Effect of junction temperature on heat dissipation of high power light emitting diodes
Dae-Suk Kim and Bongtae Han

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Effect of junction temperature on heat dissipation of high power light emitting diodes

Dae-Suk Kim and Bongtae Han
Department of Mechanical Engineering, University of Maryland, College Park, Maryland 20742, USA
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The effect of junction temperature on heat dissipation of high power light emitting diodes (LEDs) is investigated. The theoretical aspect of junction temperature dependency of two major parameters—the forward voltage and the radiant flux—on heat dissipation is reviewed. Actual measurements of the heat dissipation over a wide range of junction temperatures are followed to quantify the effect of the parameters using commercially available LEDs. The results show that (1) the effect of the junction temperature dependency on heat dissipation is governed largely by the LED power efficiency and (2) each parameter contributes to the total heat dissipation in an opposite way so that the absolute changes of the heat dissipation are not significant over a wide range of junction temperature. An empirical model of heat dissipation is proposed for applications in practice. © 2016 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4944800]

I. INTRODUCTION
Thermal management is essential for the design of light emitting diode (LED) based luminaires because a higher junction temperature reduces light output, luminous efficacy, and reliability.1–6 Numerous analytical, experimental, and/or numerical analyses have been conducted to address various thermal issues of high power LEDs.7–11

The temperature-dependent heat dissipation of an LED operated at a given forward current is defined as12

\[ P_h(T_j)|_{I_f} = P_e(T_j)|_{I_f} - P_o(T_j)|_{I_f} = I_f \cdot V_f(T_j)|_{I_f} - \Phi(T_j)|_{I_f}, \]  

where \( I_f \) is the forward current [A]; \( T_j \) is the junction temperature [°C]; \( P_h \) is the heat dissipation [W]; \( P_e \) is the electrical input power [W]; \( P_o \) is the optical output power [W]; \( V_f \) is the forward voltage [V]; and \( \Phi \) is the radiant flux [W]. The electrical input power is the product of the forward current and the forward voltage. The optical output power is the radiant flux.

The electrical input power, the optical output power, and thus the heat dissipation are altered by the junction temperature. It has been well-known that the forward voltage decreases as the junction temperature increases because of the reduction of band gap energy at higher junction temperatures.13–16 Consequently, the electrical input power will decrease as the junction temperature increases, which helps to reduce the heat dissipation.

It has also been well-known that the radiant flux decreases as the junction temperature increases because the non-radiative recombination increases with higher junction temperatures.17,18 As a result, the optical output power will also decrease as the junction temperature increases, which gives rise to the heat dissipation. To the best of authors’ knowledge, the net results of this opposite effect on the final heat dissipation have not been clearly understood.

The objective of this paper is, thus, to investigate quantitatively the effect of junction temperature on the heat dissipation. The theoretical aspect of junction temperature dependency of two major parameters—the forward voltage and the radiant flux—is reviewed first. Actual measurements of heat dissipation over a wide range of the junction temperatures are followed to quantify the opposite effect of the two parameters using commercially available LEDs. The results are presented and the practical implications are discussed.

II. BACKGROUND: JUNCTION TEMPERATURE DEPENDENT FORWARD VOLTAGE AND RADIANT FLUX

The theoretical aspect of junction temperature dependency of the forward voltage and the radiant flux is reviewed.

A. Forward voltage

By considering the intrinsic carrier concentration, the band-gap energy, and the effective density of states, Xi and Schubert developed a theoretical model for the junction temperature dependency of the forward voltage, which was expressed as14

\[ \frac{dV_f}{dT_j} \approx \kappa \frac{e}{N_{NC}N_{NV}} \left( \frac{N_{DA}}{N_{NC}N_{NV}} \right) \exp \frac{e(T_j + \beta)}{2kT_j} \]  

where \( k \) is the Boltzmann constant [J/K]; \( e \) is the elementary charge [C]; \( N_A \) and \( N_D \) are the acceptor and donor concentrations [m\(^{-3}\)]; \( N_C \) and \( N_V \) are the effective density of states at the conduction band and valence band edges [m\(^{-3}\)]; and \( \alpha \) [eV/K] and \( \beta \) [K] are the Varshni parameters. Using the parameters for the GaN blue LED, they obtained \( dV_f/dT_j = -1.76 \text{mV/K} \). This negative linear relationship between the forward voltage and the junction temperature has been widely used to measure the junction temperature of...
high power LEDs, which has been known as the forward voltage method.\textsuperscript{14,16,19}

