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Accelerated life test of white OLED based on lognormal distribution

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In order to acquire the life information of white organic light-emitting diode (WOLED), an accelerated life test (ALT) model was established with increased working current. The lognormal distribution was applied to describe the life distribution, while the least square method (LSM) was employed to estimate the logarithm mean value and the logarithm standard deviation. Statistics and analysis on constant stress and step stress test data were performed by using the self-developed software. The numerical results show that the WOLED life is consistent with lognormal distribution and the accelerated model meets the inverse power law. The key acceleration parameter, which was calculated accurately, enables a rapid estimation of WOLED life.

Keywords: White organic light emitting diode, Accelerated life test, Lognormal distribution, Least square method

1 Introduction

Organic light-emitting diode (OLED) is a display device, consisting of lithography electrode substrate and organic light-emitting materials, bringing about light phenomenon due to injection and compound of carriers[1,2]. Having advantages of high brightness, thinness, wide viewing angle, low power consumption, fast response and so on, OLED has been considered to be the next generation of flat panel display[3] after LCD. Now a days, the latest MP4 watch screens and MP3 touch screen are developed by using excellent features of OLED as shown in Fig. 1.

Since Tang and Slyke reported double OLED in 1987, a rapid progress on theoretical and experimental research of OLED have been made. However, the service life remains a key issue limiting the development of OLED due to the aging of the organic luminescence materials[4]. At present, the OLED life[5] reaches more than 10000 hours and OLED products might be updated before conventional life tests are terminated. As a result, the significance of the conventional life test may disappear. To address this issue, accelerated life test[6] is proposed in the present paper to predict OLED life in a relatively short period of time.

As far as reliability of OLED is concerned, Jiun-Haw Lee[7] studied the operation lifetime of OLED with different device structure. In this study, the organic materials were fixed while the thickness of the hole transport layer (HTL) and electron transport layer (ETL) was varied. The results indicated that device lifetime increased with increasing device efficiency, which indicated the electron-hole balance is one of the key issues to control the lifetime of OLED. Kapil *et al*[8]. carried out qualitative and quantitative analysis of the main factors that led to the failure of a-Si AMOLED display, and obtained the acceleration factor, which can reduce the testing time significantly. Xu *et al*[9]. investigated the degradation characteristics of sealed OLED devices at four different constant currents by using OLED aging tester. They found that OLED luminance degradation was not entirely Coulombic, and that there was a relationship between luminance and lifetime when the current density was smaller than 200 mA/cm^2. Chang-Jung Juan *et al*[10]. introduced an OLED life test system, which can test the life of 256 OLED panels in the meantime.

It is evident that the research of OLED reliability plays a crucial role in the development and renewal of the series OLED products. However, to obtain the life information accurately and rapidly has become a technical problem. In the present paper, three groups of constant-step stress tests were conducted. The lognormal distribution and LSM were employed to achieve the statistical analysis of ALT data, and author-designed software was used to accurately predict WOLED life.

Fig. 1 — OLED electronic products

2 ALT Program

All samples were divided into several groups for constant stress test and ALTs for each group samples were carried out at a constant stress level. Step stress test placed all samples at the lowest accelerated stress level, and then the samples without failure were put at a higher stress level when regulation time or specified number of failure samples was reached. The test would continue with the stress being increased gradually. Constant stress accelerated life test (CSALT) has the following advantages: simple test method, low demand for test equipment, highly successful rate and accurate test data. Further, step stress accelerated life test (SSALT) can shorten test time greatly. Therefore, we carried out two constant stress tests and a step stress test for WOLED ALT.

WOLED is a current-mode device, and current is the main factor that affects its life. So current is selected as the accelerated stress. In order to ensure the test accuracy and efficiency, there should be a larger interval between the maximum stress and the minimum one. Furthermore, the maximum stress should be not greater than the extreme stress that the structure material and fabrication technology can withstand. Additionally, it should not bring new failure mechanism. Therefore, the following four stress levels were selected: I_1=9.64 mA, I_2=12.36 mA, I_3=17.09 mA, I_4=22.58 mA. Two constant-stress tests (I_1 and I_3) and one step-stress test ($I_1 \rightarrow I_2 \rightarrow I_3 \rightarrow I_4$) were carried out. Finally, the normal working current of the test sample is I_0=3.20 mA.

2.1 Failure Criteria and Test Termination Time

The failure time for each test sample was recorded when WOLED brightness fell below 50% of its initial intensity. Test terminated as all the test samples failed at each current stress level.

