Accurate determination of junction temperature in a GaN-based blue light-emitting diode using nonlinear voltage-temperature relation

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Abstract
We investigate the junction temperature measurements for GaN-based blue light emitting diodes (LEDs) using nonlinear dependence of the forward voltage ($V_f$) on temperature. Unlike the conventional linear model of the dependence of $V_f$ on temperature, the modeling of the temperature dependent $V_f$ with a quadratic function showed good agreements with measured data in the temperature range between 20 and 100 °C. Using the proposed quadratic model, the junction temperature and thermal resistance of the measured LED could be accurately determined as the ambient temperature varied. It was observed that the junction temperature increment remained almost unchanged as the ambient temperature increased from 20 to 80 °C, which could be attributed to the interplay between the decrease in series resistance and the increase in non-radiative recombination with increasing temperature. The presented method for accurate determination of the junction temperature is expected to be advantageously employed for the thermal management of high-power LEDs.

Keywords Light-emitting diode · Blue LED · GaN · Junction temperature

1 Introduction

The demand for light emitting diodes (LEDs) as applied to commercial and residential solid-state lighting, display backlighting, and automobile headlights continues to rise (Chang et al. 2012; Pust et al. 2015; Cho et al. 2017; Bhardwaj et al. 2017). The internal quantum efficiency (IQE) of state-of-the art blue LEDs can exceed 90% (Hurni et al. 2015; Kuritzky et al. 2018; David et al. 2020). However, the IQE of GaN-based blue LEDs may be reduced significantly at high current density and at high temperature, respectively referred to as current droop and thermal droop (David et al. 2019; Meneghini et al. 2020). Increasing the operation temperature of an LED decreases light output power (LOP) mainly because of the increase in non-radiative recombination with increasing temperature.
Therefore, thermal management of LEDs has become increasingly important with the development of high power LEDs. Junction temperature ($T_j$) is an important parameter which could significantly influence IQE, device reliability, and color stability of LEDs. High electrical power consumption by commercial high-power LEDs results in device heating, making $T_j$ an essential figure of merit that requires a reliable method of measurement. Because of the importance of thermal management in LEDs, $T_j$ of GaN-based LEDs has been intensively studied.

In addition to LOP, the forward voltage ($V_f$) of GaN-based LEDs has been demonstrated to show strong dependence on temperature (Xi et al. 2004, Ryu et al. 2005). $V_f$ decreases with increasing temperature mainly because of the reduction in the energy band gap and series resistance (Varshini 1967, Xi et al. 2005). The large variation of $V_f$ with temperature can provide a convenient and reliable method to determine $T_j$ (Xi et al. 2004, Ryu et al. 2005, Keppens et al. 2008, Feng et al. 2012). This forward voltage method has been known to be more accurate than the emission-peak-shift method (Xi et al. 2005). In the forward voltage method, the temperature coefficient of voltage ($K$), which is defined as the derivative of forward voltage with respect to temperature, is measured firstly. Then, $T_j$ is determined by dividing the voltage difference between pulsed and continuous-wave (CW) operation by the measured $K$ value. Up to now, $K$ was mostly regarded to be constant independent of temperature in determining $T_j$ of LEDs, assuming almost linear dependence of $V_f$ on temperature. However, $K$ can be a strong function of temperature because of nonlinear dependence of $V_f$ on temperature, which should be considered in determining $T_j$.

In this paper, we report on the method for accurate determination of $T_j$ of a GaN-based blue LED package in the temperature range between 20 and 100 °C using nonlinear temperature dependence of the forward voltage. It will be shown that $V_f$ can be fit quite well with a quadratic function of the temperature, and hence the $K$ value depends linearly on the temperature. Using the obtained $K$-factor, the junction temperature increment ($\Delta T_j$) relative to the ambient temperature was determined. In addition, thermal resistance ($R_{th}$) of the measured LED package was determined using $\Delta T_j$ and dissipated electrical power. We compare the temperature dependence of $T_j$ and $R_{th}$ for the constant and variable $K$ values, and show the importance of using nonlinear temperature dependence of $V_f$ for the accurate characterization of thermal properties of LEDs.

