Invited Paper

Junction temperature measurement on light-emitting diodes and its application

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ABSTRACT

Recently, the GaN based LED white light illumination technology has been developed rapidly. It is required to measure the p-n junction temperature of LED which has been encapsulated in the lamp with the temperature measurement error less than 1*K*. We present a spectroscopy approach to measure this p-n junction temperature of LED encapsulated in the lamp. The electroluminescence peak shift is used to determine the temperature difference between the junction and the ambient. At ambient temperature of 300*K*, the junction temperature can be determined by the formula of $T=300+27.8\Delta\lambda_p-1.22\Delta\lambda_p^2$ with the unit of temperature T in K and electroluminescence peak shift $\Delta\lambda_p$ in *nm*. This method has been used on the high power lamp made by LED. The LED lamp has been fabricated for the illuminated application on the satellite and the spacecraft in China.

Keywords: LED lamp, Junction temperature, spectroscopy, peak shift

1. INTRODUCTION

In the optoelectronic field, the III-V group GaAs-based semiconductor quantum well structure has achieved big breakthrough in last 20 years on quantum well infrared detector[1]. Then the LED for illumination is a great breakthrough in recent 10 years on the III-V group GaN-based semiconductor quantum well structure. With the improvement of the material quality of GaN-based semiconductor, the efficiency and lifetime for the white light LED chip has been increased. Still determined by the property of GaN-based quantum well structure, the quantum efficiency and Joule heating problems are studied intensively. By the optimization of GaN/InGaAs quantum well, the quantum efficiency can be improved and the Joule heating effect will be reduced. However, the Joule heating effect will be affected by both the property of GaN-based semiconductor material and the encapsulation technology. The stronger Joule heating effect will result in lower quantum efficiency and also the shorter lifetime for LED. All the factors contributing to the Joule heating will increase the p-n junction temperature in LED chip.

The junction temperature has been recognized as the key parameter to characterize the Joule heating effect. Moreover, the junction temperature is used to characterize the lifetime of LED when it is working as a lamp. It is very important to measure the junction temperature for LED chip encapsulated in the lamp. The package process will affect the cooling efficient of radiator in the lamp. With the exact same LED chip, the junction temperature and consequently the lifetime of LED chip in the lamp with different package process will not be same. This junction temperature of LED chip is the important parameter to determine the lifetime of LED chip in the lamp and in the application. However, the electrical method by using I-V curve can not be used, because the different electrical link among many LEDs in the lamp makes the I-V curve measured from the electrodes of lamp be very complicated. Moreover, the pin temperature measuring method, which is considered as a high accuracy way, cannot be applied to it, since the LED is encapsulated in the lamp. The spectroscopy method appears to be the best approach. But the accuracy of blue/white spectrum method cannot reach the level at 1 K which is required in the reliability investigation[2]. In this paper, we present a good approach to measure the LED junction temperature based on the electro-luminescence peak shift from the InGaN/GaN quantum well interband transition.

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2. THE METHOD FOR JUNCTION TEMPERATURE DETERMINATION

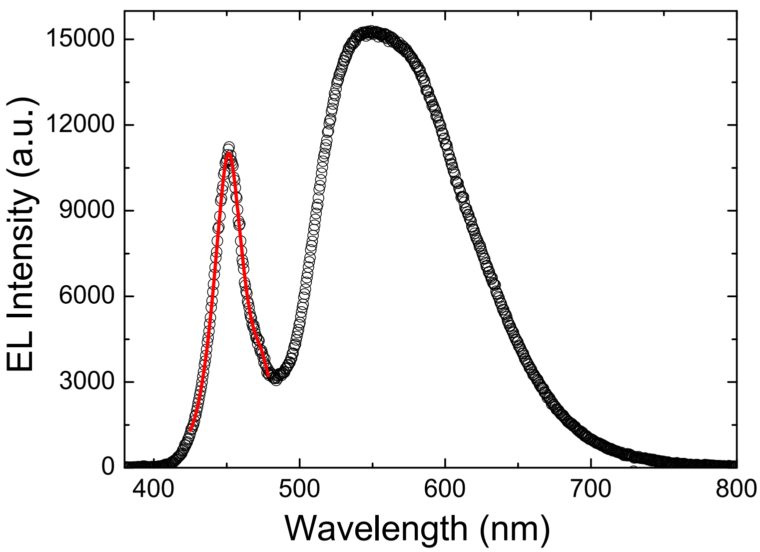

Figure.1 The spectrum of white light LED measured from the 100W LED lamp shown by black dots, the red line is the best fitting curve for blue peak of electro-luminescence.

