Junction-Temperature Determination in InGaN Light-Emitting Diodes Using Reverse Current Method

Biqing Wu, Siqi Lin, Tien-Mo Shih, Yulin Gao, Yijun Lu, Lihong Zhu, Guolong Chen, and Zhong Chen

***Abstract*—A method is presented in this study to determine the junction temperature (T_j) of LED in terms of the relationship between the diode reverse current (I_R) and T_j. A theoretical model for the dependence of I_R on T_j is derived on the basis of the Shockley equation and is validated by our experimental results. The method is compared with the conventional forward voltage method, and its advantages have been identified.**

***Index Terms*—Junction temperature, light-emitting diodes (LEDs), reverse current.**

I. Introduction

LIGHT-EMITTING diode (LED) technology has been fast developed and widely used for backlight sources, traffic signals, display, and lighting in the last few years [1]–[3]. Advantages of LED include high light efficiency, low energy consumption, and long lifetime, among others. However, the high junction temperature (T_j) is a main limiting factor in LED applications since it will affect internal efficiency, maximum output power, reliability, peak wavelength, and spectral width [4]. Because T_j cannot be measured directly, some indirect methods for measuring T_j have been investigated by detecting the temperature sensitive parameters (TSPs), for example, the temperature coefficient of the emission peak energy [5], the ratio of the total radiant energy to the radiant energy within the blue emission (W/B) [6], the "center of mass" wavelength and full-width on half-maximum in its electroluminescence (EL) spectra [7], and the forward voltage (V_f) under a constant current [8], [9]. Other methods, such as thermal imaging [10], Raman spectroscopy [11], and the use of nematic liquid crystal [12], are limited by experimental conditions and are less convenient for practical uses. Therefore, researching T_j dependence of other electrical and optical parameters is presently considered as the most appropriate way of thermal characterization of LEDs.

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Among the TSPs mentioned earlier, V_f is most widely used and shows a linear relationship with T_j [8], [9]. A small current is applied to the LED to establish the relationship between V_f and T_j. The current should be small enough to avoid the self-heating effect of LED chip, so T_j can be regarded as being equal to the ambient temperature. However, the LED will still be lit up with a small drive current, and its T_j will rise slightly. This temperature rise will inevitably result in measurement errors.

The TSPs from the spectra are also associated with some disadvantages. The method mentioned in [6] largely depends on the width of emission spectra and is less accurate in comparison with the forward voltage method [9]. The accuracy of EL method in [7] strongly relies on the complicated precalibration, which, in turn, is carried out via the forward voltage method. Meanwhile, a highly accurate spectroradiometer is needed in these approaches. Such a need hinders practical uses of the EL method.

In this paper, a method is proposed for T_j determination using I_R as TSP. A theoretical model for the dependence of I_R on T_j is derived and validated by our experiments. This method is compared with the conventional forward voltage method in detail.

II. Measurement Theory and Procedure

A. Temperature Dependence of I_R

In order to derive the relationship between I_R and T_j, we start with the well-known Shockley equation

$$I = I_S\left[\exp\left(\frac{eV}{nkT}\right) - 1\right] \quad (1)$$

where I is the current, I_S is the saturation current, e is the elementary charge, V is the voltage on the diode, n is the ideality factor (for an LED, the value is about 1–2), k is the Boltzmann constant, and T is the absolute temperature in kelvins.

When a reverse voltage (V_R) is applied to the LED, V becomes negative. For most cases, the value of $exp(eV/nkT)$ is very small and approximately equal to zero. Therefore, (1) can be simplified to

$$I_R = -I_S \quad (2)$$

where I_R stands for the reverse current and is expressed as [13]

$$I_R = eA\left[\sqrt{\frac{D_n}{\tau_n}}\frac{1}{N_D} + \sqrt{\frac{D_p}{\tau_p}}\frac{1}{N_A}\right] N_C N_V \exp\left(\frac{-E_g}{kT}\right). \quad (3)$$

In (3), A is the cross-sectional area of the p-n junction, and D_n and D_p are diffusion constants of electrons and holes, respectively; τ_n and τ_p are the minority carrier lifetimes of electrons and holes; N_D and N_A are the donor and acceptor concentration; N_C and N_V are effective densities of states at the conduction-band and valence-band edges; and E_g is the energy bandgap.

