Thermal Effect on Junction Temperature of Light-emitting Diodes of AlGaN

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Abstract. This paper discusses the heat effect on the junction temperature of light-emitting diodes (LEDs) of AlGaN. The junction temperature of AlGaN LED based on heat balance is analyzed and agrees with the available experimental data. The junction temperature decreases with the decreasing ambient temperature and the increasing the effective thermal conductivity and effective heat-conduction area.

Introduction

The junction temperature of the LED is an important and basic thermal parameter of the LED. It not only affects the photoelectric conversion efficiency and lifetime of the LED [1-3], but also significantly affects its operating characteristics [4,5]. Effective control of the junction temperature plays an important role in ensuring the lifetime, optical efficiency, and operating characteristics of the LED [6, 7]. Therefore, it is very important to reliably measure and accurately predict the LED junction temperature.

The published papers analyzed the junction temperatures of LED using the forward-voltage method, emission-peak-shift method, high-energy-slope method, thermal-time-constant model and heat conduction model. This article analyzes the junction temperature of AlGaN LEDs using Shockley's equation and heat balance of LEDs. The results are compared with the available measured data.

Analysis

The equivalent circuit of the LED can be supposed to be a combination of an ideal diode, a series resistor, a shunt resistor, and a distributed capacitor. The series resistance $R_s$ mainly depends on the chip itself and the package. The parallel resistance $R_p$ and the distributed capacitance $C_j$ are related to the chip structure and material. Because the change in junction temperature has a small effect on $R_s$, $R_p$, and $C_j$ [8], it is assumed to be constant in subsequent calculations. In order to derive the relationship between the forward voltage $V_f$ of the diode and the junction temperature $T$, the Shockley equation is modified according to the equivalent circuit.

\begin{equation}
I_f = I_j + I_p + I_c = I_s \left[ \exp \left( \frac{e(V_f - I_f R_s)}{n_{id} k T} \right) - 1 \right] + \frac{V_f - I_f R_s}{R_p} + C_j \frac{d(V_f - I_f R_s)}{dt} \tag{1}
\end{equation}

In the formula (1), $I_f$ is the forward current of the LED, $I_j$ denotes the current through the ideal diode node, $I_p$ denotes the current through the shunt resistor $R_p$, $I_c$ denotes the current through the distributed capacitor $C_j$, $I_s$ denotes the saturation current of the diode, $n_{id}$ represents the ideal factor of the diode, $T$ represents the junction temperature of the LED, $k$ Boltzmann constant. In general, $R_p$ is large and greater than 1013 ohms in the AlGaInP LED, so the value of $I_p$ is relatively small. When operating at a DC voltage, the
distribution capacitor $C_j$ has a charging/discharging current only when the light-emitting diode is started and stopped. When the light-emitting diode is operating normally, the current $I_c$ passing through the distributed capacitor $C_j$ is 0. Therefore, the partial differential of the forward voltage $V_f$ with respect to the junction temperature $T$ is derived from Eq. (1):

$$\frac{\partial V_f}{\partial T} = \left[ \frac{k}{e} \ln \left( \frac{N_d N_p}{N_c N_v} \right) + \frac{a n_{\alpha} \beta^2}{e(\beta + T)^2} - \frac{a n_{\alpha} + 3 n_{\alpha} k}{e} \right] = \gamma$$  (2)

In the formula (2), $N_d$ denotes the doping concentration of the p-type semiconductor, $N_p$ denotes the doping concentration of the n-type semiconductor, $N_c$ denotes the effective density of the conduction band, $N_v$ denotes the effective density of the valence band edge, $\alpha$ and $\beta$ are Varshni parameters [9]. According to experimental results, $\gamma$ is approximately constant.

Series resistance is formed in a p-type or n-type neutral region and it can be assumed to be

$$R_s \approx \frac{L_{\text{eff}}^c}{e A_{\text{eff}}^c} T^{1/2} \left( \frac{N_D N_C}{g} \right)^{-1/2} e^{E_a/(2KT)}$$  (3)

where $L_{\text{eff}}^c$ is the effective length of current passage and $A_{\text{eff}}^c$ is the effective area of current passage. $g$ and $E_a$ are the ground-state degeneracy and the acceptor activation energy.

