ in terms of $J$. Let us analyze the carrier recombination process inside the quantum well by means of the traditional ABC model for simplicity\textsuperscript{14} (although the traditional ABC model somewhat fails to explain the “efficiency droop” phenomenon of InGaN-based MQW LEDs), namely $J/\rho = An + Bn^2 + Cn^3$, where $A$ and $C$ represent Shockley-Read-Hall (SRH) and Auger coefficients; $q$ the elementary charge; $d$ the thickness of the MQW. Solving this ABC model directly for deriving a formula expressing $n$ in terms of $J$, however, is quite complicated, prompting us to seek another approach instead. According to the carrier recombination process, at low current densities (typically smaller than 5 $A/cm^2$), the $An$ term dominates, i.e., $An \gg Bn^2$ and $An \gg Cn^3$. Hence, $J/\rho = An = A\sqrt{R_{\text{spon}}/B}$, which leads to $R_{\text{spon}} = B(J/\rho)^2$. Likewise, for large $J$ values, the $Cn^3$ term is known to dominate, yielding $J/\rho = Cn^3 = C(R_{\text{spon}}/B)^{3/2}$, which subsequently becomes $R_{\text{spon}} = B(J/C\rho)^{2/3}$. Omitting the algebra for moderate $J$ values, we combine terms for all three regimes and obtain,

$$R_{\text{spon}} = \beta_o J^2 + \beta_b J + \beta_c J^{3/2}.$$  \textsuperscript{13}

(3)

Coefficients, $\beta_o \propto B(1/A\rho q)^2$, $\beta_b \propto 1/A\rho q$, and $\beta_c \propto B(1/C\rho q)^{2/3}$ are all functions of temperatures, like three weighting factors. Experimentally, it is wise to strive for establishing a similar form as,

$$P_o = \xi_o J^2 + \xi_b J + \xi_c J^{3/2},$$

(4)

where $\xi_o$, $\xi_b$, and $\xi_c$ are fitting coefficients. Then, an exponential expression, $P = P_o \exp[-\xi_d(T - T_o)]$, is considered,\textsuperscript{20} where $T_o$ is the reference temperature taken to be 298.0 K in our study (it can also be taken as any other arbitrary temperature, such as 308.0 K, 318.0 K, 328.0 K, and 338.0 K, etc.); $P_o$ is the EL optical power at $T = T_o$. Finally, we can find an optical-electrical-thermal model (OETM) as

$$P = (\xi_1 J^2 + \xi_2 J + \xi_3 J^{3/2})e^{-\xi_d(T - T_o)},$$

(5)

where $\xi_1$, $\xi_2$, $\xi_3$ and $\xi_d = \xi_d$ are four fitting coefficients to be determined below.
III. EXPERIMENT AND DISCUSSION

The MQW-structured blue InGaN-based packaged LED samples, with its chip size as 1 mm \( \times \) 1 mm \( \times \) 0.1 mm, are fabricated by the metal-organic chemical vapor deposition (MOCVD) on the c-plane sapphire substrate. In this study, three samples, sample #1, #2, and #3, manufactured by three well-established companies are used. During experiments, these LED samples are placed on a temperature-controlled heat sink (Keithley-2510, Keithley Inc.) with the heat-sink temperature maintained between 298.0 K and 338.0 K, varying with an increment of 5.0 K. They are driven with a direct current ranging from 0.25 A to 0.75 A with an increment of 0.05 A, corresponding to the current density ranging from 25 A/cm\(^2\) to 75 A/cm\(^2\), supplied by an electrical source meter (Keithley-2611, Keithley Inc.) with an accuracy of 0.1 nA. Finally, the emitted light is collected by a 500 mm-diameter integrating sphere (ISP-500, Instrument System Inc.), which is connected to a spectrometer (Spectro-320e, Instrument System Inc.) that provides measurements of spectra. Figure 1(a) shows the schematic assembly of the InGaN-MQW LED, the copper base, and the heat sink, along with the optical instrumentation. Figure 1(b) shows the EL spectrum of the InGaN-MQW LED (driven at 0.25 A), with an emission peak wavelength locating at around 453 nm. Inset of Fig. 1(b) depicts the photograph of this assembly.

In Figs. 2(a) and 2(b), measured spectra of one representative InGaN-MQW LED with various heat-sink temperatures and current densities are plotted versus the wavelength. Figure 2(a) shows that the EL peak increases as the current density increases, due to the fact that a great amount of electrons are injected into the active region of LEDs. As the heat-sink temperature increases, the EL peak decreases oppositely, as shown in Fig. 2(b). The decrease of the emission is due to several factors, such as the non-radiative recombination via deep levels and carrier losses.\(^{20}\) From Eq. (5), we first realize that, as \( T \) is set to \( T_0 \), coefficients of \( \xi_i (i = 1 \sim 3) \) in this equation can be determined by fitting the curve of the optical power versus \( J \) at \( T_0 \). In Fig. 3(a), optical powers integrated over

![FIG. 1.](image1.png) (a) The schematic assembly of the InGaN-MQW LED, the copper base, the heat sink, and the optical instrumentation. (b) The EL spectrum of the InGaN-MQW LED, with an emission peak wavelength locating at around 453 nm (driven at 0.25 A). Inset: the photograph of this assembly.

![FIG. 2.](image2.png) (a) The optical power of EL spectra versus the wavelength parameterized in the current density for sample #1 at 298 K heat-sink temperature. (b) The optical power of EL spectra versus the wavelength parameterized in the heat-sink temperature for sample #1 driven at 0.25 A electrical current (Here, the temperature is heat-sink temperature).
the entire spectrum of sample #1, #2, and #3 are plotted versus \( J \) with an average \( R \)-squared value of 0.9991, which indicates that data agree fairly with the model.