2 Theory

The relation between $V_f$ and injection current ($I$) at temperature $T$ of a diode is given by the Shockley equation that includes a series resistance term (Xi et al. 2005):

$$I = I_s \left[ \exp \left( \frac{eV_j}{nkT} \right) - 1 \right] = I_s \left[ \exp \left( \frac{eV_f - eIR_s}{nkT} \right) - 1 \right]$$  

(1)

where $I_s$ is the saturation current, $V_j$ is the junction voltage, $R_s$ is the series resistance, and $n$ is the diode ideality factor. Solving Eq. (1) for the case of $eV_j \gg nkT$, $V_f$ is expressed as

$$V_f = V_j + IR_s = \frac{nkT}{e} \ln \left( \frac{I}{I_s} \right) + IR_s$$  

(2)

By taking the derivative of $V_f$ with respect to $T$ in Eq. (2), the temperature coefficient of voltage, $K$ is obtained:
Assuming that the series resistance of GaN-based LEDs is dominantly influenced by p-type layers, $R_s$ can be written as (Xi et al. 2005; Feng et al. 2012; Chen et al. 2017 et al.)

$$R_s = \frac{1}{e\mu_p p L A}$$

where $\mu_p$ and $p$ are the hole mobility and hole concentration, respectively. $L$ and $A$ are the length and cross sectional area of the device, respectively. Generally, $\mu_p$ is proportional to $T^S$, where $S$ has a typical value of $-1/2$ for phonon scattering (Rubin et al. 1994; Xi et al. 2005), and $p$ is proportional to exp(-$E_a/2kT$), where $E_a$ is the acceptor activation energy (Xi et al. 2005; Feng et al. 2012; Meyaar et al. 2013). Using Eq. (4) and the temperature-dependent model of $\mu_p$ and $p$, Eq. (3) can be rewritten as

$$K = \frac{dV_f}{dT} = \frac{dV_j}{dT} + I \frac{dR_s}{dT}$$

In Eq. (5), $dV/dT$ was found to be weakly dependent on the temperature, which showed an almost constant value around -1.5 mV/K for InGaN blue LEDs (Xi et al. 2005; Meyaar et al. 2013). The second summand of the right hand side of Eq. (5), which corresponds to the contribution of the series resistance, can be strongly dependent on the temperature and current. This term has complicated temperature dependence as $R_s$ is also dependent on the temperature. Up to now, $K$ of LEDs was mostly regarded to be constant independent of temperature and current (Xi et al. 2004, Keppens et al. 2008, Meyaar et al. 2013, Kim et al. 2016, Chen et al. 2017). However, it will be shown later that the constant $K$ could lead to large errors in determining $T_j$, and the temperature dependence of $K$ should be considered for accurate determination of $T_j$.

Using the definition of $K$ in Eq. (3), the difference in $V_f$ between CW and pulsed operation is expressed as

$$\Delta V_f = \int_{T_a}^{T_j} KdT$$

where $T_a$ is the ambient temperature. Equation (6) is based on the assumption that the temperature of LEDs corresponds to $T_j$ and $T_a$ for the CW and pulsed operation, respectively. It should be noted that both $\Delta V_f$ and $K$ are negative quantities. If the voltage-temperature ($V$-$T$) relation was assumed to be linear, $K$ would be constant. In that case, $\Delta T_{jj}$ is simply given by

$$\Delta T_j \equiv T_j - T_a = \frac{\Delta V_f}{K}$$

If $V_f$ is quadratically proportional to the temperature as will be shown experimentally, $K$ can be written as

$$K = aT + b$$

where $a$ and $b$ are fitting parameters that can be obtained by the fit of measured $V$-$T$ relation. Using Eqs. (6) and (8), the following quadratic equation for $T_j$ is obtained:
\[ aT_j^2 + 2bT_j - (aT_a^2 + 2bT_a + 2\Delta V_j) = 0 \]  

Solving Eq. (9) yields \( T_j \) for given \( T_a \) and \( \Delta V \). In addition, thermal resistance of the LED package can be calculated using the measured \( T_j \) and light output power, \( P \):

\[ R_{th} = \frac{\Delta T_j}{IV_f - P} \]  

3 Experiments

The epitaxial layers of an LED used for this study were grown on a c-plane sapphire substrate by metal–organic chemical vapor deposition. The layer structure consisted of a Si-doped n-GaN layer, InGaN/GaN multiple-quantum-well active region, a Mg-doped p-AlGaN electron-blocking layer, and a Mg-doped p-GaN contact layer. The peak emission wavelength was \(~450\) nm at \( 20^\circ\text{C} \). The LED chip was fabricated as a lateral-injection structure with the chip dimension of \( 650\,\mu\text{m} \times 650\,\mu\text{m} \). The fabricated LED chip was encapsulated with epoxy resin and mounted in a ceramic package as a type of surface-mount device. Then, the LED package was soldered on a metal PCB and the temperature was controlled by a thermo-electric cooler.

