1-1-2014

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10.1080/15980316.2014.889613

This is an Author's Accepted Manuscript of: Zhang J., Liu C., Cheng G., Chen X., Wu J., Zhu Q., Zhang L. (2014). Constant-stress accelerated life test of white organic light-emitting diode based on least square method under Weibull distribution. Journal of Information Display, 15(2), 71-75. Available here

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Constant Stress Accelerated Life Test of White OLED Based on Least Square Method under Weibull Distribution

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Currently, it is hard to estimate the reliability parameters of organic light emitting diode (OLED) when conducting life test at normal stress, due to the remarkably improved life of OLED to thousands hours. This work adopted three constant stress accelerated life tests (CSALT) to predict the life of white OLED in a short time. Weibull function was applied to describe the life distribution, and shape parameters and scale parameters were estimated by least square method (LSM). Experimental test data were statistically analyzed by using self-developed software. The life of white OLED predicted via this software is well agreement with those reported from customers. Numerical results indicated that the assumptions of CSALT are correct and the CSALT is feasible to predict the life of white OLED. Our work confirms that the life of white OLED meets Weibull distribution and that the accelerated life equation conforms to inverse power law. Furthermore, the precise accelerated parameters are shown to be particularly useful to enable a rapid estimation of the white OLED life.

Keywords: Accelerated life test; white OLED; least square method (LSM); Weibull distribution; constant stress

1. Introduction

In recent years, flat panel display (FPD) technology has made a great progress with the emerging of color mobile phone, flat panel television and computer. FPD includes liquid crystal display (LCD), plasma display panel (PDP), light emitting diode (LED), organic light emitting diode (OLED), and so on. Compared with other FPD technologies, OLED is an initiative lighting device which does not need backlight or environmental light. Owing to its advantages such as self-emitting, fast response time, wide viewing angle, good low temperature property and high luminance, OLED display technology is becoming a hotspot in the field of current display, which attracts considerable research attention [1-2].

Lifetime is one of the most important properties of OLED, which directly influence its business prospect [3]. During the past decade, the life property and reliability estimation methods for OLED have been significantly investigated by researchers worldwide. JANKOVIC et al. [4] proposed a simple active-matrix organic light-emitting diode (AMOLED) pixel with conventional voltage driving and ability to compensate for the V_{th} shift of thin-film transistors

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(TFTs), where a stable pixel operation was achieved by the employment of dual-gate TFT for OLED driving. CHANG et al. [5] put forward a white organic light-emitting diode (WOLED) with color filter embedding in a dual-plate OLED display (DOD) structure protected by SiN_x passivation film. Tests demonstrated that this structure significantly improved the life of white OLED. Compared the efficiency, heat resistivity and reliability of OLEDs with ITO and IZO as anode, PINATO et al. [6] considered the material selection of OLED anode and carried out accelerated life test. Results showed that OLED with IZO as anode has a higher reliability. SHI et al. [7] revealed the factor affecting the lifetime of OLED lighting module by researching on the relationship between the temperature distribution and photoelectric degradation characteristics.

With the innovation of the material design field, the reliability and the life of OLED have been improved remarkably. The life of most OLED display devices in massive commercial application has greater than 10 thousand hours. For such long lifetime, it is hard to estimate the reliability parameters of OLED when carrying out life test at normal stress, because the life test may last very long time but only few samples fail [8]. The main life test methods include accelerated degradation test (ADT) [9-11] and accelerated life test (ALT). ALT is a more commonly used method, which is employed to reduce test time by increasing test stress levels while keeping failure mechanism unchanged. ALT can be classified into several categories [12]: constant stress accelerated life test (CSALT), step stress accelerated life test (SSALT), and progressive stress accelerated life test (PSALT). Among these three categories of ALTs, CSALT is the most accurate and is also a better option if the amounts of the test samples and stresses are quite small. LIU et al. [13] presented a design approach for sequential constant-stress accelerated life test (CSALT) with an auxiliary acceleration factor (AAF), which can further amplify the failure probability of highly reliability testing items at low stress levels while maintaining an acceptable degree of extrapolation for reliability inference. LIU et al. [14] selected the accelerated mode and accelerated stress level in pneumatic solenoid valve ALT by analyzing the sensitive stress in three kinds of failure mechanisms such as wear, fatigue and aging, carried out the ALT, and concluded that the mechanical performance of the solenoid valve is more stable than its electrical performance.

In this study, CSALT was performed to obtain the failure time and cumulative failure probabilities of white OLED samples, and least square method (LSM) was used to fit curves at each stress level. Afterwards, Kolmogorov-Smimov tests were employed to testify whether OLED life follows Weibull distribution or not. OLED curve of life characteristic pattern can be obtained by LSM, and it can verify that the OLED life characteristic pattern meets the inverse power law. In addition, white OLED life information can be acquired.