Keppens et al. studied the issue further to derive a more extensive forward voltage equation as a function of forward current and junction temperature, which was expressed as\textsuperscript{16}

\begin{equation}
V_f(I_f, T_j) = \left[ \frac{n_{\text{ideal}} k}{e} \ln \left( \frac{I_f}{C_5} \right) - \frac{\alpha^*}{e} T_j + \frac{E_{g,300} + 300 \alpha^*}{e} \right],
\end{equation}

where $n_{\text{ideal}}$ is the diode ideality factor; $C_5$ is the combined temperature independent parameter; $\alpha^*$ is the fitting parameters for the bad gap energy [eV/K]; and $E_{g,300}$ is the bandgap at 300 K [eV].

Equation (3) is valid for the junction temperature range from 295 K to 400 K, over which the relationship between the bandgap energy and the junction temperature is virtually linear.\textsuperscript{16} As a result, the forward voltage and the junction temperature also have a linear relationship over the temperature range. The linear slope can be estimated from the parameters for the GaN blue LED available in the literatures. Using the values of $n_{\text{ideal}} = 1.52$, $k = 8.617 \times 10^{-5}$ eV/K, $\epsilon = 1.602 \times 10^{-19}$ C, $C_5 = 255$, $\alpha^* = 0.0003$ eV/K, and $E_{g,300} = 2.926$ eV,\textsuperscript{16} the slope can be expressed in terms of the forward current as $1.31 \times 10^{-4} \ln(I_f) - 1.026 \times 10^{-3}$, which is negative for any operating current.

It should be noted that the bandgap energy cannot be approximated as a linear function of junction temperature at junction temperatures higher than 400 K. Consequently, a non-linear relationship between the junction temperature and the forward voltage should be established if the LED behavior at junction temperatures higher than 400 K is considered.

### B. Radiant flux

Reduction of the radiant flux is attributed to various temperature-dependent factors including non-radiative recombination, surface recombination, and carrier loss over heterostructure barriers.\textsuperscript{15,20–22} At the constant forward current, the radiant flux is proportional to the external quantum efficiency (EQE), $\Phi$,\textsuperscript{15,23} i.e.,

\begin{equation}
\Phi \propto \eta_i \eta_{\text{ext}},
\end{equation}

where $\eta_i$ is the internal quantum efficiency (IQE) and $\eta_{\text{ext}}$ is the extraction efficiency. The extraction efficiency is affected largely by the LED chip configuration and refractive index,\textsuperscript{24,25} and thus it is reasonable to assume that the temperature dependency of the radiant flux is caused mainly by IQE. The internal quantum efficiency has been described by the ABC model,\textsuperscript{26,27} which is expressed as

\begin{equation}
\eta_i = \frac{Bn}{A + Bn + Cn^2},
\end{equation}

where $n$ is the carrier concentration $[m^{-3}]$; $A$ is the Shockley-Read-Hall $[s^{-1}]$; $B$ is the radiative coefficients $[m^3/s]$; and $C$ is the Auger coefficients $[m^6/s]$.

Due to this extreme complexity, the temperature dependence of the radiant flux has been often described by an empirical equation that describes the experimental results without a strong theoretical framework. The empirical equation can be expressed as\textsuperscript{15,22}

\begin{equation}
\Phi \propto \exp \left( -\frac{T_j - T_{\text{ref}}}{T_{\text{ch}}} \right) = \exp \left( -\frac{1}{T_{\text{ch}}} T_j + \frac{T_{\text{ref}}}{T_{\text{ch}}} \right),
\end{equation}

where $T_{\text{ref}}$ is the reference temperature [K] and $T_{\text{ch}}$ is the characteristic temperature [K], which determine the characteristic of the temperature dependency. It has been known from the previous studies\textsuperscript{15,18,22,23,28} that the characteristic temperature of GaN LEDs ranges from 79 K to 1639 K at the reference temperature of 300 K. Relative radiant flux changes as a function of junction temperature at the characteristic temperature at 79 K and 1639 K are shown in Figure 1. The radiant flux decreases as the junction temperature increases and has stronger temperature dependency with the lower characteristic temperature.

