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Degradation of light emitting diodes: a proposed methodology*

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Abstract: Due to their long lifetime and high efficacy, light emitting diodes have the potential to revolutionize the illumination industry. However, self heat and high environmental temperature which will lead to increased junction temperature and degradation due to electrical overstress can shorten the life of the light emitting diode. In this research, a methodology to investigate the degradation of the LED emitter has been proposed. The epoxy lens of the emitter can be modelled using simplified Eyring methods whereas an equation has been proposed for describing the degradation of the LED emitters.

Key words: LED; light; degradation; lumen; overstress current; temperature
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1. Introduction

Due to their long lifetime and high efficacy, light emitting diode (LED) has the potential to revolutionize the illumination industry such as head lamps for automotive application and street lighting. They are known to have an efficacy of 150 lm/W, as compared to only about 15 lm/W for a conventional 60–100 W incandescent light bulb[1, 2]. Furthermore, LED luminaries also claimed to have a life of more than 50000 h and this exceeds the life of nearly all the other light sources[3].

The long lifetime claimed by the manufacturers is often based solely on the estimated depreciation of lumen for a single LED operating at 25 ℃. However, LED luminaries seldom operated at this temperature but at a much harsher environment. For example, LEDs' temperature for automotive headlamp can go as high as 125 ℃. This will shorten the life of the LED emitter. In addition, most of the LED emitter in the markets transformed a high percentage of the input power, up to 80%, into heat. This will increase the junction temperature which also decreases the life of the LED emitter and the luminosity[4−6]. The study conducted by Narendran *et al.*[6] showed that even the degradation rate is highly dependent on the junction temperature of the LED emitter.

Meneghini *et al.*[7] evaluated the electrical and optical parameters' stability of the LEDs during DC and pulsed current stress. Figure 1 shows that the higher electrical overstress can significantly degrade the life of the LED. d in Fig. 1 is the duty cycle of the pulsed current.

In short, literature reviews of the factors influencing the life of LED lamps are identified as follows:

(1) Degradation of the epoxy lens and plastic package due to the junction temperature and voltages;

(2) Degradation of the LED emitter due to the junction temperature and input voltages;

(3) Failure of solder joint due to the temperature distribution and change in temperature (stress).

Since the scope of this research mainly focuses on the LED lamps, the solder joint failure will not be discussed in this paper. Hence, accordingly, the aim of this paper is to propose a methodology to investigate the degradation of the LED emitter which in turn can be sub-divided into the degradation of the epoxy lens and the degradation of the emitter. Only the theoretical calculation will be presented for the degradation of the emitter as we are still in the process of setting up the test set-up.

2. Degradation of the epoxy lens

Since the effect of the applied voltage and the junction temperature on the LED's life is independent for the degradation of the epoxy len, simplified Eyring models[8], as shown in Eq. (1), can be used to correlate the mean time to failure as a function

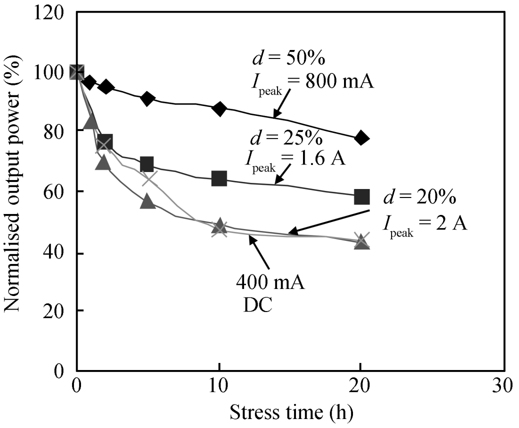

Fig. 1. Degradation of LED due to high electrical overstress[7].