3 ALT Theory Model

3.1 Basic Assumptions

Assumption 1: At each current stress I, WOLED life follows the lognormal distribution:

$$F(t) = \Phi(z) \int_{\infty}^{z} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{z^2}{2}\right) dz \qquad \ldots(1)$$

where $z = (\ln t - \mu)/\sigma$, μ is the logarithmic mean and σ is logarithmic standard deviation.

Assumption 2 : At normal work stress I_0 and the accelerated stress $I_i (i = 1,2,3,4)$, WOLED failure mechanism keeps unchanged. Namely, $\sigma_i (i = 1,2,3,4)$ at each stress should be the same. In general, the logarithmic standard deviation σ is the weighted average:

$$\sigma = \sum_{i=1}^{4} n_i \sigma_i \Big/ \sum_{i=1}^{4} n_i \qquad \ldots(2)$$

where n_i is the number of each group sample.

Assumption 3: For WOLED, the accelerating model conforms to the inverse power law, and hence the mean μ and current stress level I satisfy the following relation:

$$\mu = \alpha + \beta \ln I \qquad \ldots(3)$$

where α, β are estimated acceleration parameters.

Assumption 4 : In 1980, Nelson proposed the famous principle[11]. The remaining life of a sample is only related to the cumulative failure part and the stress level at that time, but has nothing to do with cumulative way. The cumulative distribution function (CDF) is $F_i(t_i)$ when the product is working for the time t_i at the stress I_i, and the CDF is $F_j(t_j)$ with the time t_j at the stress I_j. Then we have the following formula:

$$F_i(t_i) = F_j(t_j) \qquad \ldots(4)$$

3.2 Theory Model on CSALT

For lognormal distribution function, Eq. (1) is transformed to:

$$\Phi^{-1}(F(t)) = \frac{1}{\sigma}\ln t - \frac{\mu}{\sigma} \qquad \ldots(5)$$

let

$$x = \ln t,\ y = \Phi^{-1}(F(t)) \qquad \ldots(6)$$

$$a = 1/\sigma,\ b = -\mu/\sigma \qquad \ldots(7)$$

Then, Eq. (5) can be simplified to a linear relationship:

$$y = ax + b \qquad \ldots(8)$$

The failure time is arranged from the shortest to the longest, and then the CDF $F(t_j)$ with the time t_j can be calculated using following median rank formula:

$$F(t_j) = \frac{j-0.3}{n_i+0.4},\ j = 1,2,\ldots,n_i \qquad \ldots(9)$$

Now, we can get the following experimental data:

$$(t_j, F(t_j)),\ j = 1,2,\ldots,n_i \qquad \ldots(10)$$

The least square method is used to estimate the lognormal distribution parameters. According to Eq. (6), Eq. (10) can be converted into the linear model data:

$$(\ln t_j, \Phi^{-1}(F(t_j))) = (x_j, y_j) \qquad \ldots(11)$$

By using LSM for linear regression, the coefficient expressions[12] are:

$$a = \frac{\sum_{j=1}^{n_i} x_j y_j - (\sum_{j=1}^{n_i} x_j \sum_{j=1}^{n_i} y_j)/n_i}{\sum_{j=1}^{n_i} x_j^2 - (\sum_{j=1}^{n_i} x_j)^2/n_i} \qquad \ldots(12)$$

$$b = \sum_{j=1}^{n_i} y_j/n_i - a\sum_{j=1}^{n_i} x_j/n_i$$

One can get the mean μ and standard deviation σ by Eq. (7) as follows:

$$\sigma = 1/a \quad \mu = -b/a \qquad \ldots(13)$$

The determination coefficient of x_j and y_j is obtained as:

$$R^2 = \frac{(\sum_{j=1}^{n_i} x_j y_j - (\sum_{j=1}^{n_i} x_j \sum_{j=1}^{n_i} y_j)/n_i)^2}{(\sum_{j=1}^{n_i} x_j{}^2 - (\sum_{j=1}^{n_i} x_j)^2/n_i)(\sum_{j=1}^{n_i} y_j{}^2 - (\sum_{j=1}^{n_i} y_j)^2/n_i)} \qquad \ldots(14)$$

It is necessary to mention that x_j and y_j in Eqs. (12) and (14) are calculated using the failure time t_j and Eqs. (9)-(11). In addition, the closer R^2 is to 1, the higher the linear correlation degree of the two variables is.