The following relation is achieved using the partial differential of variable.

$$V_f = \int \frac{\partial V_f}{\partial I} dI + \int \frac{\partial V_f}{\partial T} dT$$  (4)

Forward voltage $V_f$ is obtained by substituting equations (2) into (4)

$$V_f(T, I) = \gamma T + I_f R_s + C$$  (5)

The integral constant C in Eq. (5) is the turn-on voltage of the light emitting diode.

If the external quantum efficiency of the LED is symbolically represented by $\eta$ and the other power loss is converted into the dissipated heat, then the thermal power $P$ is

$$P_{\text{Heat}} = I_f V_f - \eta I_f V_f$$  (6)

Using Fourier's law to derive the approximate thermal balance equation in LED [10] is

$$P_{\text{Heat}} = \frac{k A^h}{L^h_e} (T - T_a)$$  (7)

Equation (7) shows the relation of the thermal dissipated power to the ambient temperature, the effective area of heat conduction, the effective length of heat conduction, the thermal conductivity and the junction temperature of LED. Substituting Equation (4) and Equation (6) into Equation (7)

$$\frac{k A^h}{L^h_e} (T - T_a) = (1 - \eta) I_f V_f + \eta I_f^2 R_s$$  (8)

$V_f$ in (8) is determined by Equation (5), and the expression of the dependency of the junction temperature of the LED on the injection current is obtained.

$$T = \frac{T_a + \frac{L^h_e}{k A^h_e} (I_f^2 R_s + I_f C - \eta I_f C)}{1 + \frac{L^h_e}{k A^h_e} \eta I_f \gamma - \frac{L^h_e}{k A^h_e} I_f \gamma}$$  (9)
**Results and Discussion**

The relationship between the junction temperature $T$ and the injection current $I_f$ of the LED is predicted according to the derivation formula (9). The parameter values used in the prediction for the junction temperature of AlGaN are shown in Tab. 1. These parameters are determined by referring to the papers [11-13].

Substituting the parametric values in Tab. 1 into equation (9) can lead to Fig. 1 relating the junction temperature to injection current for different ambient temperature. Figure 1 shows that the junction temperature of AlGaN UV LED changes with the injection currents for emission peak shift method, forward voltage method and proposed method in this work. In this case, the junction temperatures calculated by emission peak shift method significantly deviate from forward voltage method. The possible reason is that the ambient temperature taken by emission peak shift method is different from that used in forward voltage method. This is because the partial parametric values used for calculating the junction temperature in emission peak shift method and forward voltage method are obtained from experiments. When experiments are conducted at different ambient temperatures, the parametric values obtained from different ambient temperatures lead to different junction temperatures predicted by emission peak shift method and forward voltage method. This model proposed by this work employs two different ambient temperatures to predict the junction temperature variations of AlGaN UV LED with injection current. The junction temperatures calculated by this work agree well with these obtained from emission peak shift method for ambient temperature $T_a=300\text{K}$. Similarly, the junction temperatures calculated by this work are consistent with these obtained from forward voltage method for ambient temperature $T_a=324\text{K}$. This result indicates that the difference of the junction temperatures predicted by emission peak shift method from forward voltage method is only shifted by the change value of ambient temperature. The results agree with these measured by Ho [14].

<table>
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<tr>
<th>Material Parameter</th>
<th>AlGaN UV LED</th>
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<td>$\lambda_{\text{peak}}$</td>
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<td>$\Delta T$ (10~60mA)</td>
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Figure 1. Junction temperature variations of AlGaN UV LED with injection currents for emission peak shift method, forward voltage method and proposed method in this work at different ambient temperature.

Summary
This paper applied the Shockley's equation, Ohm's law and Fourier's law to predict the variation of the junction temperature with injection current. The predicted results are consistent with the experimental data. Junction temperature of AlGaN LED increases with the injection current and ambient temperature.

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References


