IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 4, 2017, accepted May 22, 2017, date of publication June 16, 2017, date of current version July 17, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2716781

Improving Peak-Wavelength Method to Measure Junction Temperature by Dual-Wavelength LEDs

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This work was supported in part by the National Key R&D Program of China under Grant 2016YFB0400801, in part by the National Natural Science Foundation of China under Grant 61574114, and in part by the China Scholarship Council under Grant 201506280046.

ABSTRACT In this paper, the improvement of the method measuring the junction temperature of light-emitting diodes (LEDs) has been studied experimentally. A practical method is proposed with only three measurement procedures. With the consideration of indium (In) composition and blue shift, the method has a high applicability, which is practical for the LED chips vary from blue to green chips under different currents, including the packaged chips. On the other hand, according to the experimental and derived results, the junction-temperature difference and peak-wavelength shift in both blue-shift and red-shift fields show similar parabolic-like relations. To simplify the experimental processes, dual-wavelength LEDs were fabricated and measured instead of conventional single-wavelength LEDs.

INDEX TERMS Junction temperature, dual-wavelength light emitting diodes, peak-wavelength method, practicability.

I. INTRODUCTION

Due to the extraordinary characteristics of low power consumption, environment protection, long lifetime and high luminous efficiency, gallium nitride (GaN) based light-emitting diodes (LEDs) have been widely used in our daily lives [1]–[3]. As the internal quantum efficiency (IQE), maximum output power, reliability and lifetime of LEDs strongly depends on the heat at the semiconductor's *p*–*n* junction, junction-temperature measurement is crucial for designing and building a reliable LED product [4]–[7]. One of the traditional methods for measuring LED junction temperatures is detecting the drop of forward voltage [8]–[10]. However, it requires direct contact with the pin of the LED, which is very difficult for a packaged LED chip [11], [12]. Therefore, the indirect measurement methods based on spectral properties, including the peak-wavelength shift, show great potential for the utilization in packaged LED chips [12]–[15]. For instance, Chen and Narendran [12] proposed a method to estimate the junction temperature of LED arrays based on the shift of the wavelength at full width at half maximum (FWHM). However, for conventional peak-wavelength methods, it is still difficult to eliminate the effect of blue shift, which mainly results from the band-filling effect and piezoelectricity-induced quantum-confined Stark effect (QCSE) [7], [8], [13]–[17]. Meanwhile, besides blue shift, the peak-wavelength shift is also influenced remarkably by the indium (In) composition [8], which limits the accuracy and practicability of the conventional peak-wavelength method significantly [12]. Therefore, peak-wavelength shift in a LED device does not have a simple correlation with junction temperature [7]. To date, although some methods have been used for improving measurement on junction temperature, it is still a severe challenge to propose a practical method to measure the junction temperature of packaged LEDs accurately, quickly, and cheaply.

In this work, to improve the traditional peak-wavelength method, we report a practical method with three measurement procedures, which has the consideration of In composition and blue shift. To simplify the experimental processes, dual-wavelength LEDs were utilized instead of conventional single-wavelength LEDs.

II. EXPERIMENTS

Fig. 1 illustrates the schematic plot of the LED structures with dual-wavelength multiple quantum well (MQW)

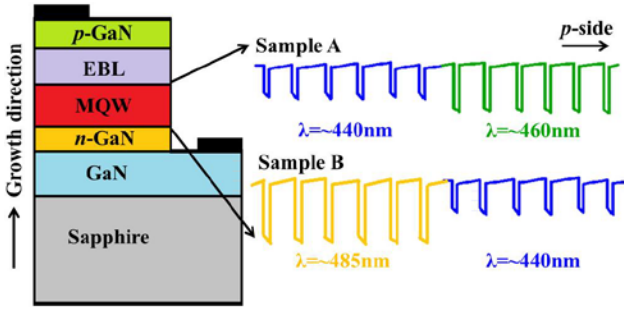

FIGURE 1. Schematic plot of the epitaxial structures of LED chips for samples A and B.

