Accurate measurement and influence on device reliability of defect density of a light-emitting diode*

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A method of accurately measuring the defect density of a high-power light-emitting diode (LED) is proposed. The method is based on measuring the number of emitting photons in the magnitude of 10^5 under the injection current as weak as nA and calculating the non-radiative recombination coefficient which is related to defect density. Defect density is obtained with the self-developed measurement system, and it is demonstrated that defect density has an important influence on LED optical properties like luminous flux and internal quantum efficiency (IQE). At the same time, a batch of GaN-based LEDs with the chip size of 1 mm×1 mm are selected to conduct the accelerated aging tests lasting for 1000 hours. The results show that defect density exhibits a greater variation and is more sensitive to LED reliability than luminous flux during aging tests. Based on these results, it is concluded that for the GaN-based LED with a chip size of 1mm×1mm, if its defect density is over $10^{17}/\text{cm}^3$, the LED device performance suffers a serious deterioration, and finally fails.

Keywords: accurate measurement, defect density, LED, reliability

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1. Introduction

The reliability of the high-power light-emitting diode (LED) chip has significant influence on expansion of solid state lighting applications. The introduction of defects in the chip growth process is an important factor affecting the reliability of the high-power LED chip. In the active layer, defects act as non-radiative recombination centers and capture carriers without emitting photons. It has been proved that the failure of an LED is related closely to the increase of defects during its lifetime. That is to say, defect density indicates LED reliability to a large extent.[1]

Recently there have been lots of reports to clarify the influence of defect density on the luminescence properties of LEDs.[2–4] However, the measurement of LED defect density is still under discussion. With the LED chip surface covered with complex structures of the electrode and the active layer being located inside the chip, existing defect detection technology including XRD (X-ray diffraction) and TEM (transmission electron microscope) cannot detect LED defect density within the active layer effectively.[5–8]

Under common operating current, radiative recombination of an LED is dominant over non-radiative recombination. However, to obtain the defect density, non-radiative recombination must be dominant and that means the LED needs to work under quite weak current. According to this principle, an accurate measurement method of determining the defect density of high-power light-emitting diodes (LEDs) is proposed in this paper. It is based on the definition of "initial detection point", that is, at this point carriers in the active layer mainly contribute to non-radiative recombination with an extremely small number of carriers becoming radiative photons in the magnitude of 10^5 under injection current as weak as nA. The number of emitting photons and the injection current of "initial detection point" will be measured. Then the defect density will be obtained by calculating the non-radiative recombination coefficient which is proportional to defect density. With accurate and rapid measurement of defect density, this method provides direct evidence for the evaluation of LED reliability.

2. Theory

The carriers injected into the LED active layer will transport through different mechanisms as shown in Fig. 1. The injection current J is assigned into several processes including radiative recombination with emitting photons, non-radiative Shockley–Read–Hall recombination, Auger recombination, and leakage current out of the active layer. [9,10]

Then the rate equation can be expressed as[11,12]

$$\mathrm{d}n/\mathrm{d}t = J/ed - An - Bn^2 - Cn^3 - J_{\mathrm{L}}/ed_1, \qquad (1)$$

where n is the carrier density; J is the injection current density; e is the unit charge; d is the active layer thickness; A, B, and C are the coefficients of SRH, radiative, and Auger recombination; J_{L} is the leakage current; d_1 is the minority carrier diffusion length in the p-type confining layer.

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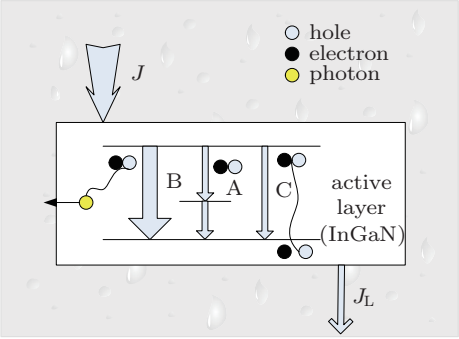


Fig. 1. (color online) Illustration of carrier transport mechanism in or near the active layer of GaN-based LED.

In a multi-quantum-well (MQW) GaN-based LED, Auger recombination C and leakage current J_L can be ignored, so equation (1) reduces to

$$dn/dt = J/ed - An - Bn^2. \tag{2}$$

Under steady-state conditions, $dn/dt = 0$, and equation (2) reduces to

$$J/ed = An + Bn^2 = N_R + R, \tag{3}$$

where An is the non-radiative SRH rate and Bn^2 is the radiative rate, as they can be replaced by N_R and R, i.e., $N_R = An$ and $R = Bn^2$.