For the LED device in the stage of final application, a lot of factors will influence the performance of LED, including the microstructure of InGaN/GaN quantum wells (QWs), the package process of LED chip and lamp, the working condition of LED, and so on. In order to measure the junction temperature of LED, it is necessary to use a temperature-dependent-only-parameter for the determination of junction temperature, because the design, fabrication of LED and package of LED lamp will be changed from case to case. The electrical calibration method is strongly dependent on the microstructure. All the contact method will be very difficult in the application on the LED lamp, because all the LED electrodes are encapsulated into the lamp. The best way to measure the junction temperature of LED in the lamp will be the non-contact method. The spectroscopy method has shown its advantage[2]. A typical spectroscopy method is so called white-Blue (W/B) method[2]. However, the W/B method will dependent on whether the fluenscence powder is closely contact with LED chip or not. It is also dependent on the blue peak position. Here we will propose to use the electro-luminescence peak shift to determine the junction temperature for the LED lamp.

The illumination LED lamp is composed by a lot of white light LED chips connected electrically together. The emission spectrum of a 100W LED lamp is measured as shown in figure 1 by black dots. The peak at about 450nm is from the interband transition of InGaN/GaN quantum well, which is enhanced by the quantum dot like structure in quantum well[3]. The broad band from 500nm to 700nm is the fluorescence resulted from the excitation of blue light. The intensity of broad band will be affected by the temperature[2], this intensity will reflected the temperature of the fluorescence powder heated by the LED chip. Only when the temperature of fluorescence powder has the same temperature as LED junction, one can use this parameter to measure the junction temperature as suggested by W/B method[2]. However, the accuracy of this approximation will strongly dependent on the package process for white light LED. Another temperature sensitive parameter is the band gap of GaN-based material. Since the p-n junction in LED is made by the material of GaN thin film and InGaN/GaN quantum wells, the temperature of these materials will be the real junction temperature without any approximation. Moreover, the temperature coefficient of band gap for the GaN-based material will not sensitive the quantum structure of LED material and device structure. In principle, the interband transition energy can be used to characterize the junction temperature[4,5]. The electro-luminescence spectrum is measured as shown in Fig.1 by black points. The peak overlapped by the red line is the interband transition from InGaN/GaN quantum wells in LED. From Fig.1 it can be found that the precious determination of the blue peak at about 450nm is not easy due to the strong influence of the broad band in long wavelength side and the quite broad band of the blue peak itself [4].

In order to determine the blue peak shift with the junction temperature in the precision of sub-nanometer, one should select a good region of spectrum for the best fitting on blue peak band. Two factors should be considered in the spectrum region determination. One is from the influence of broad fluorescence emission band. In order to eliminate this influence on the blue peak position determination, the data for best fitting from blue peak band should be away from the fluorescence emission band as much as possible. The data of blue peak in long wavelength side should be excluded a lot. The other factor is from the relative broad band behavior of blue peak itself. For high precision of peak position determination, the data for the blue peak band should be included as much as possible. By the tradeoff on these two factors, the spectrum region used for the best fitting is selected from 425nm to 478nm. The best fitting curve is presented as red line in Fig.1.The two Lorenzian and Gauss mixed line shape peaks are used to fit the blue peak:

$$EL(\lambda) = \sum_{j=1}^{2} S_j \left[(1-f)\frac{2}{\pi}\frac{\gamma_j}{\gamma_j^{\,2} + 4(\lambda-\lambda_j)^2} + f\sqrt{\frac{2}{\pi}}\,\frac{e^{-\frac{2(\lambda-\lambda_j)^2}{\gamma_j^{\,2}}}}{\gamma_j} \right] \tag{1}$$

where the $EL(\lambda)$ is the electro-luminescence intensity at wavelength λ, j=1,2 is the index of the spectrum peak, f is the percentage of the Gaussian line shape component in the peak, λ_j and γ_j are the peak wavelength and broadening factor of the peak j. Two peaks are used to the blue peak position determination in numerical fitting process. This method can eliminate the influence of the small shoulder on the precise determination on the blue peak position at about 450nm. Only the peak wavelength parameter for blue peak at about 450nm are used to determine the junction temperature in the all parameters obtained by best fitting. The spectrum in Fig.1 is from the lamp having the junction temperature of 45 ^oC,