The optical and electrical characteristics of an LED sample were measured as the injection current increased up to \( 150\,\text{mA} \) for a fixed ambient temperature \( (T_a) \) from \( 20 \) to \( 100 \) °C, and the LOP versus current \( (L-I) \) and \( V_f \) versus current \( (V-I) \) relations were obtained for each temperature. The LED sample was operated under CW and pulsed current injection for a given \( T_a \). For the pulsed operation, the pulse width and the duty cycle were \( 0.1\,\text{ms} \) and the duty cycle of \( 1\% \), respectively, which is expected to have negligible effect on temperature rise of the LED junction.

Figure 1 shows \( L-I \) and \( V-I \) curves of the measured LED sample under CW operation for \( T_a \) of \( 20, 40, 60, 80, \) and \( 100 \) °C. In Fig. 1a, the LOP increased sublinearly with injection current, and it decreased slowly with increasing temperature. In Fig. 1b, \( V-I \) curves under pulsed operation are shown for various \( T_a \) between \( 20 \) and \( 100 \) °C. It is observed that \( V_f \) decreased with increasing temperatures. In Fig. 2a, \( V-I \) curves under pulsed and CW
operation are compared when the ambient temperature is 20 °C. $V_f$ under pulsed operation was higher than that under CW operation as a result of the difference in the LED temperature between pulsed and CW operation. In Fig. 2b, the voltage difference $\Delta V_f$ between pulsed and CW operation was plotted as a function of $T_a$ from 20 to 100 °C for currents of 20, 50, 100, and 150 mA. Using Eq. (7) or (9) with the $\Delta V_f$ data in Fig. 2b, $T_j$ was determined as $T_a$ varied from 20 to 100 °C.

4 Results and discussion

An accurate thermal measurement evaluation requires an ideal fit to the forward voltage versus temperature ($V$-$T$) relation. Figure 3 shows $V_f$ under pulsed operation as a function of $T_a$ when the injection current was 20, 50, 100, and 150 mA. Because of the pulsed operation, it can be regarded that $T_a$ is the same as $T_j$ in Fig. 3. The linear fit (red line) and a quadratic fit (blue line) to the measured data are also shown in Fig. 3. As mentioned before, the dependence of $V_f$ on temperature has often been modelled with a linear function (Xi et al. 2004). However, inspection of Fig. 3 shows that the linear fit did not agree well with the measured data for all currents, 20, 50, 100, and 150 mA. On the contrary, the quadratic fit showed good agreement with the measured voltage-temperature relations for all injection currents. In fact, a linear fit implies a constant slope and consequently a single value of the series resistance in the entire temperature, which in reality is not the case. Increasing the temperature activates the acceptor atoms in the $p$ doped region resulting in a changing series resistance.

To quantitatively compare the accuracy between the linear and quadratic fit, $R$-squared value ($R^2$) for the linear and quadratic fit is plotted as a function of current in Fig. 4. $R^2$ is a statistical measure of how close the data are to the fitted curve. In the current range between 10 and 150 mA, $R^2$ of the quadratic fit was larger than 0.9997 whereas that of the linear fit varied from 0.992 to 0.9985. By modelling the temperature dependent forward voltage with a quadratic function, $V_f= aT^2 + bT + c$, a nearly ideal fit which agreed well with the experimental data was demonstrated.