3.3 Theory Model on SSALT

To perform statistical analysis on the step stress data, the failure time t_i at I_i should be converted into the failure time t_j at I_j. According to Eqs (1) and (4), we have:

$$\Phi((\ln t_i - \mu_i)/\sigma_i) = \Phi((\ln t_j - \mu_j)/\sigma_j) \qquad \ldots(15)$$

Using Assumption 2, we can obtain:

$$t_i = t_j \left(I_i / I_j \right)^{\beta} \qquad \ldots(16)$$

where β is the acceleration parameter in Eq. (3).

Denoting $\tau_{ji} = t_j / t_i$ as accelerated coefficient[13], Eq. (16) is rewritten as:

$$\tau_{ji} = \frac{t_j}{t_i} = \left(\frac{I_j}{I_i} \right)^{\beta} \qquad \ldots(17)$$

Letting j=0 in Eq. (17), one can get the expression of the accelerated coefficient, which is ($I_1 \rightarrow I_2 \rightarrow I_3 \rightarrow I_4$) relative to I_0.

$$\tau_i = \tau_{0i} = t_0 / t_i = \left(\frac{I_0}{I_i} \right)^{\beta} \qquad \ldots(18)$$

4 Test Data

For the M00071 white OLED mixed with red, green and blue colours as shown in Fig. 2, two CSALTs and one SSALT were carried out. In the tests, the accelerated effect was up to maximum and the failure mechanism remained unchanged. Failure times of CSALT samples at I_1=9.64 mA and I_3=17.09 mA are listed in Table 1.

For the step stress test, applied models for specific test stress ($I_1 \rightarrow I_2 \rightarrow I_3 \rightarrow I_4$) are shown in Fig. 3, and failure time for each step stress is given in Table 2.

5 Statistical Analysis of Test Data

5.1 Test Data Processing for CSALT

Combined Eqs. (6), (9) and (12)-(14), test data in Table 1 were processed using LSM, and results were summarized in Table 3. In addition, the straight fitting lines were plotted in Fig. 4.

5.2 Accelerated Life Equation

Substituting μ_1=7.7840, I_1=9.64 mA and μ_3=6.7445, I_3=17.09 mA into Eq. (3), respectively,

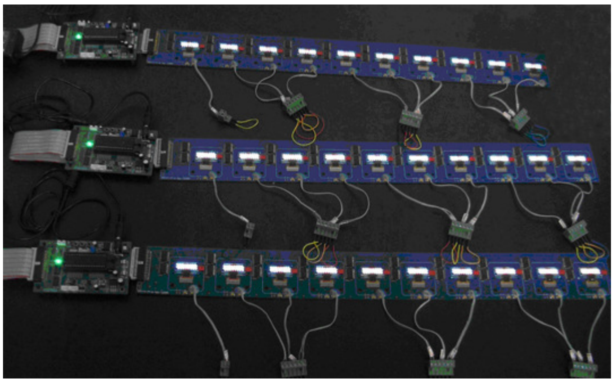


Fig. 2 — M00071 WOLED samples and control circuit board

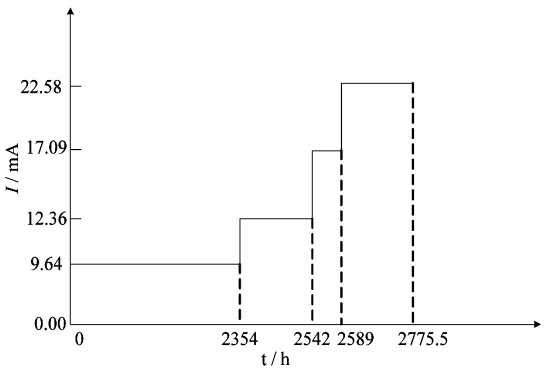


Fig. 3 — Applied stress models of step-stress tests

Table 2 — Sample failure time of step-stress tests

Sample	Failure time/ h			
	I_1	I_2	I_3	I_4
1	2330.5	—	—	—
2	—	2377.5	—	—
3	—	2518.5	—	—
4	—	—	2565.5	—
5	—	—	2589.0	—
6	—	—	—	2700.5
7	—	—	—	2740.5
8	—	—	—	2775.5

Table 3 — Lognormal distribution parameters under each stress

Stress	I_1	I_2	I_3	I_4
μ_i	7.7840	7.5119	6.7445	6.4179
σ_i	0.1913	0.1966	0.2762	0.1966
R_i^2	0.9093	0.9401	0.9490	0.9401

