Degradation behaviors of high power GaN-based blue light emitting diodes*

Zhong Can-Tao(钟灿涛), Yu Tong-Jun (于彤军)†, Yan Jian(颜 建), Chen Zhi-Zhong(陈志忠), and Zhang Guo-Yi(张国义)

State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, *China*

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The degradation mechanism of high power InGaN/GaN blue light emitting diodes (LEDs) is investigated in this paper. The LED samples were stressed at room temperature under 350-mA injection current for about 400 h. The light output power of the LEDs decreased by 35% during the first 100 h and then remained almost unchanged, and the reverse current at −5 V increased from 10^{-9} A to 10^{-7} A during the aging process. The power law, whose meaning was re-illustrated by the improved rate equation, was used to analyze the light output power-injection current (*L–I*) curves. The analysis results indicate that nonradiative recombination, Auger recombination, and the third-order term of carriers overflow increase during the aging process, all of which may be important reasons for the degradation of LEDs. Besides, simulating *L–I* curves with the improved rate equation reveal that higher-than-third-order terms of carriers overflow may not be the main degradation mechanism, because they change slightly when the LED is stressed.

Keywords: light emitting diodes, degradation, rate equation

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1. Introduction

InGaN/GaN multiple quantum well (MQW) light emitting diodes (LEDs) have attracted considerable attention because of their wide applications, such as solid state lighting, traffic lights, display backlighting, and so on. In recent years, many researchers have focused on the improvement of the light output power of LEDs, and it has been greatly increased. However, another important problem impeding the further applications of LEDs is their reliability. Several groups have been making efforts to investigate the degradation mechanisms of LEDs. Up to now, the reported results seem to be supported mainly by the relation of degradation mechanisms with the formation of nonradiative centers in quantum wells,[1,2] modifications of the metal/p-GaN contact,[3,4] changes in the carrier injection mechanisms,[5] and the heat effect.[4,6,7] Other than the degradation of the Ohmic contact and the packaging of LEDs, discussions on the intrinsic mechanism of decline in quantum wells remain controversial. Although the reliability of high power GaN-based LEDs is very important for their applications, proper methods for evaluating the lifetime and failure processes are still lacking. Therefore, in order to improve device reliability, a greater understanding of LED degradation behaviors is necessary.

In this paper, the changes of the optical and electrical characteristics of high power blue LEDs during the aging process are investigated. Combined with the analysis of the power law and simulations with the improved rate equation $A'B'C'$ model, several physical mechanisms of degradation are discussed in depth.

2. Experiment details

The high power blue LEDs in this paper were grown on the *c*-plane (0001) planar by metal organic chemical vapor deposition (MOCVD). The LED structure consisted of a low temperature GaN buffer layer, a 2-μm n-GaN layer, a five-period InGaN/GaN MQW active region with 2.5-nm wells and 12-nm doped quantum barriers, and a 120-nm p-GaN contact layer on top. The LED wafers were processed into chips with square mesas of 1 mm×1 mm in size, by photolithography and inductively coupled plasma reactive ion etching (ICP). Contacts consisting of a Cr/Pt/Au multilayer and indium tin oxide, which performed a current spreading function, were deposited onto the n-GaN and p-GaN layers, respectively. The chips were encapsulated with silicone resin for subsequent measurements. The peak wavelength of these LEDs was ∼ 454 nm at 350 mA.

The aging experiments of high power blue LEDs were operated over 400 h under 350-mA current at room temperature. To keep the LED working at a steady condition of humidity and temperature, the LED aging test module was set in a cabinet with automatic N_2 purging. Light output power,

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†Corresponding author. E-mail: tongjun@pku.edu.cn

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I–V curves, and electroluminescence spectrum were measured at different stress times. An HAAS-2000 high accuracy array spectroradiometer and an Agilent HP 4155C semiconductor parameter analyzer were applied for the measurements of optical and electrical properties. To avoid thermal effects on the results, LEDs were tested under the pulse mode, and the data were the average values from several LED chips.

3. Result and discussion

Figure 1 shows the normalized light output power of high power blue LEDs at 350 mA as functions of the stress time. It is found that the light output power of these LEDs decreases by 35% during the first 100 h, and then almost keeps unchanged until 400 h.

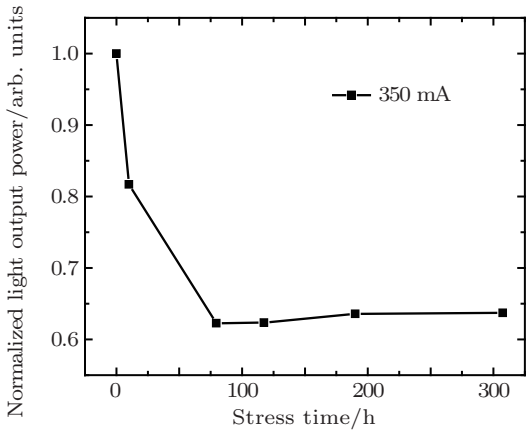


Fig. 1. Normalized light output power of high power blue LEDs at different stress times.