Neamen [14] has shown that diffusion constants D_n and D_p exhibit a $T^{-1/2}$ temperature dependence, while the temperature dependences of N_C and N_V can be given by $T^{3/2}$ [15]. Dopants with concentrations N_D and N_A are supposed to be fully ionized, and the carrier lifetimes can decrease (nonradiative recombination) or increase (radiative recombination) with temperatures. Thus, the concentration and the minority-carrier lifetimes are supposed to be independent of the temperature.

Let us define four parameters D_1, D_2, D_3, and D_4 as

$$D_1 = D_n T^{\frac{1}{2}} \quad (4)$$

$$D_2 = D_p T^{\frac{1}{2}} \quad (5)$$

$$D_3 = N_c T^{-\frac{3}{2}} \quad (6)$$

$$D_4 = N_v T^{-\frac{3}{2}}. \quad (7)$$

According to the theory mentioned earlier, D_1, D_2, D_3, and D_4 are independent of T. Now, (3) can be rewritten as

$$I_R = eA\left[\sqrt{\frac{D_1}{\tau_n}}\frac{1}{N_D} + \sqrt{\frac{D_2}{\tau_p}}\frac{1}{N_A}\right] T^{-\frac{1}{4}} D_3 D_4 T^3 \exp\left(-\frac{E_g}{kT}\right). \quad (8)$$

In order to simplify (8), we define a temperature-independent parameter D_5 as

$$D_5 = eA\left[\sqrt{\frac{D_1}{\tau_n}}\frac{1}{N_D} + \sqrt{\frac{D_2}{\tau_p}}\frac{1}{N_A}\right] D_3 D_4. \quad (9)$$

Consequently, (8) can be simplified to

$$I_R = D_5 T^{\frac{11}{4}} \exp\left(-\frac{E_g}{kT}\right). \quad (10)$$

Equation (10) can be transformed to

$$\ln\left(I_R T^{-\frac{11}{4}}\right) = \ln D_5 - \frac{E_g}{k} \cdot \frac{1}{T}. \quad (11)$$

The temperature dependence of the energy bandgap (E_g) is expressed by the Varshni formula [16]

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \quad (12)$$

where α and β are the Varshni parameters and $E_g(0)$ presents the energy bandgap for $T = 0$ K. According to the results of Keppens [9], the $E_g(T)$ decreases with T and can be approximated by a linear expression for temperatures higher than 295 K [9]. Generally, T_j of LEDs under working condition ranges between 300 K and 370 K. Therefore, (12) in this temperature range can be approximated by

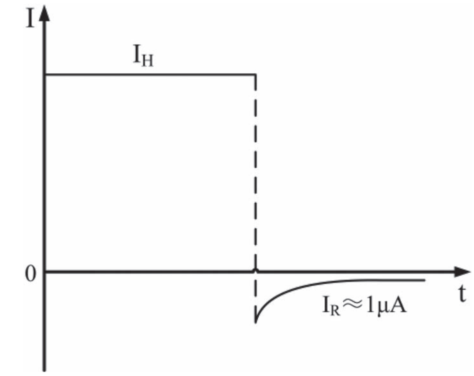

Fig. 1. Current signal timing for step 2.

$$E_g(T) = E_g(300\text{ K}) - \alpha' T \quad (13)$$

where $E_g(300\text{ K})$ is the energy bandgap for $T = 300$ K and α' is a positive constant calculated from the corresponding α and β values [16]. Substituting (13) into (11) and combining all temperature-independent parameters into two single parameters η_1 and η_2, we can rewrite (11) as

$$\ln\left(I_R T^{-\frac{11}{4}}\right) = \eta_1 + \frac{\eta_2}{T}. \quad (14)$$

From (14), a linear relationship between $\ln(I_R T^{-11/4})$ and inverse temperature $(1/T)$ is observed. Therefore, I_R can be used as a new TSP to measure T_j of LEDs.

B. *Measurement Procedure of the Reverse Current Method*

The reverse current method consists of two steps: 1) determination of parameters η_1 and η_2 and 2) acquisition of transient I_R data.