Second, we need to determine the coefficient of \( \xi_4 \). Figure 3(b) shows optical powers of sample #1, #2, and #3 versus \( T_s \) at 25 A/cm\(^2\). We also fit the curve of the optical power versus the heat-sink temperature at this fixed \( J \), and obtain \( \xi_4 \). Therefore, average coefficients of \( \xi_i (i = 1 \sim 4) \) for three InGaN-MQW LED samples are determined as 1.00 \( \times 10^{-8} \) W\cdot cm\(^4\) A\(^{-2}\), 5.20 \( \times 10^{-3} \) W\cdot cm\(^2\) A\(^{-1}\), 1.87 \( \times 10^{-2} \) W\cdot cm\(^{4/3}\) A\(^{-2/3}\), and 1.85 \( \times 10^{-3} \) K\(^{-1}\), respectively. These values differ in LEDs with various types and structures, like InGaN, GaP, and AlGaInP LEDs, but are almost the same for LEDs with same types and structures. The \( \xi_1 \) value is so low that it could be ignored in this study, hence, the simplified formula of OETM is expressed as follows,

\[
P = (\xi_2 J + \xi_3 J^2) e^{-\xi_4 T_s}.
\]

Figure 4 shows the optical power measured by optical instrumentation (solid scatter) and calculated by OETM (open scatter) for sample #1. It is observed that experimental results agree satisfactorily with the computational counterpart. Therefore, this model can be adopted to concisely predict optical powers. We also expand our studied range of currents and temperatures, and observe the similar agreement.

So far, the junction temperature can be predicted through the OETM. We rearrange the Eq (6) and approach an expression of \( T_j \) with respect to \( J \),

\[
T_j = T_{j0} + \frac{\ln(\xi_2 J + \xi_3 J^2) - \ln(P)}{\xi_4}.
\]
if we have measured the optical power and determined above relevant parameters, including $\xi_i (i = 2 \sim 4)$ and $T_{jo}$ (in our case, $T_{jo}$ represents the junction temperature at 25 A/cm$^2$ and 298.0 K heat-sink temperature). In order to prove the usefulness of this expression, we have carried out experiments as follows. The sample is driven at 35 A/cm$^2$. The heat-sink temperature is maintained at 298.0 K, 308.0 K, 318.0 K, 328.0 K, and 338.0 K, respectively. For comparison, we also adopt the transient thermal tester (T3Ster, MicReD Ltd., with an accuracy resolution of 0.1 K) by employing the widely-used forward-voltage method (FVM) to measure the junction temperature at steady states parameterized in various current densities. In the calibration of the temperature-sensitive parameter (TSP, $k$) of voltage, we adopt a small measurement current ($I_m$) of 2 mA, and apply it within the temperature range from 298.0 K to 328.0 K, with an increment of 10.0 K. The TSP can be written as,

$$k = \frac{\Delta V}{\Delta T}, \quad (8)$$

where $\Delta V$ is the voltage variation at $I_m = 2$ mA. Figure 5(a) plots the voltage versus the temperature at $I_m = 2$ mA. A linear relationship between the voltage variation and the temperature rise can be noticed, along with $R$-squared value of 0.9963, suggesting an excellent agreement. Therefore, the average TSP for three samples is determined by least-squared methods as -1.227 mV/K. After this calibration, the temperature rise versus time at various current densities is measured by the T3Ster.

Polynomial relationships between the temperature rise and the current can be observed in Fig. 5(b). In the present case, $T_{jo}$ is determined by the FVM as 300.7 K (at 298.0 K heat-sink temperature).

Therefore, junction temperatures calculated by OETM (Equation 7) and measured by the FVM at 35 A/cm$^2$ and under five heat-sink temperatures for sample #1 are listed in Table I.

We also calculate the absolute value of the change of temperature ($\Delta T$) determined by OETM and FVM. Results show that junction temperatures determined by OETM and FVM are in fair agreement ($\Delta T \leq 2$ K). Here, we have re-calculated the parameter of $\xi_4$ by determining the relationship between optical power and junction temperature (measured by FVM), and have found that this value becomes $1.80 \times 10^{-3}$ K$^{-1}$, which is close to $1.85 \times 10^{-3}$ K$^{-1}$. This small difference indicates that the parameter of $\xi_4$ derived by the relationship between optical power and heat-sink temperature in our work can still be used in the junction temperature calculation, and dose not affect the accuracy of this model. Therefore, this OETM proves useful in fast predicting the junction temperature of the InGaN-based LED if we obtain its real-time optical power at an arbitrary current density and at an arbitrary ambient temperature, after determining three coefficients of $\xi_i (i = 2 \sim 4)$ and only one reference junction temperature value.

<table>
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<th>$T_s$ (K)</th>
<th>298.0</th>
<th>308.0</th>
<th>318.0</th>
<th>328.0</th>
<th>338.0</th>
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<td>303.9</td>
<td>314.0</td>
<td>324.0</td>
<td>334.0</td>
<td>344.2</td>
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<td>$T_j$ (K) by FVM</td>
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<td>312.4</td>
<td>322.4</td>
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<td>$\Delta T$ (K)</td>
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<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.8</td>
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</tbody>
</table>
IV. CONCLUSION

In summary, based on theories of the spontaneous emission rate and the ABC model, we have derived a relationship among optical powers, current densities, and temperatures. Via measuring EL spectra, we confirm the validity of this model. Results show that computations and experiments are in satisfactory agreement. Future studies will focus on the application of OETM to the LED array and transient behaviors of this model.

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