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Estimating the Junction Temperature of InGaN and AlGaInP LEDs

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1. Introduction

Typically, the amount of heat energy that is generated inside LED strongly depends on its construction and epitaxial material, and defines its junction temperature. The heat that is generated close to the LED's junction determines the junction temperature, and not only reduces the overall efficiency of the LED, but also significantly affects its operating characteristics [1, 2].Therefore, the junction temperature is essential to evaluating the performance of an LED, and the reliable measurement of junction temperature, associated with an appropriate thermal model, is very important. In this study, a series of temperature-dependent electrical and optical measurements of InGaN and AlGaInP LEDs are made to estimate their junction temperatures. The theoretical derivation and possible determinants of the physical dependence of the junction temperature of an LED on the injected current are also analyzed and discussed.

2. Theoretical Model

The junction temperature of an LED is estimated using the Shockley equation, which clearly describes the temperature-dependent *I-V* characteristic of an ideal diode [3]. In practice, the parasitical effects on LEDs of an excessive number of contacts and bypassing channels as in surface states or threading defects, are inevitable and the introduced series (R_S) and parallel (R_P) resistances are considered in this study. Accordingly, the Shockley equation is modified to,

$$I = I_J + I_P = I_S\left(\exp\left(\frac{e(V_f - IR_S)}{n_{ideal}kT}\right) - 1\right) + \frac{(V_f - IR_S)}{R_P} \qquad (1)$$

where I_J, I_P, and I_S denote the junction, leakage, and saturation currents, respectively; and V_f and n_{ideal} are the forward voltage and the ideality factor of the diode. Figures 1 (a) and (b) plot the typical *I-V* characteristics of InGaN and AlGaInP LEDs on a semi-log scale at junction temperatures of T=300K and T=400K.

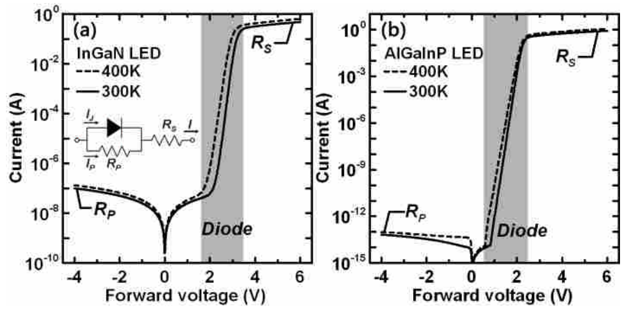

Fig. 1 Dependence of $ln|I|$ vs V_f at 300K and 400K for (a) InGaN and (b) AlGaInP LEDs.

Figures 1 (a) and 1 (b) include gray regions in which the behavior of *I-V* characteristics is dominated by the diode. The junction temperature does not greatly influence the R_S and R_P of an LED, since the *I-V* characteristics of both LEDs barely change on either side of the gray region. Since a change in junction temperature only causes a minor change in the R_S and R_P of an LED, for the time being, R_S and R_P are assumed to be constant in the subsequent calculation. Therefore, the partial differential of V_f with respect to junction temperature is derived from Eq. (1) as,

$$\frac{\partial V_f}{\partial T} = \left[\frac{k}{e}\ln\left(\frac{N_D N_A}{N_C N_V}\right) - \frac{\alpha n_{ideal}}{e} + \frac{\alpha n_{ideal}\beta^2}{e(\beta+T)^2} - \frac{3n_{ideal}k}{e}\right] = \gamma \qquad (2)$$

where N_A and N_D are the concentrations of acceptors and donors, respectively. N_C and N_V are the effective densities of states at the conduction-band and valence-band edges, respectively. α and β are the Varshni parameters. Figure 2 (a) plots the calculated γ for InGaN and AlGaInP LEDs. Accordingly, γ is approximately a constant, whose value is related simply to the epi-structure of the LED.

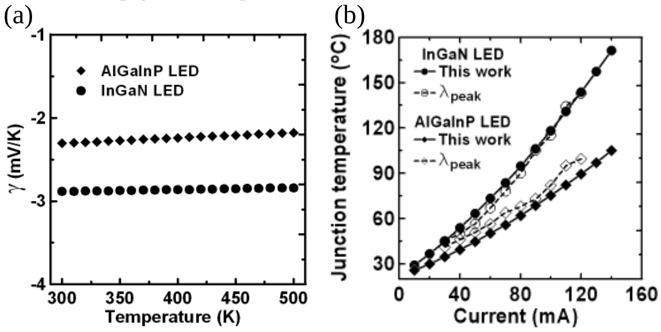

Fig. 2 (a) Calculated γ against junction temperature for InGaN and AlGaInP LEDs. (b) Dependence of junction temperature on injected current for InGaN and AlGaInP LEDs.

Similarly, from Eq. (1), the partial differential of V_f with respect to injected current is,

$$\frac{\partial V_f}{\partial I} = \frac{n_{ideal}kTR_P}{e\left[I(R_P + R_S) + I_S R_P - V_f\right] + n_{ideal}kT} + R_S \qquad (3)$$

By considering the fact that R_P is normally large, and that for V_f > turn-on voltage of LED, $I >> I_S$ and $R_S > \frac{n_{ideal}kT}{e}\frac{1}{I}$, Eq. (3) can be further reduced to

$$\frac{\partial V_f}{\partial I} = R_S \qquad (4)$$

Accordingly, $\partial V_f / \partial T = \gamma$ and $\partial V_f / \partial I = R_S$, and both γ and R_S are equal constants. Consequently, V_f can essentially be described as a linear function of I and T:

$$V_f(I,T) = \int \frac{\partial V_f}{\partial I} dI + \int \frac{\partial V_f}{\partial T} dT \tag{5}$$