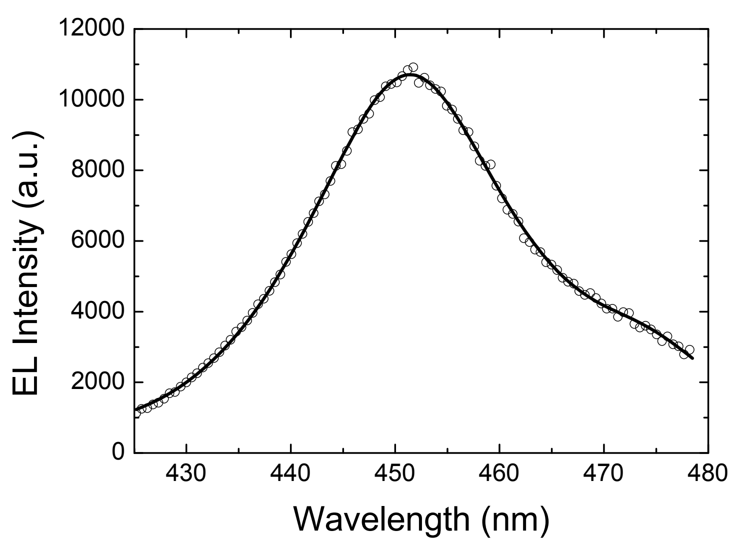

Figure.2 The blue peak spectrum of white light LED measured from the 100W LED lamp shown by black circle dots, the solid line is the best fitting curve.

the blue peak position is λ_p=451.27 *nm.* This fitting result can be more clearly observed in Fig.2, where the experimental data and fitting curve are presented by circle dots and solid line. One can see that it is quite difficult to determine the blue peak position simply by take the maximum value of the peak, because the noise in spectrum will strongly affect the determination of the peak position in this quite broad band. By the fitting process, about 200 data have been used to determine the peak position. Then the precision on the peak position will be increased relative to the method of simple maximum intensity determined peak position, where only 1 data is used to determine the peak position.

By the fitting process on a good selected spectrum region, the precision of the peak wavelength λ_p can be improved a lot. In order to determine the junction temperature, one should obtain the peak wavelength shift $\Delta\lambda_p$. One should get the peak wavelength at its ambient temperature, which is a known temperature during the measurement. We find that when the ambient temperature is higher than 40 ^oC, with the cycle duty of 1% pulse power, the LED chip will have the junction temperature same as the ambient temperature, since the Joule heating energy is not large enough to increase junction temperature in LED chip packaged in lamp. We approximate the junction temperature of LED chip with the pulse power of 1% cycle duty to be the temperature of ambinet. Then one should get the peak wavelength at its normal working condition. The difference of the peak wavelength at two different LED work condition will give the peak wavelength shift $\Delta\lambda_p$.