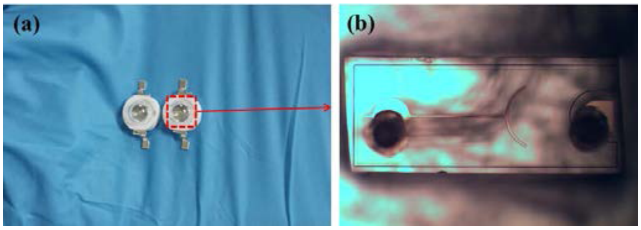

FIGURE 2. (a) Side-view image of LED samples. (b) Top-view optical image of a LED chip.

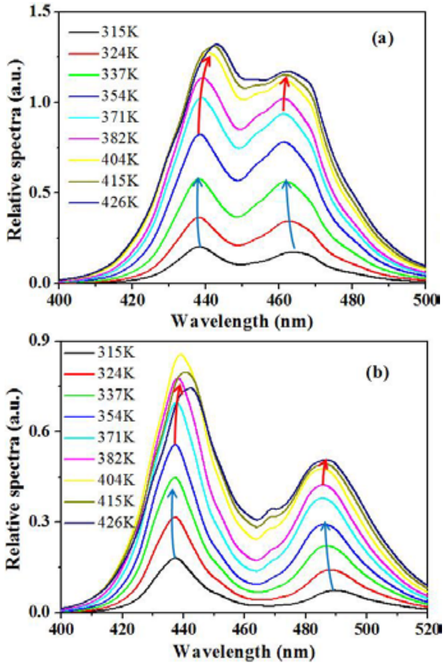

FIGURE 3. Experimental EL spectra of (a) sample A, and (b) sample B. Blue arrows represent blue shift, and red arrows represent red shift.

structures. All samples were grown on (0001)-oriented sapphire substrates by metal-organic chemical vapor deposition (MOCVD). During epitaxial growth process, trimethylindium, trimethylgallium, trimethylaluminum, and ammonia were used as the source materials of In, Ga, Al, and N, respectively. A 2-μm-thick un-doped GaN layer was grown, followed by 2.5-μm-thick Si-doped n-GaN layers. The active region consisted of a 12-period of un-doped InGaN/GaN ($\sim$3 nm/$\sim$12 nm) MQWs with different emission wavelengths. Compare to blue QWs ($\sim$440 nm), the cyan ($\sim$460 nm) and green ($\sim$485 nm) QWs were grown in a lower temperature to increase the In composition. Then the AlGaN electron-blocking layer (EBL) was grown, followed by a Mg-doped p-GaN:Mg layer (p-doping $= \sim 5 \times 10^{19}$ cm^{-3}). As shown in Fig. 1, sample A has 6 cyan QWs (close to p-side) and 6 blue QWs (close to n-side). Sample B has 6 blue QWs (close to p-side) and 6 green QWs (close to n-side). Furthermore, it is difficult to measure the In composition of each chip exactly. To simplify the process of measuring the In composition, we use the commonly employed Varshni equation [7], [12], [18], [19]. By the numerical simulations of APSYS software, the three peak wavelengths of the QWs with $\sim$15%, $\sim$18% and $\sim$21% In compositions are around 440 nm, 460 nm and 485 nm, respectively.

For experimental measurements, the lateral LED chips were fabricated [Fig. 2(a)], and the chip size is $\sim$250 × 580 μm^2 with a rectangular shape [Fig. 2(b)]. The electroluminescence (EL) spectra of un-encapsulated LED chips were measured under different injection currents (DC mode) in a calibrated integrating sphere at room temperature.