By substituting Eq. (2) and Eq. (4) into Eq. (5), and differentiating, $V_f(I,T)$ can be rewritten as,

$$V_f(I,T) = R_S \cdot I + \gamma \cdot T + C \tag{6}$$

where C is an integral constant and can be determined from the initial conditions. Additionally, the light output-power (P_{out}) of LEDs is well accepted to be proportional to the input-power that is applied to the junction. Hence, the conversion efficiency (η) of an LED can be defined as,

$$\eta = \frac{P_{out}}{IV_J} = \frac{P_{out}}{I\left(V_f - IR_S\right)} \tag{7}$$

where V_J is the voltage-drop across the junction. Accordingly, η of the InGaN and AlGaInP LEDs can be determined by their *L-I-V* characteristics. In the steady state, the total electrical input-power can be reasonably treated as the summation of the light output-power and the dissipated power. Hence, the dissipated power that is converted to heat, P_{heat}, is given by,

$$P_{heat} = P_{in} - P_{out} \tag{8}$$

where P_{in} is the total electrical input-power, and $P_{in}=IV_f$. Additionally, in Eq. (8), P_{heat} also equals the rate of heat generation in the LED and is given by,

$$P_{heat} = \frac{\Delta T}{R_{th}} = \frac{T - T_a}{R_{th}} \tag{9}$$

where T_a is the ambient temperature and R_{th} is the thermal resistance of the LED. R_{th} is primarily determined by the size of the LED chip, and the thickness and thermal conductivity of constituent materials, and therefore can be estimated accurately. The calculated thermal resistances of InGaN and AlGaInP LEDs are R_{th}=300K/W and R_{th}=265K/W, respectively. Equations (7) – (9) yield,

$$IV_f - \eta I\left(V_f - IR_S\right) = \frac{T - T_a}{R_{th}} \tag{10}$$

Consequently, substituting V_f from Eq. (6) into Eq. (10) yields a very useful expression for the dependence of the junction temperature of the LED on the injected current:

$$T = \frac{T_a + CR_{th}(1-\eta)I + R_S R_{th} I^2}{1 - \gamma R_{th}(1-\eta)I} \tag{11}$$

For $R_{th}=0$, in the limit of Eq. (11), as T approaches to T_a, the junction temperature is no longer related to the injected current, and is approximately equal to the ambient temperature.

Figure 2 (b) displays junction temperature as a function of injected current for InGaN and AlGaInP LEDs. For comparison, Figure 3 shows the measured peak-position vs. oven temperature calibration results for (a) InGaN and (b) AlGaInP LEDs, respectively. The junction temperature of InGaN LEDs (open circles) and AlGaInP (open squares) obtained by using the emission peak shift method was also plotted in Fig. 2 (b) for comparison. Apparently, the junction temperature estimated by our proposed approach agrees closely with that determined by the emission peak shift method, for both InGaN and AlGaInP LEDs. Moreover, as the emission spectrum of an LED is generally broad GaInP LED), our approach for estimating of junction temperature of an LED shall be more accurate.

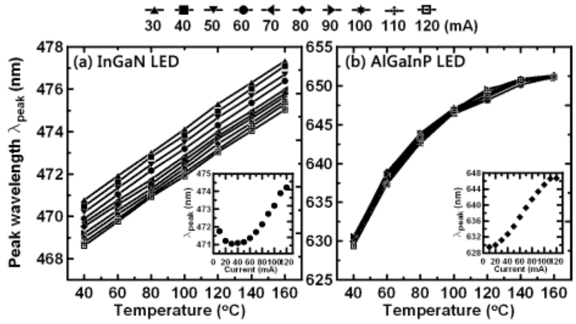

Fig. 3 Experimental peak-position vs. oven temperature for different pulsed injected currents in (a) InGaN and (b) AlGaInP LEDs.

Finally, the physical determinants of the junction temperature of the LED in Eq. (11) are considered. Figure 4 plots the junction temperature vs. variations of (a) η, (b) R_S and (c) R_{th} for AlGaInP and InGaN LEDs at an injected current of I=120mA, respectively.

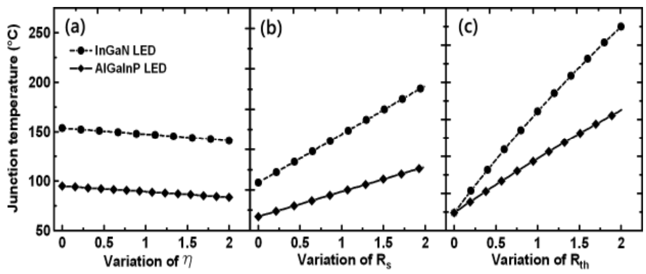

Fig. 4 Junction temperature vs. the variation of (a)η, (b) R_S and (c) R_{th} for both LEDs at an injected current of I=120mA.

Clearly, the variation of η only slightly affects the estimate of the junction temperature for both LEDs, and therefore the efficiency-droop in InGaN LEDs is therefore neglected. In contrast, variations of R_S and R_{th} significantly influence the junction temperature of LEDs. It suggests the advanced packaging schemes for more effective thermal management, and the diminishing of heat generated in the high-resistance region, are direct ways to alleviate the effect of junction temperature on LEDs.

3. Conclusions

This work proposes an approach for directly determining the dependence of junction temperature on injected currents in InGaN and AlGaInP LEDs. Various important physical parameters that affect the junction temperature of an LED are also considered.

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