### III. MEASUREMENT OF HEAT DISSIPATION

The forward voltage and the radiant flux have to be measured as a function of junction temperature in order to quantify the opposite effect of the forward voltage and the radiant flux on heat dissipation. The heat dissipation is measured using two commercially available blue LEDs.

#### A. Specimen and test procedure

The cross-section image of high power blue LEDs tested in this study is shown in Figure 2. It is a typical high power blue LED for lighting applications, which has an internal thermal resistance of 9–10 K/W. The GaN blue chip is mounted on a ceramic substrate to form a package, which is subsequently mounted on a metal core printed circuit board (MCPBC) using solder connections. Two LEDs from different manufactures were tested (will be referred to as LED1 and LED2).

A measurement setup is shown schematically in Figure 3. The junction temperature of the LED was controlled by a high precision hot plate (mk2000 and HCP304SC: ISTEC); it
provided a temperature resolution of ±0.05 °C. The junction temperature at the operating current was measured using the forward voltage method. The LED was operated by a source meter (2420: Keithley Instruments); it provided the current source accuracy of ±(0.067% + 900 μA). A data acquisition (DAQ) module (USB-6212: National Instruments) was utilized to measure the forward voltage of the LED with 16-bits resolution. When a desired junction temperature was reached, the spectral power distribution (SPD) was measured by an integrating sphere equipped with 16-bits resolution of a spectrometer (SMS-500: SphereOptics).

The heat dissipation was measured over a wide range of junction temperatures (from 25 °C to 200 °C) at a low (250 mA) as well as high forward current (1000 mA) which was the maximum forward current suggested by the manufactures.

B. Junction temperature measurement

The relationship between the junction temperature and the forward voltage (known as the calibration curve) can be obtained by measuring the forward voltage using a low probe current (5 mA) for a short period of time (10 ms). The calibration curve of LED1 and LED2 is shown in Figure 4, where a linear fit as well as a polynomial fit are given.

For the current study, the calibration data were obtained over a temperature range much wider than a typical LED operating temperature range, which exceeded the linear region (400 K) as discussed in Section II A. In Figure 4, deviation from the linearity is evident beyond 125 °C for the both LEDs. The error of the forward voltage at 200 °C between the linear fitting and the measured data is approximately 13 mV and 5 mV for LED1 and LED2, respectively, which corresponds to the junction temperature error of 10 °C and 2 °C. For the current study, a cubic polynomial was used, which produced an ideal fit with the experimental data.

In the actual measurements, the probe current is applied after an LED reaches the steady state condition. As discussed extensively in Ref. 29, the forward voltage shows the combined behavior of RC delay and thermal delay. The forward voltage decreases exponentially due to RC delay, which is caused by a resistance of an LED and a capacitance of a current source, while the forward voltage increases due to the thermal delay, which is caused by the exponential decrease of the junction temperature.

Figure 5(a) shows the transient voltage behavior of LED1 obtained after the probe current of 5 mA is applied. The enlarged view of the region marked by a dashed box is shown in Figure 5(b). The RC delay dominates initially (Zone 1). The thermal delay begins to override the RC delay (Zone 2). Then, the voltage behavior follows an exponential increase (Zone 3). This exponential voltage behavior only after the RC delay-affected period (Zones 1 and 2) represents the junction temperature accurately, i.e., this voltage is only valid for junction temperature estimation using the calibration curve.

The voltage of Zone 3 converted by the calibration curve is shown in Figure 6. The square root of the time scale is used in Figure 6, which is required to implement the linear extrapolation. The extrapolation is based on the theory that a junction temperature changes linearly in a square root time scale if heat is dissipated in one direction (i.e., one-dimensional space) through a homogenous material. The linear fitting is also shown in Figure 6 with the estimated junction temperature at the operating current. The repeatability of the junction temperature measurement was less than 0.1 °C, which was attributed to the current source accuracy.
C. Heat dissipation measurement

The radiant flux can be calculated from SPDs. The SPDs of LED1 at the operating currents of 250 mA and 1000 mA are shown in Figure 7. It is worth noting that a significant center wavelength shift is observed as the bandgap energy is reduced significantly over the large temperature range.\textsuperscript{13} The SPDs of LED2 have a similar behavior and is not included here.