III. RESULTS AND DISCUSSIONS

To measure two single-wavelength LEDs with different In compositions, such as blue and cyan LEDs, we commonly need to measure them separately, which requires more measurement time than measuring only one LED. As it is very difficult to measure the temperature within small region (the thickness of MQW region is typically <0.5 μm), a large deviation could be produced. Furthermore, as the MQW thickness is very small, the temperature in the MQW region is possible to be regarded as equilibrium. Therefore, it is assumed that the measured junction temperatures of dual-wavelength (such as blue and cyan) LEDs are those of corresponding blue and cyan LEDs under the same measurement conditions. Those indicate that it is easier to utilize dual-wavelength LEDs instead of single-wavelength LEDs to measure the junction temperatures with different In compositions. Thus, two dual-wavelength LEDs shown in Figs. 1 and 2 were fabricated.

The EL spectra in Fig. 3 clearly show that, with the increases of currents or junction temperatures (T), the peak wavelengths (λ) undergo a small blue shift firstly and then a red shift. When T is low, the band-filling effect and piezoelectricity-induced QCSE could have a major effect on the λ shift, which could cause the blue shift [7], [8], [13]–[17]. While T is high, the thermal effect could have the major effect on the λ shift, resulting in the red shift [7], [12]–[15]. Thus, the point between the blue-shift field and red-shift field is the shortest peak wavelength (λ_0). On the other hand, the T data of cyan QW region are obtained based on the curves (T vs DC current) for the InGaN LED ($\lambda \approx 460$ nm) in [8], which are shown in Table I. Then the λ data of blue QWs can be achieved at the same T conditions by sample A. It is

TABLE 1. **Junction temperature (T) under different currents (I).**

I (mA)	8	16	28	44	60	70	90	100	110
T (K)	315	324	337	354	371	382	404	415	426

possible to assume that for the QWs with the comparative In compositions, the peak-wavelength shifts ($\Delta\lambda$) are similar under comparative T differences (ΔT). Thus, according to the $\Delta\lambda$ data of blue QWs in both samples A and B, the T and λ data of green QWs in sample B could also be derived.

To better analyze the relationship among the In composition (x), T, ΔT, and $\Delta\lambda$ in both blue-shift and red-shift fields, we define the point with the shortest peak wavelength as the inflection point (λ_0, T_0, I_0). For instance, as shown in Fig. 3(a), the inflection point of the cyan QWs in sample A is (461.1 nm, 371 K, 60 mA). The inflection points of the three kinds of λ are shown in Fig. 4(a). When x is 0, the piezoelectricity-induced QCSE could be limited [13]–[17], [20]. x is 0 means that no QWs exist in the active region, thus, the band filling effect could be limited. Therefore, it is possible to assume that the LEDs chips have no blue shift when In composition decreases to 0, and the T_0 of corresponding inflection point is regarded as 298K. Moreover, according to the Varshni equation, the relationship between T and λ is not linear. Therefore, to achieve the better coefficients of determination (R^2), we use Eq. (1) to fit curves.

$$y = A \cdot X^{B} + C, \tag{1}$$

where A, B and C are the variables. C is the value when the abscissa variable (X) is 0. According to the four data points, the relationship between the x and T_0 can be shown as the fitted line in Fig. 4(a)

$$T_0 = 1740.8x^{1.9} + 298. \tag{2}$$

The R^2 of this fitting line is ~0.945. In the blue-shift region (λ_1, T_1, I_1), the difference values of the parameters are calculated as

$$\Delta\lambda_1 = \lambda_1 - \lambda_0, \tag{3}$$
$$\Delta T_1 = T_0 - T_1. \tag{4}$$

The data of ($\Delta\lambda_1$, ΔT_1) for the three kinds of λ are illustrated in Fig. 4(b). The average data of ΔT_1 are fitted as

$$\Delta T_1 = 37.7\Delta\lambda_1^{0.41}, \tag{5}$$
$$T_1 = T_0 - \Delta T_1 = 1740.8x^{1.9} + 298 - 37.7\Delta\lambda_1^{0.41}. \tag{6}$$

R^2 of Eq. (5) is ~0.997. In addition, in the red-shift region (λ_2, T_2, I_2), the difference values of the parameters are calculated as

$$\Delta\lambda_2 = \lambda_2 - \lambda_0, \tag{7}$$
$$\Delta T_2 = T_2 - T_0. \tag{8}$$