In Eq. (3) the term A is given by the non-radiative SRH recombination rate as

$$A = \frac{1}{2} N_T \sigma v, \tag{4}$$

where N_T is the defect density, σ is the capture cross section, and v is the thermal velocity. As σ and v are constants, N_T is obtained by calculating A from Eq. (3). In Eq. (3), to calculate the value of A accurately, N_R term needs to be dominant over R term, that is to say, $N_R \gg R$. This condition will be satisfied if n is small enough, which means that the LED needs to work at the "initial detection point" which is defined above. Generally, it is considered to be the "starting luminous point" if $N_R/R > 10^3$.

Then there are equations at the "initial detection point", expressed as follows:

$$\begin{cases} J/ed = An, \\ L = Bn^2 sd, \\ A = \frac{1}{2} N_T \sigma v, \end{cases} \tag{5}$$

where J is the injection current density, s is the surface area of LED chip, d is the active layer thickness, e is the unit charge, L is the number of emitting photons, B is radiative recombination coefficient considered to be a constant related to material, and N_T is the defect density and can be obtained from Eq. (5) as

$$N_T = \frac{2J}{ed * \sigma v} \sqrt{\frac{Bsd}{L}}. \tag{6}$$

In summary, defect density N_T can be obtained by the measurement of the injection current density, J, and the number of emitting photons, L at "initial detection point". Equation (6) can be applied to all the GaN-based LEDs because they have the same mechanisms in the introduction of defects.

3. Experiment

3.1. Measuring instruments

Figure 2 shows the experimental apparatus of measuring the defect density of GaN-based LED.

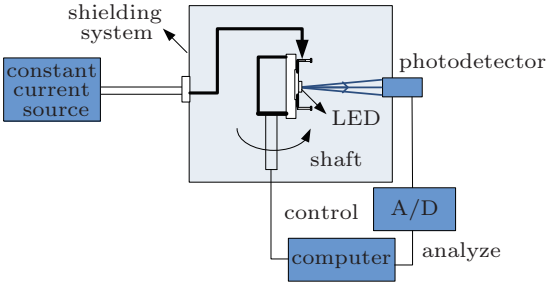


Fig. 2. (color online) Experimental apparatus of measuring the defect density.

The constant current source provides constant current for the LED whose range is from 10^{-12} A to 10^{-3} A. A shielding system is used to shield the ambient light and electromagnetic interference. The LED works at the "initial detection point" by adjusting the current source and it will rotate 180° about the shaft in steps of 0.5°. At the same time, the photodetector measures the LED spatial number of photons distributed in the minimum magnitude of 10^5. Then the total number of photons emitted by LED, L, is obtained by integrating the spatial photon distribution. Finally, on the basis of calculation with the parameters J and L at the "initial detection point", the defect density of LED is given by computing.

3.2. Aging tests

Two groups of 1-W commercial blue LEDs are selected to conduct aging tests which are denoted as a and b, three samples for each group. The parameters of each sample are as follows: surface size of the chip is 1 mm×1 mm, active layer thickness is 100 nm, radiative coefficient B is 10^{-10} cm^3/s, the capture cross section σ is 10^{-15} cm^2 and the thermal velocity v is 10^7 cm/s. Then equation (6) is given as

$$N_T = \frac{2J}{ed \cdot \sigma v} \sqrt{\frac{Bsd}{L}} = 4 \times 10^{23} \cdot \frac{J}{\sqrt{L}}. \tag{7}$$

The accelerated aging tests of samples are conducted at the aging platform with the temperature of substrate at 50 °C and aging current at 500 mA, and last for 1000 hours. As for the junction temperature of the sample, it is measured by self-developed junction temperature test apparatus and the result

shows that junction temperature is 60 °C.[13] At 150, 300, 450, 750, and 1000 hours, the defect densities and optical and electrical properties of the samples are measured. The measured values of defect density during aging are given in Table 1.

Table 1. Measured values of defect density (/cm^3) during aging.

Sample	0 h	150 h	450 h	750 h	1000 h
a1	6×10^{13}	1.2×10^{14}	4×10^{14}	5×10^{14}	5.6×10^{14}
a2	1×10^{14}	2.1×10^{14}	8×10^{14}	1×10^{15}	1.2×10^{15}
a3	1.2×10^{14}	2.5×10^{14}	1.1×10^{15}	1.5×10^{15}	2×10^{15}
b1	4.8×10^{14}	1×10^{15}	5×10^{15}	7×10^{15}	1×10^{16}
b2	5×10^{14}	1.2×10^{15}	6.5×10^{15}	8.5×10^{15}	1.5×10^{16}
b3	1×10^{15}	3.5×10^{15}	2.5×10^{16}	5×10^{16}	8×10^{16}

4. Results and discussion

4.1. Defect density and optical properties of LED

Figure 3 shows the plots of the number of emitted photons versus injected electrons for three LED samples. Their "starting luminous points" are shown as illustrated in the inset of Fig. 3. The values of N_R/R are also given in the figure. It is obvious that the sample with higher defect density has a greater value of N_R/R. Under higher injected electrons the radiative recombination is dominant. The three samples emit almost the same number of photons. With injected electrons decreasing, the sample with higher defect density emits fewer photons since non-radiative recombination starts to dominate.