The reasons for the degradation of light output power mainly include the worsening of the encapsulated epoxy resin and decay of the chip itself. Earlier studies showed that epoxy resins did not change obviously in aging experiments.[8] Thus, the degradation of light output power may be caused by the LED chip itself.

The I–V curves of high power blue LEDs in aging experiments are shown in Fig. 2. The currents at a reverse bias and at a small forward bias increase obviously as functions of the stress time. The inset of Fig. 2 shows the tendency of reverse currents at -5 V at different stress times, which increase from 10^{-9} A to 10^{-7} A. This result indicates that parasitic leakage paths supplied by structural defects increase during the aging process. Combined with the reduction of light output power, it is suggested that the increase of parasitic leakage paths is closely relation with the decay of light output power.

To further investigate the degradation mechanisms, the power law $L \propto I^{\alpha}$ is used to analyze the L–I curves of different stress stages.[9] Meneghini *et al.* proposed the meaning of coefficient α using the rate equation,[10] however, its meaning was inaccurate because the effects of Auger recombination and carriers overflow were ignored. Therefore, a more accurate meaning of coefficient α was re-illustrated by using an improved rate equation $A'B'C'$ model[8] including Auger recombination and carriers overflow.

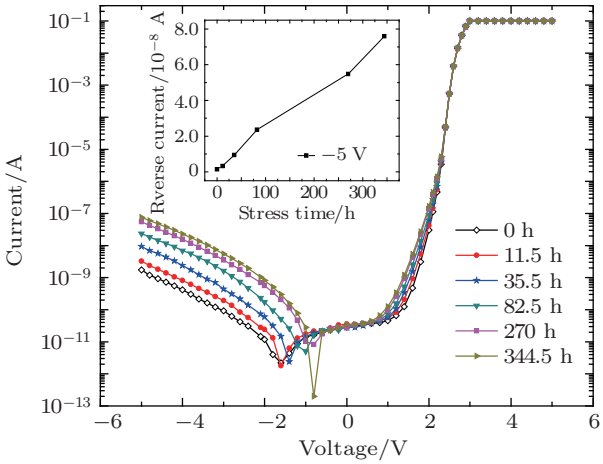


Fig. 2. (color online) Current–voltage characteristics under injection current 350 mA. Inset shows the reverse current at -5 V versus the stress time.

In this improved rate equation, carriers overflow current $f(n)$ can be expanded into a power series (Taylor series), that is $f(n) = \alpha n + \beta n^2 + \gamma n^3 + \delta n^4 + \cdots$. In addition, in low and moderate current regions, the first three terms of the rate equation include the most important parts of carrier recombination processes. Therefore, the rate equation can be rewritten as

$$\frac{\eta_j I}{eV} = A'n + B'n^2 + C'n^3, \tag{1}$$

where $A' = A + \alpha$, $B' = B + \beta$, $C' = C + \gamma$, A, B, C represent the nonradiative, radiative, and Auger coefficients, respectively, n is the carrier concentration, η_j is the current injection efficiency, V is volume of active region.

Next, the meaning of coefficient α is discussed in different current regions. In the low current region, nonradiative recombination $A'n$ dominates over others recombination parts $B'n^2$ and $C'n^3$, that is $A'n \gg B'n^2$, $A'n \gg C'n^3$, Therefore

$$\frac{\eta_j I}{eV} \approx A'n. \tag{2}$$

Since the light output power can be expressed as $L = \eta_{\text{ext}} VBn^2$, ($\eta_{\text{ext}}$ is the light extraction efficiency), $L \propto n^2 \propto I^2$ can be deduced, on the condition that B does not change obviously during the low current region. Then, the value of coefficient α should be close to 2 and represent the nonradiative recombination contribution to overall recombination.

In the mediate current region, nonradiative recombination centers saturate, and recombination parts $B'n^2$ dominate, that

is $B'n^2 \gg A'n$, $C'n^3$ can not be omitted, therefore

$$\frac{\eta_j I}{eV} \approx B'n^2 + C'n^3. \tag{3}$$

Therefore, the value of coefficient α should satisfy $2/3 < \alpha < 1$ according to Eq. (3), and it would represent the contribution of the recombination part $C'n^3$ to overall recombination.