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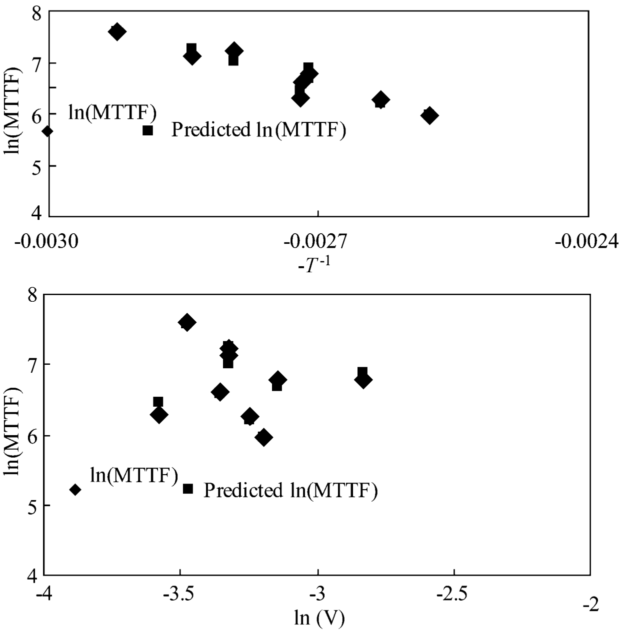

Fig. 2. Close agreement between our predicted times to failure with the experimental value from the literature.

of the junction temperature and the inputted voltage.

$$t = A\mathrm{e}^{\frac{q}{kT}} V^{c}. \tag{1}$$

In Eq. (1), t is the time to failure, q is the activation energy, V is the input voltage, and A and C are the fitting parameters.

Using the experimental data from Ref. [9] to obtain the L70 life for LED with operating under different junction temperatures and inputted voltages, the parameters for simplified Eyring model for degradation of the epoxy lens are found to be as follows:

$A = 0.004355, q = 0.45138$ eV/K, and $C = 0.66$.

Figure 2 shows the close agreement between the computed L70's life with the published result. The P-value from ANOVA analysis is found to be less than 5% so that we can reject the hypothesis of type I error.

Using the same procedure for L60 and L80 life, the relationship between the efficiency, n_{e}, (which is the ratio of luminosity at time t to the initial luminosity) and the fitting parameters A, q and C can be computed as shown in Fig. 3. Hence, the degradation of epoxy caps can be predicted using Fig. 3. P-value for all the cases are less than 5% signify the appropriateness of this model.

Figure 3 shows that the activation energy q remains constant at about 0.45 as the epoxy lens degraded indicating the same thermal activated failure mechanisms.

3. Degradation of the emitter

Since we are in the process of setting up the experimental set-up, only the theoretical calculation will be presented in this section. The experimental data will be published as soon as possible.

Since the LED emitter is basically a P–N junction, the intensity of the radiated light is proportional to the carriers' concentration. However, the carrier' concentration is dependent on

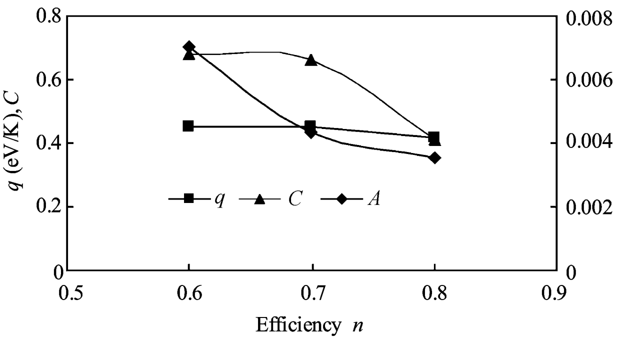

Fig. 3. Relationship of A, C and q with respect to the efficiency.

the current density, which is just the summation of the diffusion current, space charge combination current and the leakage current[10] as depicted in Eq. (2).

$$J_{\mathrm{T}} = J_{\mathrm{d}} + J_{\mathrm{SRC}} + J_{\mathrm{leakage}}. \tag{2}$$

In Eq. (2), J_{SRC} is the space charge current whereas J_{d} is the diffusion current forward current and they can be computed using Eqs. (3) and (4) respectively[10, 11]. J_{leakage} is the leakage current.

$$J_{\mathrm{SCR}} = J_{\mathrm{r}} \exp\left(\frac{e(V)}{2kT}\right), \tag{3}$$

$$J_{\mathrm{d}} = J_{\mathrm{s}} \exp\left(\frac{e(V)}{kT} - 1\right). \tag{4}$$

In Eqs. (3) and (4), k is the Boltzmann's constant and V is the applied voltage.

