The Reliability of Tunnel Junction Regenerated Light Emitting Diodes

Wang Xiaoming, Guo Weiling, Tian Yongtao, Guo xia, Gao Guo and Shen Guangdi

(The school of electronic information& control Engineering, Beijing University of technology and Beijing Optoelectronic technology Laboratory, Beijing, 100022, China)

Abstract: The theory of Light Emitting Diodes(LEDs) life tests and mathematic model of life tests were introduced. The performance of LEDs was affected by the drive current and by the ambient temperature. Life tests of tunnel junction regenerated AlGaInP LEDs were performed at different currents and ambient temperatures. On axis output intensity of tunnel junction regenerated LED had decreased 35.53% after 5203 hours at 30mA and 25℃. At the ambient temperature of 80℃, on axis output intensity of tunnel junction regenerated LED had degraded 19.26% after 3888 hours at 20mA. According to the results mentioned above, the normal working lifetime of tunnel junction regenerated LEDs were concluded. Moreover, the main Failure Mechanisms of it were described. Our work reviews the failure analysis that was performed on the degraded LEDs and the degradation mechanisms that were identified. The results show a thermal degradation mechanism that dominates degradation at high ambient temperatures.

Key words : Light Emitting Diodes (LEDs), Life tests, Degradation , Tunnel junction regenerated

1. INTRODUCTION

A bright LED, if it could be proven reliable with a lifetime on the order of 10000h, would be very attractive in applications such as flat panel displays, LCD backlights, outdoor traffic signals, and indoor room lighting.[1-2] We performed a reliability study of tunnel junction regenerated LEDs, which have better characteristic compared with conventional LEDs, with the intention to investigate the degradation of the samples. At the same time, failure mechanisms were analysed.

In general, the on-axis luminous intensity of conventional LEDs saturate under the high injection level.[3] Besides the material quality, there are still two factors in restricting the increase of the on-axis luminous intensity under high injection level. One is the large leakage current, which has the exponential dependence on the potential barrier height.[4] The other one is the nonradiation recombination at the interface between the active region and the p-cladding layer. The overheating at

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the interface induces the temperature rising and the distribution of carrier widening, which in turn causes more leakage current and more heat. Thus, the quantum efficiency and the brightness of conventional LEDs under the higher injection level decreases.

2. LED STRUCTURE

The energy band diagram of our sample fabrication--tunnel junction regenerated AlGaInP LEDs with high-quantum efficiency and high brightness is shown in Fig. 1, which contains a reversed biased tunnel junction sandwiched between two conventional LEDs p-i-n structures. Theoretically speaking, after an electron-hole pair is recombined in the previous active region, the electrons in the p-side valence band, under the action of high electrical field, will tunnel into n-side conduction band and can generate radiate recombination again in the next active region.[5-6] In this way, the quantum efficiency and the brightness will scale linearly with the number of the active regions, and higher output power can be obtained under the lower injection level, resulting in lower leakage current and heat level comparing with a conventional LEDs.

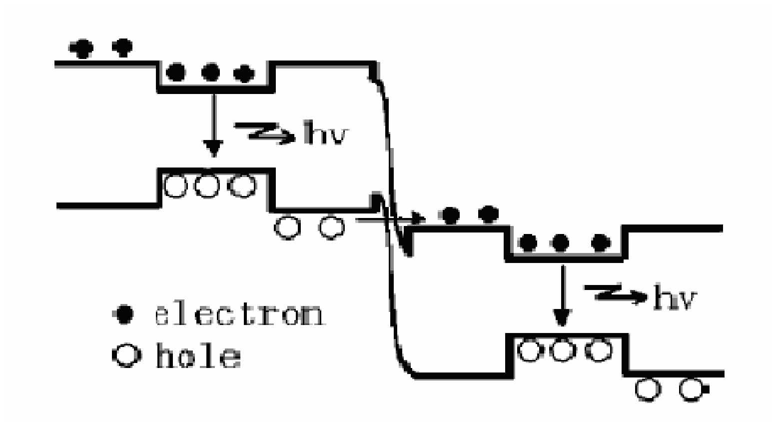

Fig. 1 The energy band diagram of tunnel junction regenerated LEDs

Such tunnel junction regenerated LEDs were grown by low pressure metalorganic chemical vapor deposition on n-GaAs substrate. The detail layer structure was shown in Fig. 2. The forward voltage drops of the tunnel junction regenerated LEDs are about 4V at 20 mA DC injection current while those of the conventional ones are 2V, which indicate the negligible resistance of the tunnel junction.