The temperature coefficient of voltage $K$ is the slope of the $V$-$T$ relation, which is obtained by the derivative of the fit function. For the linear fitting, $K$ is a constant value. The $K$ values of $-1.97$, $-2.98$, $-3.91$, and $-4.34$ mV/K were obtained at 20, 50, 100, and
For the quadratic fitting, \( K \) is given by a temperature dependent function, \( K = 2\alpha T_a + \beta \). Figure 5 shows the variation of \( K \) with \( T_a \) for the quadratic fit when the injection current is 20, 50, 100, and 150 mA. For all currents, the absolute value of \( K \) decreased with increasing \( T_a \) as a result of the negative \( \alpha \) value. In the case of 100-mA injection current, \( \alpha \) and \( \beta \) were obtained to be \(-8.74 \times 10^{-6} \) V/K² and \( 4.96 \times 10^{-3} \) V/K, respectively. It has been shown that the slope of the \( V-T \) curve decreased as the series resistance was reduced (Meyaard et al. 2013). Therefore, the negative value of the slope \( \alpha \) with increasing temperature implies a decreasing value of the series resistance with temperature.
The junction temperature increment, $\Delta T_j$, of the LED was determined using Eq. (7) and Eq. (9) for the linear and quadratic $V$-$T$ fit, respectively. The $\Delta V_f$ data in Fig. 2b were employed for determining $\Delta T_j$. Figure 6a shows the variation of $\Delta T_j$ as a function of $T_a$ for 100-mA injection current. The result reveals slowly varying $\Delta T_j$ for the quadratic $V$-$T$ fitting and rapidly decreasing $\Delta T_j$ for the linear fitting. The conventional linear $V$-$T$ fit could lead to large errors in determining $\Delta T_j$ of LEDs at low and high $T_a$. $\Delta T_j$ for the quadratic $V$-$T$ fitting varied between 19 and 23 K as $T_a$ increased from 20 to 100 °C. Increase in temperature will increase the activation of acceptor atoms in the p-region thereby reducing the series resistance contribution to the junction heating. On the contrary, nonradiative recombination via SRH recombination and Auger recombination increases at elevated temperatures, resulting in the increase of heat generation at the junction. The slowly varying $\Delta T_j$ observed in Fig. 6a can be attributed to the interplay between the contributions of the series resistance of the p-region and the nonradiative recombination to the junction heating.

With the obtained results of $\Delta T_j$, LOP, and $V_f$ under CW operation, $R_{th}$ was calculated using Eq. (10). Figure 6(b) shows the variation of $R_{th}$ with $T_a$ for the linear and quadratic $V$-$T$ fitting at 100-mA injection current. The dependence of $R_{th}$ on $T_a$ is similar to that of $\Delta T_j$ on $T_a$ in Fig. 6a for both the linear and quadratic fitting. As the temperature increased from 20 to 100 °C, $R_{th}$ decreased from 159 to 98 K/W for the linear fitting whereas it slowly
varied from 126 to 147 K/W for the quadratic fitting. As in the case of $\Delta T_j$, the linear fitting of $V$-$T$ relation could lead to incorrect information on $R_{th}$. Since $R_{th}$ is strongly influenced by thermal conductivity of thermal interface materials (TIMs), the slowly varying behavior of $R_{th}$ with temperature implies that the thermal conductivity of TIMs in the LED package is believed to be weakly dependent on the temperature.

In addition, we evaluated $\Delta T_j$ for other injection currents using the quadratic fitting of $V$-$T$ relations and Eq. (9). Figure 7 shows $\Delta T_j$ as a function injection current for $T_a$ of 20, 40, 60, and 80 °C. $\Delta T_j$ increased nearly linearly with increasing current for all temperatures. This linear relationship has also been reported in previous works on the junction temperature of LEDs (Xi et al. 2005; Feng et al. 2012; Kim et al. 2020). The slope of $\Delta T_j$ versus current was calculated to be ~0.24 K/A. In addition, only slight difference in $\Delta T_j$ was observed at a given injection current for all temperatures from 20 to 80 °C. As the temperature increases, the series resistance decreases whereas nonradiative recombination increases. These counteractive effects are believed to result in the insensitivity of $\Delta T_j$ to ambient temperatures.

5 Conclusion

We have reported on the determination of the junction temperature of GaN blue LED using a non-linear modelling of the forward voltage dependence on temperature. It was found that the temperature dependence of $V_f$ was fitted ideally with a quadratic function in contrast to the linear dependence in previous studies. This resulted in decreasing values of the temperature coefficient of voltage, which is an implication of the variation of the series resistance with temperature. Using the quadratic model, $\Delta T_j$ of the LED could be accurately determined as the ambient temperature increased from 20 to 100 °C. On the contrary, when the conventional linear fit of the voltage-temperature relation was employed, large errors could occur in determining $\Delta T_j$. As the temperature varied between 20 and 80 °C, $\Delta T_j$ was found to change only slightly with the ambient temperature, which could be explained by the opposite temperature-dependent contribution of series resistance and nonradiative recombination to heat generation. The presented analysis model on the voltage-temperature relation is expected to provide the method to accurately determine the junction temperature of LEDs, and thereby contribute to the thermal management of high-power LEDs.
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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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