3. THE DEPENDENCE OF ELECTROLUMINESCENCE PEAK SHIFT ON TEMPERATURE

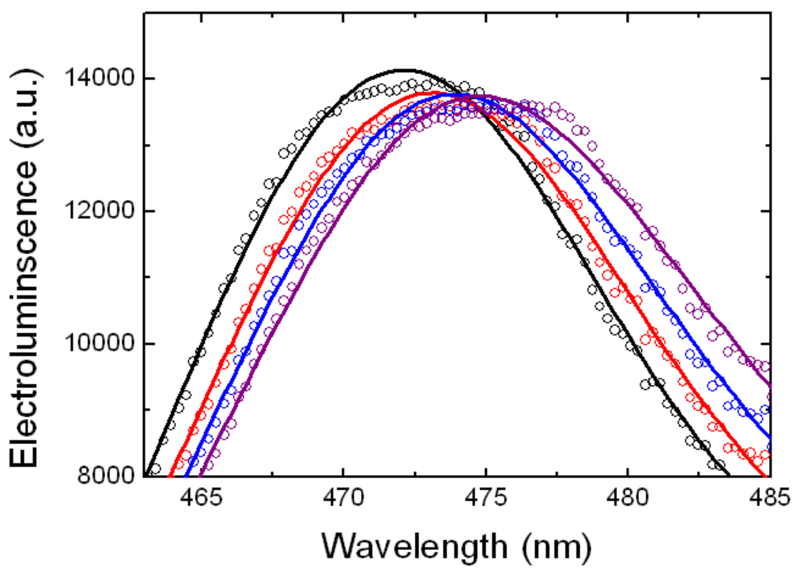

Figure 3. The peak part of electro-luminescence spectrum of LED chip at different temperature. The colors of black, red, blue and violet are used to present the spctra at 300*K*, 330*K*, 350*K* and 370*K*, respectively. The experimental data and fitting curve are given by the circle dots and solid line, respectively.

In order to obtain the junction temperature of LED lamp from the peak wavelength shift $\Delta\lambda_p$, it is necessary to calibrate the dependence of $\Delta\lambda_p$ on the temperature. Since this dependence is determined by the GaN-based material itself, the unpackaged LED chip is used for calibration in a temperature controlled Dewar system. The chip is mounted on the thermal finger to keep the LED chip be in the same temperature as that of thermal finger. The temperature of the thermal finger is precisely controlled with the temperature fluctuation less than 0.1*K*. By changing the temperature of thermal finger, the electro-luminescence spectrum of LED chip is obtained at different junction temperature. It is shown in Fig.3. The dot line is the experimental data and the solid line is the best fitting curves by Eq.(1). The fitting spectrum range is from 446nm to 499nm by setting the peak in the middle of this range. From Fig.3, one can see that the peak of the spectrum is not sharp as the typical single peak spectrum. It will cause big error to determine the peak position simply by consider the maximum value of spectrum. From Fig.3 we can see that the blue peak is at 471.65nm, 472.61nm, 473.33nm and 474.05nm for the LED chip at temperature of 300K, 330K, 350K and 370K, respectively. More data on the blue peak shift $\Delta\lambda_p$ with different temperature are obtained by the spectrum measurement and fitting process. This dependence is obtained as follows:

$$T = 300 + c\Delta\lambda_p + d\Delta\lambda_p^{\,2}$$
$$c = 27.8 \pm 0.2, d = -1.22 \pm 0.08 \qquad (2)$$

where the units for the temperature T and peak wavelength shift $\Delta\lambda_p$ are *K* and *nm*. The deviation between the experimental data and the value from Eq.(2) is not less than 0.5*K*. This deviation has the distribution as shown in Fig.4(a). It is clearly seen that most of the deviation is less than ±0.5*K*. In order to check this deviation again, the LED chip is measured in the temperature range from 300*K* to 302*K*. The spectra are measured in the temperature step of 0.1*K*. The variation of the temperature difference can be obtained between the real LED junction set by the thermal finger in Dewar and that deduced from Eq.(2) by spectrum fitting process. It is shown in Fig.4(b). It is also shown that the most of the deviation is less than ±0.4*K*, in well agreement with the analysis result from Fig.4(a). By Fig.4, we can deduce that the junction temperature determination method in this paper will give the temperature precision better than 1*K*.