Table 1 — Sample failure time of constant-stress tests at I_1, I_3

Current stress/mA	Failure time /h									
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}
I_1=9.46 mA	1691.5	2084.7	2100.3	2374.5	2421.5	2586.0	2621.5	2680.5	2868.0	2879.5
I_3=19.09 mA	601.5	689.7	697.3	716.5	785.5	854.5	889.5	1115.7	1131.3	1251.5

one can obtain $\alpha = 11.8978$, $\beta = -1.8155$ by combined solutions. Now the accelerated life equation becomes:

$$\mu = 11.8978 - 1.8155 \ln I \quad \ldots(19)$$

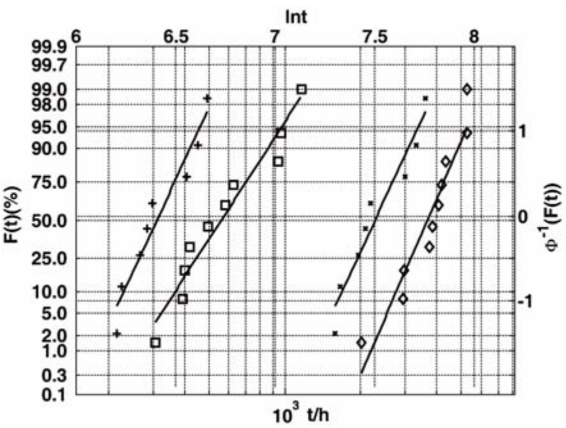
5.3 Test Data Processing for SSALT

For the purpose of statistics, the sample failure time of step stress test in Table 2 needs to be converted into the failure time at constant stress I_2, I_4. Firstly, the failure time of the samples at the step stress $I_i\,(i=1,2,3,4)$ was converted into the failure time at I_1.Then using Eq. (16) and Fig. 3, the following transition formula is obtained:

$$t_{I_1} = \begin{cases} t_i, & i=1 \\ t_1^* + \tau_{12}\left(t_i - t_1^*\right), & 2 \le i \le 3 \\ t_1^* + \tau_{12}\left(t_2^* - t_1^*\right) + \tau_{13}\left(t_i - t_2^*\right), & 4 \le i \le 5 \\ t_1^* + \tau_{12}\left(t_2^* - t_1^*\right) + \tau_{13}\left(t_3^* - t_2^*\right) + \tau_{14}\left(t_i - t_3^*\right) & 6 \le i \le 8 \end{cases} \quad \ldots(20)$$

where $\beta = -1.8154$, $t_1^* = 2354h$, $t_2^* = 2542h$, $t_3^* = 2589h$; t_i is the failure time at the step stress; τ_{12}, τ_{13}, τ_{14} are the acceleration coefficients being I_1 relative to I_2, I_3, I_4, respectively, and can be calculated using Eq. (17). Consequently, the sample failure time at the step stress is converted into the failure time at the constant stress I_2, I_4 by accelerated coefficient. The following equivalent formulas are obtained by using Eqs (17) and (20):

$$t_{I_2} = t_{I_1}/\tau_{12},\ t_{I_4} = t_{I_1}/\tau_{14} \quad \ldots(21)$$



◇, □ Constant I_1, I_3; ×, +Step conversion I_2, I_4; Data points; ——Fitting line

Fig. 4 — Statistical curves of constant-step stress data

Thus, failure time at $I_2 = 12.36$ mA and $I_4 = 22.58$ mA converted by samples of SSALT is listed in Table 4.

After applying the same processing procedures to the data in Table 4, lognormal distribution parameters at the stress I_2 and I_4 were obtained and presented in Table 3.

Fitting curves at $I_2 = 12.36$ mA and $I_4 = 22.58$ mA are also plotted in Fig. 4. It is seen in Fig. 4 that four lines keep basically parallel, which indicate that the failure mechanism remains unchanged at each current stress and confirms the basic assumption 2.

5.4 Correction of Accelerated Parameters

Combining Eq. (3) and the data in Table 3, obtained acceleration parameters using LSM are: $\alpha = 11.6820$ and $\beta = -1.7017$. The modified accelerated life equation is rewritten as:

$$\mu = 11.6820 - 1.7017 \ln I \quad \ldots(22)$$

Accelerated life curve is also known as life characteristics curve, as shown in Fig. 5. The determination coefficient R^2 is 0.9783 being very close to 1, which shows very high curve-fitting degree and demonstrates that the accelerated model is fully consistent with the inverse power law.