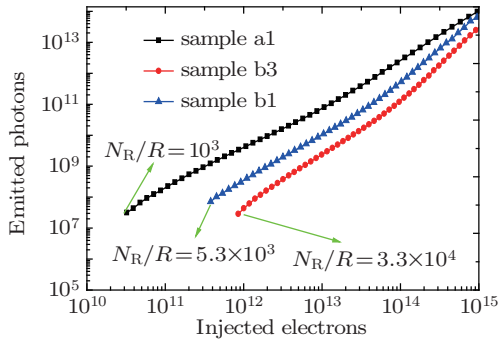


Fig. 3. (color online) Plots of number of emitted photons versus injected electrons for samples with different defect densities.

To clarify the effect of the defect density on the optical property of the LED, the relative luminous fluxes of the two groups of samples are measured under different currents as shown in Fig. 4.

In Fig. 4, the solid points represent the real measurement data and the lines denote the fitting curves. As shown in Fig. 4, under an injection current of 0.1 μA, the relative luminous flux is approximately inversely proportional to the square of the defect density. It can be expressed as

$$L = Bn^2 \approx \frac{4B}{\sigma^2 v^2}\left(\frac{J}{ed}\right)^2 \frac{1}{N_T^2}. \tag{8}$$

With the injection current increasing, the effect of defect density on luminous flux of LED becomes smaller. When injection current reaches 350 mA, the relative luminous flux almost does not change with defect density.

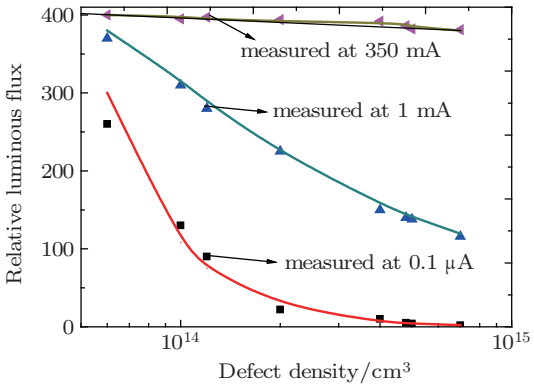


Fig. 4. (color online) Plots of relative luminous flux versus defect density under different currents.

4.2. Calculation and discussion of internal quantum efficiency (IQE)

According to *ABC* model, internal quantum efficiency can be expressed as[14,15]

$$\eta_I = \frac{Bn^2}{An + Bn^2 + Cn^3}, \tag{9}$$

where A, B, and C, represent coefficients of the Shockley–Read–Hall (SRH), radiative, and Auger recombination processes, respectively. For samples selected in this paper, $B = 10^{-10}$ cm^3/s, $C = 10^{-29}$ cm^6/s. The value of A can be calculated from Eq. (4) where $\sigma = 10^{-15}$ cm^2, $v = 10^7$ cm/s. Then IQE can be calculated from Eq. (9) and the actual value of IQE can be obtained through measurement apparatus.

As shown in Fig. 5, the solid curves represent calculated values of IQE of two samples (samples a1 and b3) with different defect densities. Under the same injection current, the sample (sample b3) with higher defect density has a smaller value of IQE. With injection current decreasing, the difference in the value of IQE between the two samples becomes larger; with injection current further increasing, the difference becomes smaller and smaller and there appears an efficiency droop in each IQE curve.[16,17] According to Eq. (9), at the maximum value of IQE, $d\eta_I/dn = 0$ and $n_{max} = \sqrt{A/C}$. As C is a constant for different samples, the sample with higher defect density (i.e., sample b3) has a higher injection current at the peak of IQE as shown with a dotted line in Fig. 5.

The measured values of IQE are shown as solid points in Fig. 5. Compared with calculated values, they are in pretty good agreement with each other under weak injection current. But with the current increasing, the measured values are less than the calculated values and the difference between them becomes larger. The reason for this phenomenon is that in the

calculated values of IQE, the coefficient of radiative recombination, B, is taken to be a constant. But in fact, when injection current increases up to higher than 1 mA, radiative recombination is saturated and the value of B will become smaller. [18]

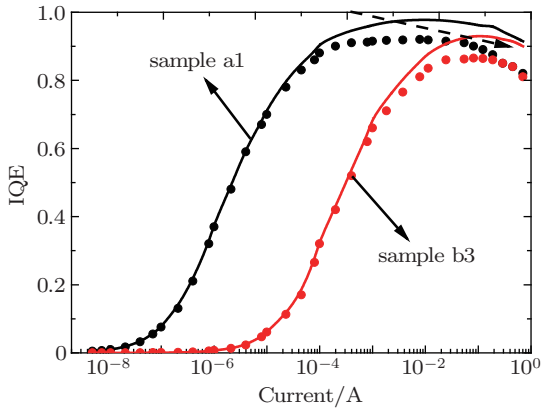


Fig. 5. (color online) Calculated and measured values of IQE versus injection current for samples with different defect densities.