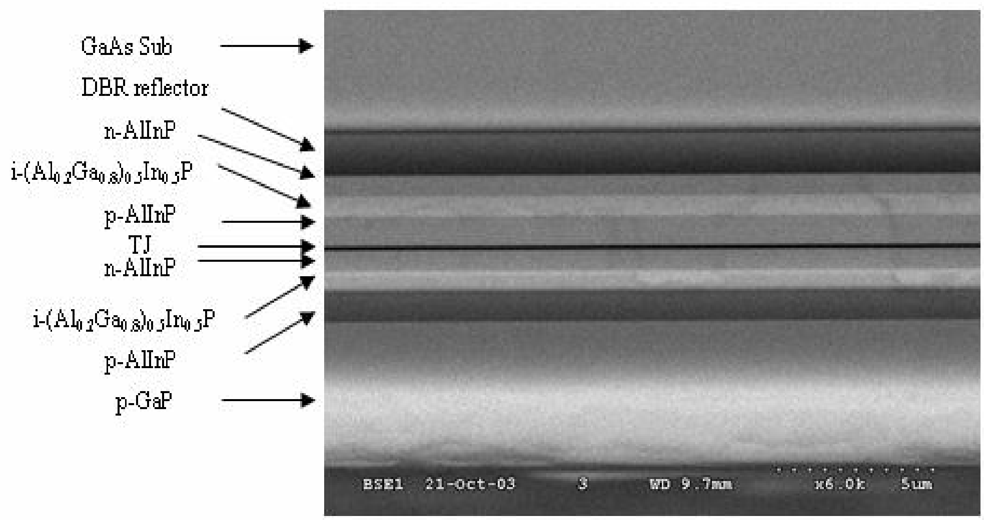

Fig. 2 SEM photo of tunnel junction regenerated AlGaInP LED

Fig. 3 shows that the light intensity of tunnel junction regenerated LEDs start to saturate at an injection current of about 80 mA, which is higher than that of the conventional one. This means that the leakage current and nonradiation recombination are reduced and both the active regions and the tunnel junction have a negligible influence on the thermal characteristic of the LEDs.

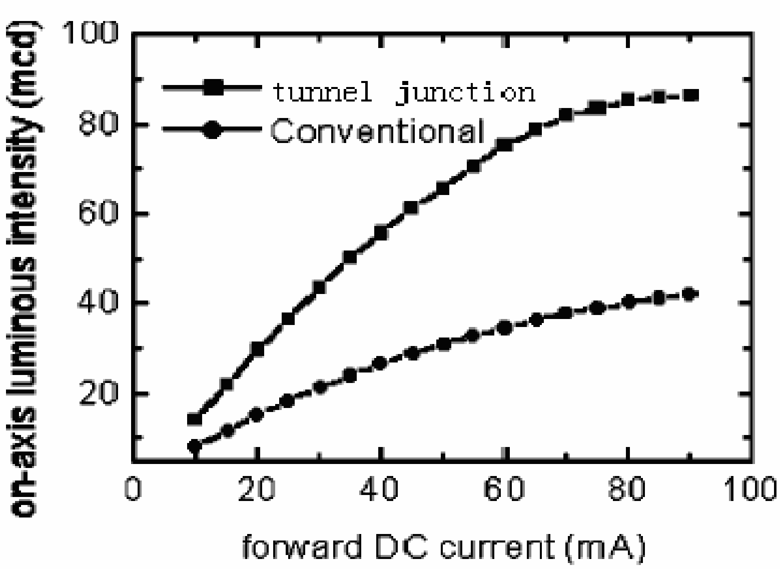

Fig. 3 On-axis luminous intensity forward DC current
for conventional and tunnel junction regenerated LEDs.