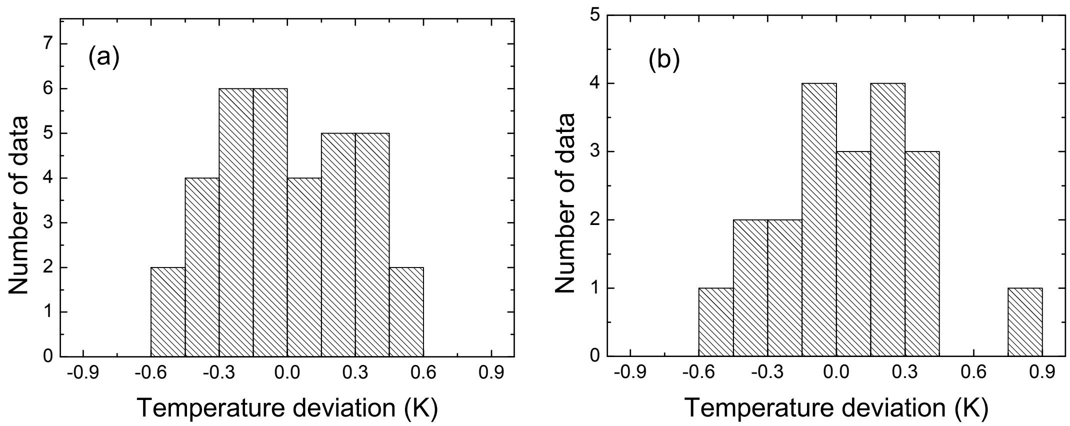

Figure 4. The temperature deviation from the value of Eq.(2) for big and small temperature region presented by (a) and (b), respectively.

4. THE APPLICATION ON THE LED LAMP

A 100W LED lamp is measured at different ambient temperature of 318*K*, 333*K*, 348*K*, 363*K* and 378*K* in the condition of 1% cycle duty of power supply. It was found that the intensity of the blue peak is not dependent on the junction temperature monotonously, while the peak wavelength shift is changed in monotone way by temperature. It confirms that the blue peak wavelength shift is a better parameter to determine the junction temperature compared with the intensity of blue peak. Relative to the spectrum at 300K, the peak wavelength shift $\Delta\lambda_p$ can be obtained by the spectrum measured at ambient temperature of 318*K*, 333*K*, 348*K*, 363*K* and 378*K*, respectively. By Eq.(2) and the value of $\Delta\lambda_p$, one can obtain that the corresponding junction temperature are 319*K*, 335*K*, 351*K*, 368*K* and 384*K*. It is in good agreement with the ambient temperature as expected. However, the measured junction temperature is always larger than the ambient temperature. The temperature difference between the junction and the ambient increases with the rise of ambient temperature. This difference is 1*K*, 2*K*, 3*K*, 5*K* and 6*K* for the ambient temperature of 318*K*, 333*K*, 348*K*, 363*K* and 378*K*, respectively. This may indicate that the hypothesis, the junction temperature being the same with the ambient temperature for our lamp with the small cycle duty power supply, is not a good approximation in high ambient temperature, because the high ambient temperature will reduce the thermal dispersion for the lamp. It confirms that the method in this paper can give a good precision on the junction temperature in LED lamp by non-contact way. When the lamp is operated in continuous DC power mode, the junction temperature of LED will increase 10*K*, 13*K*, 20*K*, 23*K* and 29*K* relative to the ambient temperature by the Joule heating energy for the ambient temperature of 318*K*, 333*K*, 348*K*, 363*K* and 378*K*, respectively. It is shown that with the increase of ambient temperature, the amount of junction temperature increase will be enlarged. This may also be resulted from the thermal dispersion efficient being reduced by the increase of ambient temperature.

The well characterized LED lamp has been used for the external-cabin illumination in space application in China. At the night of 26 Sept. 2008, astronaut performed the on-orbit electrical test for external-cabin LED lamp. The LED lamp had a good performance with fine illumination effect. At 16:10 p.m. of 27 Sept. 2008, the external-cabin activity lamp started to work, at 16:30 the astronaut began his external activity. During the whole process, the external cabin activity lamp works well with stable performance. All tech-index match the required level. After 90 minutes lasting illumination, the LED led an perfect end of the illumination task!

5. CONCLUSION

The junction temperature measurement for LED has been developed based on the interband transition luminescence peak shift. This method has been improved by the data fitting method combined with a good selection of the fitting spectrum region to reduce the fluorescence broad band influence. It is shown by the experimental data variation that the junction temperature of LED can be determined in the precision better than $1K$ for LED chip by using the calibration formula in this paper. It has been used for the LED lamp, a good temperature precision has also been obtained. The well characterized LED lamp has been used for the external-cabin illumination in space application in China.

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