Since the saturation current density, J_{s} (in Eq. (4)) is a complex function of temperatures, there is a need to reduce them into more manageable forms. The saturation current density, J_{s} can be expressed by

$$J_{\mathrm{s}} = e\left[\sqrt{\frac{D_{\mathrm{n}}}{\tau_{\mathrm{n}}}}\left(\frac{n_{\mathrm{i}}^{2}}{N_{\mathrm{D}}}\right) + \sqrt{\frac{D_{\mathrm{p}}}{\tau_{\mathrm{p}}}}\left(\frac{n_{\mathrm{i}}^{2}}{N_{\mathrm{A}}}\right)\right], \tag{5}$$

where N_{D} and N_{A} are dopant concentrations. They can be assumed to be independent of junction temperature as they will be fully ionized for LED application. D is the diffusion constant, and n_{i} is the intrinsic carrier concentration which is given by

$$n_{\mathrm{i}} = \sqrt{N_{\mathrm{D}} N_{\mathrm{C}}} \exp\left(\frac{-E_{\mathrm{g}}}{2kT}\right), \tag{6}$$

where N_{c} and N_{v} is the effective densities of states at the conduction-band and valence–band and they had a $T^{3/2}$ as shown in Eq. (7).

$$N_{\mathrm{v}} = 2\left(\frac{2\pi m_{\mathrm{h}}^{*} kT}{h^{2}}\right)^{3/2},$$

$$N_{\mathrm{c}} = 2\left(\frac{2\pi m_{\mathrm{e}}^{*} kT}{h^{2}}\right)^{3/2}, \tag{7}$$

where m_{e}^{*} and m_{p}^{*} is the effective mass of electrons and holes respectively whereas h is the Plank's constant.

Since Debye's temperature for GaN is ~600 K[12] which is much lower than the operating temperature of the LED, the

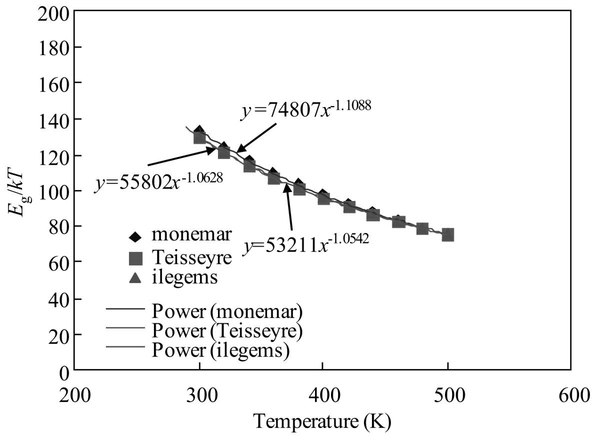

Fig. 4. Relationship between the activation energy and the temperature within the operating temperature of LED.

relationship between the activation energy E_g and the temperature T can be computed by the relationships found in Refs. [13–15].

Figure 4 shows the graphical representation of those equations with respect to the operating temperature range of the LED. For this temperature range, E_g can be approximated with the following equation with A as a fitting parameter:

$$E_g\ (\mathrm{eV}) \approx \frac{A}{T}. \tag{8}$$

Hence, combining Eqs. (6)-(8), the intrinsic concentration can be simplified to the following form:

$$n_i = CT^{3/2} \exp\frac{A}{T}. \tag{9}$$

Diffusion constant D in Eq. (5) can now be related to junction temperature as follows[10, 11].

$$D = \frac{kT}{e}\mu. \tag{10}$$

Since mobility μ (in Eq. (10)) for non-polar semiconductors is dominated by acoustic phonon interaction, it will have a temperature dependent of $T^{-3/2}$[16]. Equation (10) can be further simplified to the following equation.