The values of coefficient α at different stress times is obtained by fitting *L–I* curves in the low current region from 0.6 mA to 3 mA, which are shown in Fig. 3. It is found that the value of coefficient α increases rapidly at the first 100 h and then almost keeps unchanged. Therefore, combining with Eq. (2), the increase of coefficient α, which corresponds with the decrease of light output power, suggests that the nonradiative recombination centers supplied by structural defects increase during the aging process. Therefore the increase of nonradiative recombination centers may be an important reason for the degradation of high power blue LEDs.

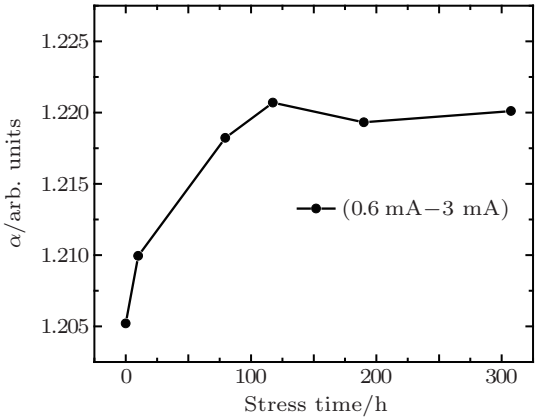


Fig. 3. Values of coefficient α versus the stress time in the low current region.

Figure 4 shows the values of coefficient α at different stress times by fitting *L–I* curves in the mediate current region from 10 mA to 30 mA, which decrease quickly during the first 100 hours and then almost keep unhanged. According to Eq. (3), the decrease of coefficient α indicates the contribution of recombination part $C'n^3$ to the overall recombination increase in the aging experiment. This result suggests that Auger recombination and the third-order term of carriers overflow may be the important degradation mechanisms.

Next, the role of higher-than-third-order terms of carriers overflow in the aging experiment is investigated. The improved rate equation $A'B'C'$ model is used and more details about the fitting process can be found from Ref. [11]. The contribution of higher-than-third-order terms of carriers overflow to light output power is illustrated in Fig. 5. It is found that the contribution of this part is small, which is about 5%, and does not change obviously during the aging process. This result suggests that higher-than-third-order terms of carrier overflow may have little influence on the degradation of high power LEDs.

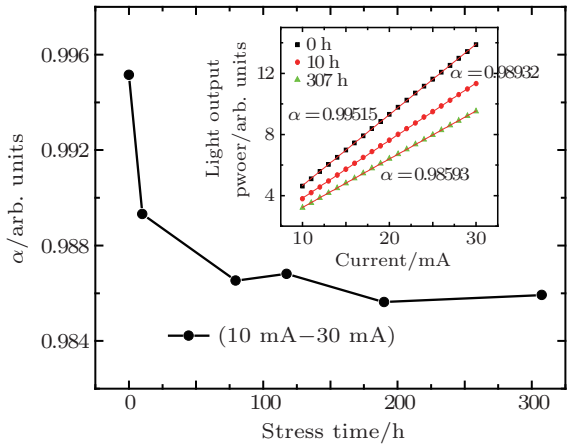


Fig. 4. (color online) The value of coefficient α versus the stress time in the mediate current region. Inset shows *L–I* curves from 10 mA to 30 mA and its $L \propto I^{\alpha}$ fits.

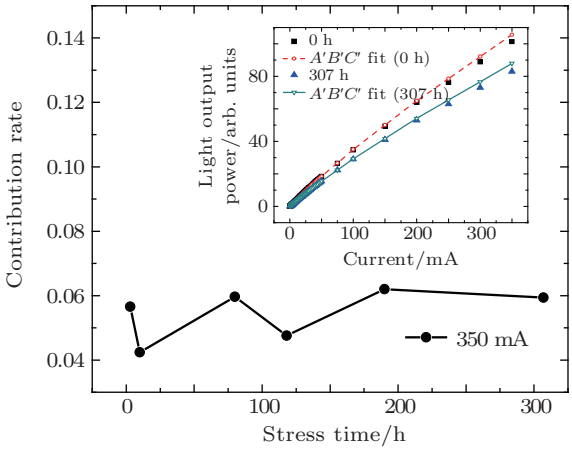


Fig. 5. (color online) The contribution of $n^{(>3)}$ to light output power versus stress time at 350 mA. The inset shows *L–I* curves and its $A'B'C'$ fits.

4. Conclusion

In summary, the optical and electrical characteristics of high power LEDs in the aging experiment were investigated. The light output power of LEDs first decreases rapidly and then almost keeps unchanged, and the reverse current and the small forward current increases as stress time increases. By analyzing *L–I* curves with the power law, the changes of coefficient α in different current regions suggests that not only the nonradiative recombination supplied by structural defects, but also the Auger recombination and the third-order term of carrier overflow may also be important degradation mechanisms. Besides, through simulating *L–I* curves with the improved rate equation, it is found that higher-than-third-order terms of car-

riers overflow may not be a dominant reason for the degradation of high power LEDs.

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