In step 1, a V_R is applied to the LED sample mounted on a temperature-controlled heat sink. The LED is not lit up under reverse bias, and the small I_R (approximately 1 μA) ensures no self-heating effect, which exists in the forward voltage method. Therefore, T_j is equal to the heat-sink temperature (T_s). A series of I_R's is measured at different values of T_s to derive η_1 and η_2 coefficients in (14) by a least square linear fit.

In step 2, as shown in Fig. 1, a dc heating current (I_H) is applied to the LED for a period of time until the thermal equilibrium state is achieved. Then, I_H is replaced by V_R instantly, and transient I_R data are measured continually for a sufficient period of time. Finally, with I_R data and η_1 and η_2 coefficients derived from step 1, we can obtain T_j under I_H by solving (14). Because I_R is apparently affected by external illumination, all the measurements should be taken in darkness.

III. Experiment

Six InGaN 1-W LEDs (Genesis Photonics Corporation) were chosen for experiments, including three blue LEDs (with a peak

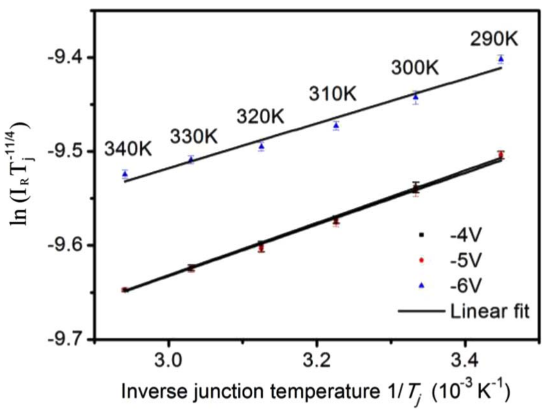

Fig. 2. The T_j dependence of I_R under different V_R values for B3 LED.

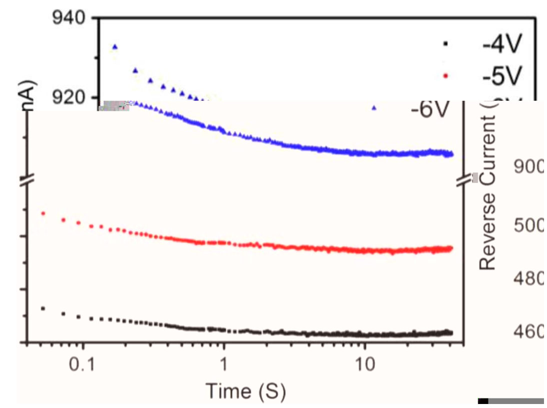

Fig. 3. Transient I_R under different V_R values for B2 LED.

wavelength of 450 nm), labeled as B1, B2, and B3, and three white LEDs (phosphor-converted with a blue emitter), labeled as W1, W2, and W3. These LEDs were mounted on a Keithley LED-850 TEC test adapter (accuracy to ± 0.1 K). The value of T_s was precisely controlled by a Keithley 2510 TEC SourceMeter. A Keithley 2611 SourceMeter (accuracy to 100 pA) was used to provide I_H or V_R and measure I_R.

In step 1, six values of T_s were taken within a range of typical LED operation temperatures from 290 K to 340 K in 10 K increments. The values of I_R were measured with -4, -5, and -6 V bias voltages applied successively.

In step 2, T_s was set to 298 K. An I_H (350 mA) was applied to the LED for 300 s and then switched to the reverse status with a V_R applied instantly. The transient I_R was measured continually for 60 s.

For comparisons, values of T_j were also measured by Transient Thermal Tester (T3Ster, MicReD Ltd., accuracy to ± 0.1 K) under same experimental conditions according to the conventional forward voltage method.

IV. Results and Discussions

A. The T_j Dependence of I_R

Fig. 2 shows $ln(I_R T_j^{-11/4})$ versus $1/T_j$ under various V_R values, with lines representing results obtained by the least square linear fitting. The lines for -4 and -5 V are almost indistinguishable, but a big offset is observed between the line for -6 V with the former. The reason for such a result is that values of I_R under -4 and -5 V are almost identical but they increase dramatically when $V_R = -6$ V, which is close to the breakdown region of the p-n junction. The internal physics mechanism for the increased current is due to the dominant tunneling effect [17]. When the reverse voltage increases, more carriers will tunnel by the strong internal electric field via leakage paths, which are located in the space-charge region and are correlated to the presence of structural defects (such as threading dislocations/V-defects) [18]. Hence, a subsequent increase of the reverse current occurs. High linearity between $ln(I_R T_j^{-11/4})$ *and* $1/T_j$ is observed under -4 and -5 V. However, the linearity for -6 V is slightly poorer compared with the former, probably due to the increased current.