$$D = dT^{-\frac{1}{2}}. \tag{11}$$

Combining Eqs. (2, 3, 5, 6, 9) and (11), we get:

$$J_T = J_r \exp\frac{e(V)}{2kT} + ET^{5/4}\exp\frac{B}{T}\exp\left(\frac{e(V)}{kT} - 1\right) + \frac{V}{R_r}. \tag{12}$$

B and E in Eq. (12) are fitting parameters that are independent of temperature and inputted voltages. Since applied voltage for HPLED is much greater than e/kT and the diffusion current is the dominant mechanism for HPLED, Equation (12) can be further simplified into the following relationship.

$$J_T = dT^{5/4}\exp\frac{E}{T}\exp\frac{e(V)}{kT} + \frac{V}{R_r}. \tag{13}$$

With Eq. (13), the efficiency of the LED emitters (Eq. (14)) can be computed by monitoring the changes of parameters E and B as time progresses (as outlined in the section of the degradation of the epoxy lens):

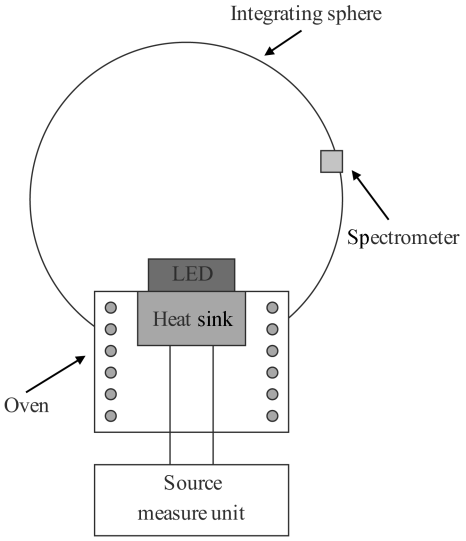

Fig. 5. Proposed experimental set-up.

$$\eta_o(t) = \frac{J_T(t)}{J_T(t=0)}. \tag{14}$$

$J_T(t)$ is the current density at time t. A candidate for characterizing B and E is as follows.

The total current can be computed by integrating Eq. (13) with respect to the area and this integration can also be represented in the frequency domain using laplace transformation,

$$\tilde{I}(s) = G_{iv}(s)\tilde{V}(s) + G_{ai}(s)\tilde{T}(s), \tag{15}$$

where $\tilde{I}(s)$, $\tilde{V}(s)$ and $\tilde{T}(s)$ is the current, inputted voltage and temperature in the frequency domain. Furthermore, the gains G_{iv} and G_{ai} can be represented as:

$$\begin{aligned} G_{iv}(s) &= \frac{\tilde{I}(s)}{\tilde{V}(s)}, \\ G_{ai}(s) &= \frac{\tilde{I}(s)}{\tilde{T}(s)} = \frac{k}{(s+p_1)^b(s+p_2)}. \end{aligned} \tag{16}$$

The gain $G_{iv}(s)$ can be characterized using the forward voltage method whereas $G_{ai}(s)$ can be characterized using spectrum analyzer and the experimental setup in Fig. 5.

4. Degradation of light emitting diodes

Using the information, the proposed methodology for predicting degradation of light emitting diodes is as follows:

(1) Subdividing the time to failure of LED into smaller time interval.

(2) Within each time-step:

(a) Computed the temperature distribution of the LED lighting system to extract the critical temperature for each component;

(b) Computed the degradation of each components ;

(c) Compute the light intensity $\phi(t)$ with respect to time: $\phi(t) = n_e(t)n_o(t)$;

(d) March the time step forward.

5. Conclusion

In conclusion, this research had proposed a methodology to investigate the degradation of the LED emitter. The epoxy lens of the emitter can be modelled using simplified Eyring methods whereas an equation has been proposed for describing the degradation of the LED emitters. The future work includes setting up the experiments to verify our calculation.

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