5. Defect density and reliability

Figure 6 shows the variations of defect density and relative luminous flux with stress time.

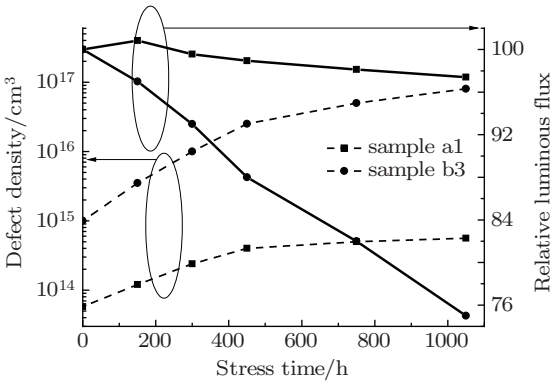


Fig. 6. Variations of defect density and relative luminous flux with stress time.

In Fig. 6, the thin solid curve (with solid squares) represents the results of sample a1, the thick solid curve (with solid circles) represents the results of sample b3, the solid line represents the luminous flux, and the dotted line represents defect density. As can be seen from Fig. 6, sample a1 has a lower initial defect density than sample b3. Defect density increases and relative luminous flux decreases with stress time. The increase of defect density and decrease of relative luminous flux for sample a1 are smaller. A reasonable explanation is that under the high temperature and high current stress aging conditions, defects act as SRH recombination centers and capture carriers without emitting photons in the active layer. Energy generated with SRH recombination is transferred to the lattice so that the lattice vibration intensifies, resulting in the generation of more defects.

Furthermore, after 1000-hour aging time, the decrease of relative luminous flux of sample b3 is 10 times that of sample a1 and the defect density increases 100 times. So the variation in the defect density can be more sensitive in reflecting the reliability of LED. It is generally believed that if the decrease of luminous flux is over 30% the LED device is thought to be in failure. In Fig. 6, the decrease of luminous flux for sample b3 is over 35%, so it is believed that sample b3 is already in failure.[19] Based on the phenomena appearing in the case with the increase of defect density, it is concluded that if the defect density is over $10^{17}/\mathrm{cm}^3$, the LED device suffers a serious deterioration in performance, and it is actually already in failure.

As shown in Fig. 7, with the increase of defect density, LED lifetime presents a decreasing trend, and it is reduced quickly with defect density increasing. When defect density is less than 10^{15} cm^3, LED lifetime is about thirty thousand hours. But when defect density increases to over $10^{17}/\mathrm{cm}^3$, its lifetime comes to an end. Figure 7 further demonstrates the conclusion mentioned above: if the defect density is over $10^{17}/\mathrm{cm}^3$ the LED device suffers a serious deterioration in performance, and it is already in failure.

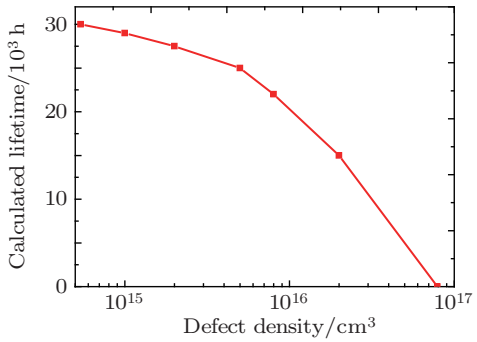


Fig. 7. (color online) calculated lifetime of LED versus defect density.

6. Conclusion

A method of accurately measuring the defect density of a high-power light-emitting diode (LED) is proposed. This method can be applied to all the GaN-based LEDs. With the self-developed measurement system based on low light level detection, the "initial detection points" of two groups of LED samples each with a size of 1 mm×1 mm are measured and they are characterized by the ratio of non-radiative recombination to radiative recombination. The relative luminous fluxes of the two groups of samples are obtained under different currents, and the results show that the luminous flux is approximately inversely proportional to the square of defect density when non-radiative recombination is dominant. The coefficient of non-radiative recombination can be calculated from defect density, and IQE curve is obtained according to *ABC* model. The value and peak point of IQE curve are related

closely to defect density. The defect density and luminous flux are measured before and after aging, and then LED lifetime is calculated with the fitting parameter. Finally, it is concluded that the defect density can be more sensitive in reflecting the reliability of the LED: if the defect density is over $10^{17}/cm^3$, the LED device suffers a serious deterioration in performance and finally it is in failure.

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