B. Transient I_R Acquisition

In Fig. 3, the transient I_R is plotted versus time, parameterized in -4, -5, and -6 V, respectively. Fast current decays are observed in the first 500 ms. The reason for such decays is that, after I_H is removed, T_j drops quickly, so that the minority carrier decreases correspondingly. As I_R is primarily generated by the minority carrier tunneling, the decrease in minority carrier will result in the current decay. We use the first value of I_R for T_j calculation after instantly switching I_H to V_R. Strictly speaking, we should use I_R value at $t = 0$. Because the switching time is within several milliseconds and the first I_R value slightly deviates from the expected value at $t = 0$, it thus can be used to calculate T_j.

C. Measured T_j and Comparison

Table I lists T_j values of all six samples measured using both the reverse current method and the forward voltage method (T3ster). The uncertainty in T_j values by the reverse current method is observed to be approximately 1%. A good agreement of the testing results is achieved and all of relative errors can be limited to less than 1%. These consistencies suggest the accuracy of the reverse current method. The T_j deviation between the column of $V_R = -6$ V and that of T3ster is larger in comparison with those of $V_R = -4$ V and $V_R = -5$ V. This trend is probably due to the poor linearity between $ln(I_R T_j^{-11/4})$ and $1/T_j$ for $V_R = -6$ V as mentioned earlier. Based on the results of Fig. 2 and Table I, we recommend that the applied voltage be slightly kept at a distance away from the reverse breakdown region for higher testing precision and to avoid the breakdown of LED during tests.

D. Temperature Sensitivity Comparison of Different TSPs

We further calculate variation percent of I_R defined as

$$\frac{[I_R(T_j) - I_R(290\text{ K})]}{I_R(290\text{ K})} \tag{15}$$

and variation percent of V_f defined as

$$\frac{[V_f(T_j) - V_f(290\text{ K})]}{V_f(290\text{ K})}. \tag{16}$$

TABLE I
THE T_j MEASURED BY REVERSE CURRENT METHOD AND FORWARD VOLTAGE METHOD (T3STER), RESPECTIVELY

Sample		Reverse current method (V_R=-4V)	Reverse current method (V_R=-5V)	Reverse current method (V_R=-6V)	Forward voltage method (T3ster)
Measured T_j (K)	B1	304.3	304.2	306.9	304.3
	B2	305.5	304.5	302.2	304.7
	B3	303.1	302.9	304.6	303.3
	W1	310.5	310.0	308.4	311.0
	W2	312.7	312.0	313.4	312.5
	W3	309.4	308.9	308.6	310.7

TABLE II
THE I_R AND V_f UNDER DIFFERENT T_j VALUES FOR B3 LED

T_j	I_R under -5V (nA)	I_R variation with T_j (%)	V_f with 5mA(V)	V_f variation with T_j (%)
290K	440.6	/	3.221	/
300K	465.6	5.7	3.193	0.9
310K	492.6	11.8	3.172	1.5
320K	522.9	18.7	3.155	2.0
330K	557.2	26.5	3.141	2.5
340K	591.7	34.3	3.123	3.0

Values of I_R and V_f and their variations at different T_j's are listed in Table II (with B3 LED as the sample). It is observed that I_R is much more sensitive to temperature variations than V_f (more than one order of magnitude), suggesting that the reverse current method will be a more sensitive measurement technique than the forward voltage method. Hence, the signal-to-noise ratio (SNR) of the measurement can be greatly improved.

V. CONCLUSION

In this paper, we have developed a novel method for measuring the junction temperature of InGaN LED using the reverse current as the TSP. A good agreement of testing results between the reverse current method and the conventional forward voltage method is observed, with a deviation of less than 1%. Advantages are twofold: 1) The reverse current method can avoid the self-heating effect of LED during tests, and (b) the reverse current is more sensitive to temperature variations than the forward voltage, suggesting that the reverse current method can be a more sensitive measurement technique than the forward voltage method and can greatly improve the SNR of measurement.

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