3. RELIABILITY

To finish our task, two experiments were carried out. In the one experiment, 8 samples signed **A1, A2……A8** were mounted inside a large environmental chamber that be maintained at a constant temperature--80℃ and at the current of 20mA for 3888 hours. In the other, 18 samples signed **B1, B2……B18** were tested at 30mA and 25℃ for 5203 hours. Subsequently, we extrapolated the lifetime of the devices by some valid reliability equations and analysed the degradation mechanisms.

3.1 Experiment 1

The life test summary of **A1, A2 …… A8** was described in Table 1. The continuous graph of percentage change in relative intensity values is shown in Fig. 4. Averaged according to drive current, on axis output intensity of the tunnel junction regenerated AlGaInP LEDs had degraded 19.26%.

Table 1. life test summary of A1,A2……A8 worked at 20mA,80℃ for 3888 hours

Parameters	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**
Initial output power(cd)	3.00	2.69	2.64	2.51	2.52	2.72	2.74	2.33
Terminated output power(cd)	2.34	2.13	2.11	2.03	2.13	2.10	2.25	1.96
Degraded percentage(%)	22.00	20.82	20.08	19.12	15.47	22.79	17.88	15.88
Lifetime(h) @20mA, 80℃	10847	11546	12026	12697	16028	10418	13678	15585

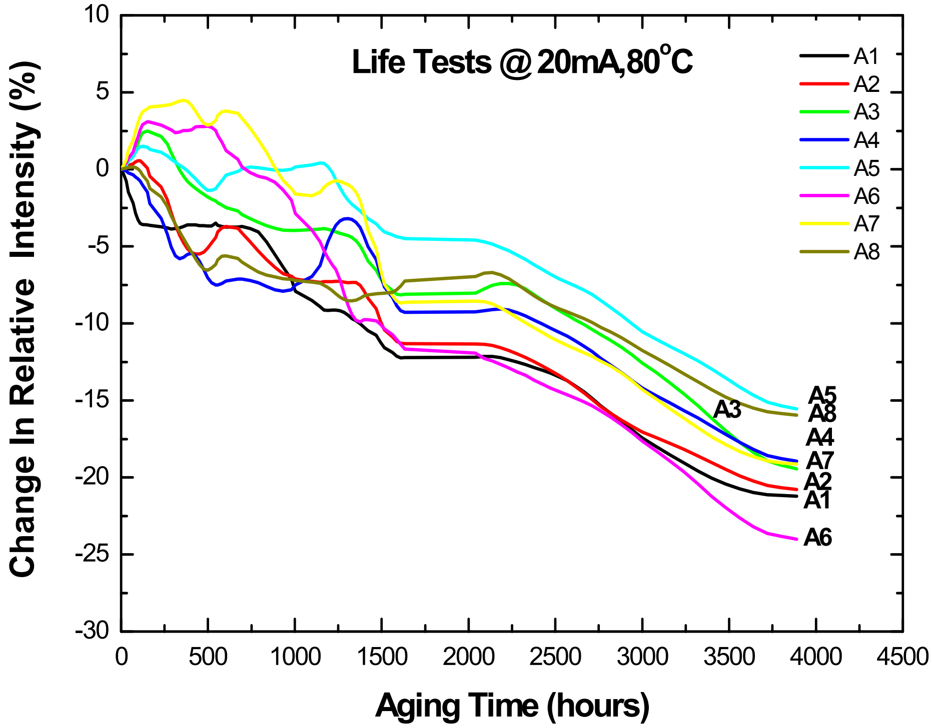

Fig. 4 Percentage change in relative intensity for the A series of LEDs

3.2 Experiment 2

The life test summary of **B1, B2 …… B18** was described in Table2. The continuous graph of percentage change in relative intensity values is shown in Fig. 5. Averaged according to drive current, on axis output intensity of the tunnel junction regenerated AlGaInP LEDs had degraded 35.53%.