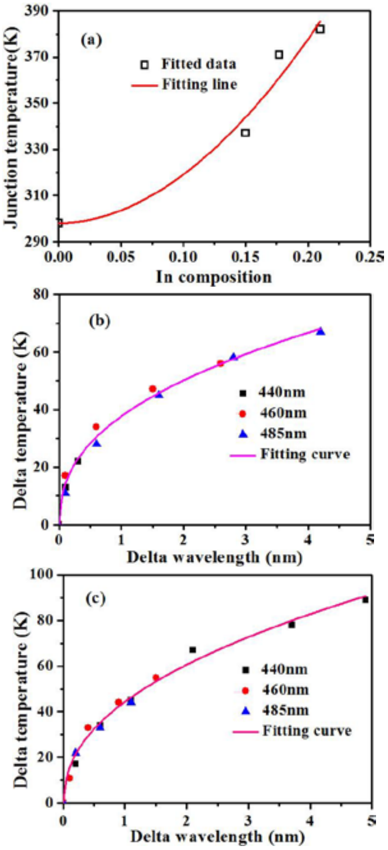

FIGURE 4. **Junction-temperature fitting of (a) T_0, (b) ΔT_1, and (c) ΔT_2.**

Fig. 4(c) shows the data of ($\Delta\lambda_2$, ΔT_2) for the three kinds of λ. The average data of ΔT_2 are fitted as

$$\Delta T_2 = 44.4\Delta\lambda_2^{0.45}, \tag{9}$$
$$T_2 = T_0 + \Delta T_2 = 1740.8x^{1.9} + 298 + 44.4\Delta\lambda_2^{0.45}. \tag{10}$$

R^2 of Eq. (9) is ~0.988.

According to Fig. 4, the relation of ΔT and $\Delta\lambda$ data in both blue-shift and red-shift fields is similar to parabolic. Therefore, a practical method is proposed to measure the T data, which contains three measurement procedures as follows:

1) The EL spectra of packaged GaN-based LED chips were measured under different injection currents (DC mode) in a calibrated integrating sphere. The x data of LED chips should be derived by Varshni equation or measured.
2) The λ data under different currents (λ, I) can be obtained by the EL spectra. Then the T_0 of the inflection point (λ_0, T_0, I_0) can be achieved by Eq. (2).
3) Using Eqs. (3) and (7) to calculate the $\Delta\lambda$ data. For the blue-shift field ($I_1 < I_0$), the corresponding T_1 results under different currents can be derived by Eq. (6). While in the red-shift field ($I_2 > I_0$), the corresponding T_2 results under different currents can be derived by Eq. (10).

As it is difficult to measure the x and T data exactly within MQW regions, the fitted variables in the functions may have non-ignorable deviations. In the process of fitting variables, the more accurate x, λ and T data measured, the more accurate variables could be achieved. For GaN-based LEDs with different structures, such as different substrates, different MQWs, different n-GaN and p-GaN thicknesses, *etc.*, the fitted variables can be different and should be corrected. However, compare to the traditional peak-wavelength method, the proposed method takes the In composition and blue shift into consideration, which could have a better practicability. Therefore, this method has potential significance for the further promotion of LED junction-temperature measurement.

IV. CONCLUSION

In this paper, dual-wavelength LEDs have been utilized to improve the conventional peak-wavelength method measuring LED junction temperatures. By considering the In composition and blue shift, a practical method has been proposed with three measurement procedures. Based on experimental and derived results, the junction-temperature difference and peak-wavelength shift in both blue-shift and red-shift fields show similar parabolic-like relations. The practical measurement method proposed here indicates a promising path to achieve junction temperatures in packaged LEDs quickly, cheaply and easily.

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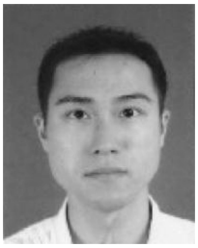

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