The junction temperature-dependent radiant flux of LED1 and LED2 is shown in Figure 8. The radiant fluxes decrease at different rates as the junction temperature
increases. As mentioned in Sec. II B, the different reduction rate is caused mainly by the IQE of LED chips.

The junction temperature-dependent forward voltage is shown in Figure 9, from which the junction temperature-dependent electrical input power is determined. The reduction rates of two LEDs are virtually the same because materials used in the epitaxial layer dictate the temperature dependency of the forward voltage. The different absolute value at the same junction temperature is attributed to the difference in internal series resistances.16

The heat dissipations were calculated by subtracting the optical output power (Figure 8) from the electrical input power. The results of LED1 and LED2 at the operating currents of 250 mA and 1000 mA are shown in Figures 10(a) and 10(b), respectively. The heat dissipation changes nonlinearly as a function of junction temperature.

IV. JUNCTION TEMPERATURE DEPENDENCY

The changes of electrical input power, optical output power, and heat dissipation with respect to the reference temperature of 25°C were calculated to quantify the effect of the junction temperature dependency. The percent changes are defined as

\[
\text{Electrical input power change in } \% \left( T_j \right) = \frac{I \cdot V(T_j) - I \cdot V(25°C)}{I \cdot V(25°C)} \times 100, \tag{7}
\]

\[
\text{Optical output power change in } \% \left( T_j \right) = \frac{\Phi(T_j) - \Phi(25°C)}{\Phi(25°C)} \times 100, \tag{8}
\]

\[
\text{Heat dissipation change in } \% \left( T_j \right) = \frac{P_h(T_j) - P_h(25°C)}{P_h(25°C)} \times 100. \tag{9}
\]

The results are shown in Figure 11. The percent change of optical output power was much larger than that of electrical input power: 2.2 and 3.1 times larger for LED1 and LED2 at 250 mA and 2.3 and 3.6 times larger for LED1 and LED2 at 1000 mA. For LED1, the percent change of heat dissipation is 10% at 250 mA and 6% at 1000 mA. The percent change of heat dissipation of LED2, however, is much larger: 27% at 250 mA and 11% at 1000 mA.

The percent change difference of heat dissipation can be explained by the power efficiency of LEDs used in the study. The heat dissipation equation (Equation (1)) can be rewritten as

\[
P_h(T_j) = P_e(T_j) - P_e(T_j) \cdot \eta_p(T_j) = I_f \cdot V_f(T_j) [1 - \eta_p(T_j)], \tag{10}
\]

where \(\eta_p\) is the power efficiency, which is defined as the optical output power divided by the electrical input power. It is clear from the above equation that the heat dissipation is governed by not only the forward voltage change but also the power efficiency change.

The power efficiency can be readily determined from the optical output power (Figure 8) and the electrical input power. The results are shown in Figure 12. At the forward current of 250 mA, the power efficiency at room temperature is 58%, and it drops to 47% and 38% at 200°C for LED1 and LED2, respectively. At the forward current of 1000 mA, the power efficiency at room temperature is 44% (LED1) and 43% (LED2), and it drops to 33% and 28% at 200°C, respectively.
The larger power efficiency change of LED2 caused the effect of the optical power change to be stronger. As a result, the junction temperature dependency of LED2 is much higher than LED1. The junction temperature dependency of the heat dissipation can be different from the results obtained from the current study if an LED has power efficiency significantly different from the values shown in Figure 12.

V. EMPIRICAL HEAT DISSIPATION MODEL

This section is devoted to practical implications of the current study for the thermal management of LED-based luminaries.

A. Practical consideration

Due to the compensation effect, the heat dissipation changes over the whole temperature range are only 0.11 W and 0.25 W for LED1 and LED2, respectively (Figure 10). The corresponding junction temperature change is less than 2.5 °C assuming the thermal resistance of 10 K/W. Therefore, it is reasonable to assume in practice that the heat dissipation of blue LEDs is only a function of forward current over the typical operation temperature range (less than 125 °C).