Table 2. life test summary of B1,B2……B18 worked at 30mA,25℃ for 5203 hours

Parameters	B1	B2	B3	B4	B5	B6	B7	B8	B9
Initial output power(cd)	4.32	4.37	4.45	3.92	4.52	4.20	4.65	4.76	4.70
Terminated output power(cd)	3.18	2.85	3.32	2.28	3.11	2.54	3.41	2.91	3.52
Degraded percentage(%)	26.39	34.78	25.39	41.84	31.19	39.52	26.67	38.87	25.11

Lifetime(h) @30mA,25℃	11771	8437	12311	6655	9646	7171	11628	7329	12475

Parameters	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**	**B16**	**B17**	**B18**
Initial output power(cd)	4.02	4.44	4.00	4.50	3.90	4.02	3.90	4.20	4.18
Terminated output power(cd)	2.90	2.55	2.31	2.98	2.26	2.30	2.43	2.51	2.48
Degraded percentage(%)	29.86	42.57	42.25	33.78	42.05	42.79	37.69	40.24	40.67
Lifetime(h) @30mA,25℃	11043	6503	6569	8750	6610	6459	7623	7006	6908

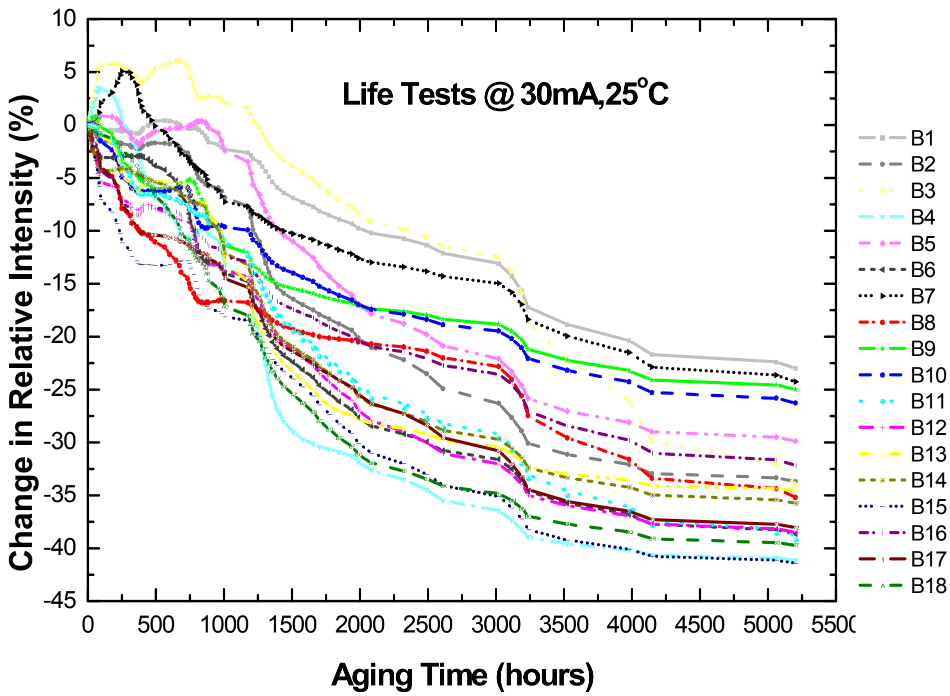

Fig. 5 Percentage change in relative intensity for the B series of LEDs

3.3 Results discussion

Seen from Fig. 4 and Fig. 5, early in the test the curves fluctuate erratically. Afterward, the LEDs continued to decline in intensity smoothly. High ambient temperature and high current appeared to be increasing the activity of the degradation mechanisms occurring within these LEDs.[7] On the one hand, high temperature reduces the quantum efficiency of LEDs, and high current will result in the increase of junction temperature. Finally, along with the quantum efficiency keeping on declining, the LEDs degrade. On the other, high current and temperature will lead to increase series resistance with consequent current crowding effects that reduce the optical power. Moreover, both Deep Level Transient Spectroscopy (DLTS) and photocurrent spectra indicate the creation of extended defects in devices treated at high temperature and high current density.[8]

However, in our tests, the average lifetime of the samples at 20mA、80℃ is 12853 hours and that of the samples at 30mA、25℃ is 8605 hours. The former is much more than the latter. In spite of that there exists an opaque layer on the device surface after tests in our experiment 1, which induces degradation of the epoxy material in contact with the heated device surface. Thus, we can draw another conclusion that tunnel junction regenerated LEDs due to their characteristic mentioned above have more efficient resistance to high temperature than high current.