5.5 K-S Test

The Kolmogorov-Smirnov (K-S) theory[14] was employed to check whether or not WOLED life follows lognormal distribution. Considering the small

Table 4 — Failure time at I_2, I_4 converted by sample ones of step-stress tests

Stress/mA	Failure time/h							
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
I_2=12.36 mA	1484.17	1522.64	1663.64	1729.46	1771.78	2104.74	2224.19	2328.71
I_4=22.58 mA	497.01	509.89	557.11	579.15	593.32	704.82	744.82	779.82

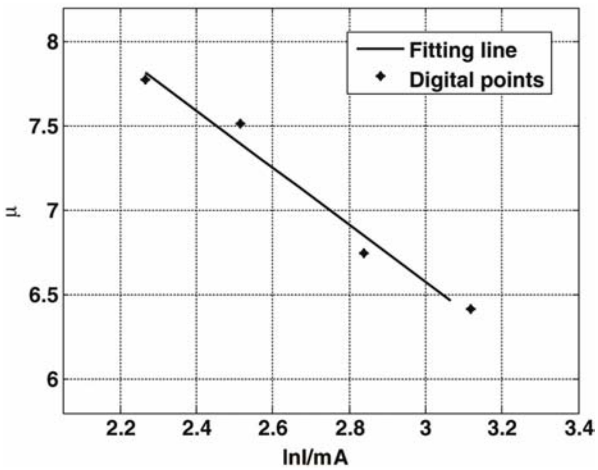


Fig. 5 — Curve of life characteristic pattern

number of test samples, a high significance[15] level (α= 0.2) was selected. The K-S test values at four accelerated stresses are calculated, respectively by the author-developed software. They are:

$$D_n^{1,3} = \{0.1761,\ 0.1382\} < D_{10,0.2} = 0.3226,$$

$$D_n^{2,4} = \{0.1899,\ 0.1899\} < D_{8,0.2} = 0.3583.$$

The results show that the failure time at each current stress level has passed K-S test successfully, which verifies that WOLED life follows lognormal distribution.

5.6 WOLED Life Prediction

When WOLED life distribution is described by lognormal function, the average life $\bar{\mu}_i$ and the median life $t_{0.5}^i$ at accelerate stress $I_i\left(i=1,2,3,4\right)$ can be calculated using the following formula:

$$\bar{\mu}_i = e^{\left(\mu_i + \frac{1}{2}\sigma^2\right)},\ \ t_{0.5}^i = e^{\mu_i} \qquad \ldots(23)$$

Combining Eqs (18) and (23), the average life $\bar{\mu}_0$ and the median life $t_{0.5}$ at I_0 is expressed as:

$$\bar{\mu}_0 = \tau_i \cdot \bar{\mu}_i,\ \ t_{0.5} = \tau_i \cdot t_{0.5}^i \qquad \ldots(24)$$

Accelerated coefficients at each stress were obtained by using Eq. (18) and they are: $\tau_1 = 6.5313$, $\tau_2 = 9.970$, $\tau_3 = 17.3045$, τ_4=27.7995. According to Eq. (2) and $\sigma_i (i=1,2,3,4)$ in Table 3, we get $\sigma = 0.2173$. Combined Eq. (23) and μ_i in Table 3, average life $\bar{\mu}_i (i=1,2,3,4)$ at each I_i were obtained as : $\bar{\mu}_1 = 2564.71\,h$, $\bar{\mu}_2 = 1680.17\,h$, $\bar{\mu}_3 = 968.01\,h$, $\bar{\mu}_4 = 602.56\,h$. Therefore, OLED life at I_0 was calculated using Eq. (24) and it is $\bar{\mu}_0 = \bar{\mu}_1 \cdot \tau_1 = \bar{\mu}_2 \cdot \tau_2 = \bar{\mu}_3 \cdot \tau_3 = 16750.97\,h$. In addition, median life $t_{0.5} = 16360.30\,h$ was found using the same method.

The present market survey indicates that the average life of this type of WOLED is about 16,000 hours. Different structures, materials and processes may lead to some differences in the lifetime. Therefore, the WOLED life obtained in this paper is reasonable and has a significant impact on the industry.

6 Conclusions

Constant-step stress ALTs of WOLED through increasing the current were conducted. Lognormal distribution function and LSM were employed to perform statistical analysis of the test data. The following main conclusions are drawn:

(1) WOLED life follows lognormal distribution, and its accelerated model confirms inverse power law.
(2) A software application was developed by authors to predict the average life and the median life, which makes complex data statistical analysis much easier.
(3) The accurate accelerated parameter enables a quick estimation of WOLED life, which not only saves test time and cost, but also provides manufacturers and customers of WOLED with some important guidelines.

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