In fact, the heat generation issue is more critical to LED-based luminaires using phosphor converted (pc-) white LEDs since thermal management is one of the most important tasks in the design. In pc-LEDs, extra heat is generated due to the energy loss known as Stokes’ shift. It has been known that the total phosphor heat generation can vary from 5% to 40% of the blue input power, depending upon the concentration, thickness, particle size, and quantum efficiency of phosphors. The phosphor heat generation has some temperature dependency due to the phenomenon known as thermal quenching, but its effect is not significant (less than 10%) over the typical luminaire operating temperature range. This implies that the junction temperature dependency of heat dissipation is also not significant for pc-white LEDs. Two pc-white LEDs using the similar blue chips were tested to investigate it experimentally.

Two white LEDs (one cool white and one warm white: will be referred to as CW-LED3 and WW-LED4, respectively) contain a conformal phosphor layer. They were tested over a junction temperature range from 50 to 125 °C. Higher forward currents (1250 and 1500 mA) were included in the test considering the trend of increased operating currents.

The results of the heat dissipation of CW-LED3 and WW-LED4 are shown in Figure 13. The heat dissipation of CW LED3 at $T_j = 50$ °C and $I_f = 1500$ mA and WW LED4 at
$T_j = 50\degree C$ and $I_f = 1250\ mA$ and $1500\ mA$ could not be measured due to the limitation of the hot plate performance.

As expected, the maximum heat dissipation changes over the whole temperature range are only $0.11\ W$ and $0.12\ W$ for CW-LED3 and WW-LED4, respectively, which correspond to the junction temperature change of $1.1\degree C$ and $1.2\degree C$ assuming that the thermal resistance is $10\ K/W$.

The results confirm that the compensation effect on the junction temperature dependency of the heat dissipation is consistent for pc-white LEDs in the current market. The effect of the temperature dependent heat dissipation will be even smaller as the thermal resistance decreases in the future LEDs. Therefore, it is reasonable to assume that the heat dissipation is virtually the same regardless of the junction temperature. Then, the governing equation for the heat dissipation can be written in an approximated form as

$$P_h(T_j)|_{I_f} = I_f \cdot V_f(T_j)|_{I_f} - \Phi(T_j)|_{I_f}. \quad (11)$$

### B. Empirical model

An empirical relationship between the heat dissipation and the forward current is proposed for applications in practice. It has been observed that the heat dissipation increases exponentially with the forward current. Considering the fact that the heat dissipation at the zero current should be zero, the relationship can be modeled as

$$P_h = A \exp\left(\frac{I_f}{B}\right) - A, \quad (12)$$

where $A$ and $B$ are variables for the exponential function. Theoretically, any two current data are sufficient to obtain the constants, but, in practice, an extra data point is usually required to minimize the effect of the measurement uncertainty. Since the model is bound at the zero current, the middle and largest values in the current range of interest are recommended for the regression.

The heat dissipations of CW-LED3 and WW-LED4 obtained at $T_j = 75\degree C$ (Figure 13) were implemented using the proposed approach. The results are shown in Figure 14(a). The heat dissipation obtained at different currents (Figure 13) is compared with the predicted value and the difference is plotted in Figure 14(b). The maximum heat dissipation difference (calculated by subtracting the predicted values from the measured values) is smaller than $0.06\ W$. The results confirm that the heat dissipation can be estimated accurately at any current by using heat dissipation data obtained at two forward currents at any junction temperature.

### VI. CONCLUSION

The effect of the junction temperature dependency on the heat dissipation was investigated. The theoretical review
confirmed that the forward voltage reduction at higher junction temperatures compensated the heat dissipation that was increased by the radiant flux reduction. Actual measurements of the heat dissipation over a wide range of the junction temperatures were performed to evaluate the compensation effect quantitatively. The results showed that (1) the effect of the junction temperature dependency on the heat dissipation was governed largely by the power efficiency and (2) the compensation effect was so strong that the absolute changes of the heat dissipation were not significant over the junction temperature range considered in the study (from 25 °C to 200 °C).

Supplementary experiments using phosphor-converted white LEDs were conducted over the typical operating temperatures of LED-based luminaires. Due to the small temperature dependency of phosphor heat generation, the heat dissipation of pc-LEDs was confirmed to be virtually the same regardless of the junction temperature.

Based on the results, the empirical heat dissipation model that was only a function of the forward current was proposed. The model requires the heat dissipation data only at two currents but can accurately estimate the heat dissipation at any forward current (and at any temperatures).