4 RELIABILITY EQUATIONS[9]

There are several methods of extrapolating source lifetime including methods of calculating lifetime given power output operating temperature, device drive currents, and decrease in output power. Below are several of the extrapolation equations for predicting source lifetime.

4.1 Output Power:

The lifetime of a LED can be approximated by the following relationship. Given an initial power output of the device P_0 and the exponential lifetime τ the power output over time t, can be extrapolated.

$$P_{out}(t) = P_0 e^{-t/\tau} \qquad (3\text{-}1)$$

Assume that for a given time t, the power output of the device has dropped to a percentage from the initial power level such that Power ratio, $P_R = Pout/P_0$ and solve for τ such that,

$$\tau = -t / \ln(P_R) \qquad (3\text{-}2)$$

Now with τ known, as well as the initial power output P_0, the power output $Pout(t)$ can be extrapolated over time t.

4.2 Temperature:

For determining the relationship between temperature of the device to predict lifetime an

Arrhenius relationship can be expressed as,

$$t = ce^{Ea/kT} \quad (3\text{-}3)$$

where

Ea is the activation energy for the device in units of eV,
K is Boltzman's constant = 1.38 * 10-23 Joules/Kelvin,
T is absolute temperature, (273.2 + °C) in units of Kelvin,
c is the device constant in units of time, and
e is electron charge = 1.6 * 10-19 Joules/eV.

Given a known activation energy *Ea*, operating temperature T_0 and lifetime of the device t_0, the constant can be calculated by

$$c = t_0^{-Ea/kT} \quad (3\text{-}4)$$

Or as a ratio, t_2 can be solved for in terms of T_2 given T_0 and t_0 such that

$$\frac{t_0}{t_2} = \frac{e^{Ea/kT_0}}{e^{Ea/kT_2}} \quad (3\text{-}5)$$

Simplifying to solve for t_2 as a function of the temperature for accelerated life testing,

$$t_2 = t_0 e^{-\frac{Ea}{k}\left[\frac{1}{T_0} - \frac{1}{T_2}\right]} \quad (3\text{-}6)$$

Note that for photodetectors the degradation mechanisms are different but the same Arrhenius relationship can be used to determine lifetime of the device given different operating temperatures.

4.3 Drive Current:

Another way of predicting source lifetime is by extrapolation of the current density. If *J* is defined as the current density, the lifetime of the device is defined as *t*, and the empirical value parameter is defined as *n*, then there exists a relationship such that :

$$t \propto J^{-n} \quad (3\text{-}7)$$

Therefore if the lifetime of the device, t_0 is known for a given operating current, I_0 then a relationship between drive current and device lifetime can be deduced from

$$\frac{t_0}{t_2} = \frac{J_0^{-n}}{J_2^{-n}} = \left(\frac{J_0}{J_2}\right)^{-n} = \left(\frac{I_0}{I_2}\right)^{-n} \quad (3\text{-}8)$$

Solving for t_2 such that a relationship exists where lifetime can be predicted as a result of elevated of decreased operating drive current I_2,

$$t_2 = t_0 \left(\frac{I_2}{I_0}\right)^{-n} \quad (3\text{-}9)$$

The values of *n* range from 1.5 to 2.0, with the larger *n* indicating more of a reduction in operational lifetime or greater sensitivity of the device to increased currents.

In our experiments, accelerated lifetime of the samples, filled in table 1 or table 2, were extrapolated from equation (3-1) and equation (3-2). Given a known *Ea* or *n* of AlGaInP, we can easily extrapolate the lifetime of the devices worked at normal conditions from equation (3-6) or equation (3-9).

5. CONCLUSION

Our studies of lifetime and the failure mechanisms of runnel junction regenerated LEDs help to identify the main degradation mechanisms of these devices: high temperature and high current. Besides this, packaging is one of the focuses of failure mechanism. Go without saying, nonoptimized packaging will enhance some reliability problems. Additional failure mechanisms are triggered in devices stressed at high temperature and at high current, leading to catastrophic package degradation and extended defects formation in the device. And that, dopant reactivation, generation of nonradiative recombination centers and deep levels has been found in devices stressed at high currents or high temperature, which need a further investigation.

6. ACKNOLEDGEMENT

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