2. OLED CSALT Plan

2.1. Selection of Accelerated Stress

OLED is a current-driving device, and current is the most important factor influencing OLED life [8]. Therefore, the current was selected as the accelerated stress of ALT in this work.

2.2. Levels and Numbers of Accelerated Stress

The levels and numbers of accelerated stress are two major factors. Both ensure that the test results scientifically reflect OLED life. The difference between the highest stress and the lowest stress should be enlarged under the accelerated stress condition in order to guarantee that both precision and efficiency of the tests. In order to avoid the present of a new failure mechanism, the highest stress should be lower than the ultimate level determined by the material structure and techniques of the product.

According to the principle of reliability, the minimum number of accelerated stress in life test should be no less than three. The M00071 white OLED mixed with red, green, and blue colors were used in this work. The three stress levels were selected as follows: I_1 = 9.64 mA, I_2 = 17.09 mA, I_3 = 22.58 mA. In addition, the normal working current of test samples is $I_0 = 3.20mA$.

2.3. Failure Criterion and Test End Time

The life of OLED device can be defined as the duration when the OLED luminance decreases to below 50% of initial luminance. According to the criterion, the failure time of each test sample was recorded. When all the samples at the three stress levels failed, the tests were terminated.

3. OLED CSALT Theory Model

3.1. Basic Assumptions

Assumption 1: For each stress level $I_i(i=0,1,2,3)$, white OLED life follows Weibull distribution, and the distribution function can be expressed as

$$F_i(t) = 1 - \exp[-(\frac{t}{h_i})^{m_i}], \quad t > 0 \qquad (1)$$

here m_i is the shape parameter which affects the geometric shape of the Weibull probability density curve; η_i is the scale parameter which directly determines the curve's smoothness.

Assumption 2: The OLED failure mechanism remains unchanged while the stress ranges from I_0 to I_3. Since the mechanism of white OLED is reflected by the shape parameter m of Weibull distribution, the shape parameter at each stress level I_i should be unchanged, which means

$$m_0 = m_1 = m_2 = m_3 \qquad (2)$$

Assumption 3: Inverse power law can be used to estimate the working life characteristics of electrical components. White OLED accelerated model satisfies the inverse power law. Namely, the relationship between scale parameter η and current stress level I is written as

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

Where α and β are accelerated parameters.

3.2. Estimation of Weibull Parameters

Equation (1) can be transformed as

$$\ln\ln[1-F_i(t)]^{-1} = m_i \ln t - m_i \ln\eta_i \qquad (4)$$

If

$$\begin{cases} y = \ln\ln[1-F_i(t)]^{-1} \quad x = \ln t \\ a = m_i \quad b = -m_i \ln\eta_i \end{cases} \qquad (5)$$

Equation (4) can be simplified as the linear relationship form

$$y = ax + b \qquad (6)$$

After the failure time $t_{k,i}$ at $I_i\,(i=1,2,3)$ is sequenced, the corresponding cumulative failure probability $F(t_{k,i})$ can be calculated by using the following median rank formula

$$F(t_{k,i}) = \frac{k-0.3}{n_i+0.4}, k = 1,2,\cdots,n_i \qquad (7)$$

where $n_1 = n_2 = 10$, $n_3 = 9$. Therefore, the test data can be written as

$$(t_{k,i}, F(t_{k,i})), k = 1,2,\cdots n_i \qquad (8)$$

According to Equation (5) and (8), one can obtain

$$(\ln t_{k,i}, \ln\ln[1-F(t_{k,i})]^{-1}) = (x_{k,i}, y_{k,i}) \qquad (9)$$

By applying LSM to Equation (9), the coefficients a_i and b_i $(i = 1, 2, 3)$ can be expressed as

$$\begin{cases} a_i = \dfrac{\sum_{k=1}^{n_i} x_{k,i} y_{k,i} - (\sum_{k=1}^{n_i} x_{k,i} \sum_{k=1}^{n_i} y_{k,i}) / n_i}{\sum_{k=1}^{n_i} x_{k,i}{}^2 - (\sum_{k=1}^{n_i} x_{k,i})^2 / n_i} \\ b_i = \sum_{k=1}^{n_i} y_{k,i} / n_i - a_i \sum_{k=1}^{n_i} x_{k,i} / n_i \end{cases} \quad (10)$$

Combined Equation (5) with (10), the shape parameter m_i and the scale parameter η_i at I_i are respectively expressed as

$$m_i = a_i, \quad \eta_i = \exp(-b_i / a_i) \quad (11)$$

The determination coefficients of $x_{k,i}$ and $y_{k,i}$ are written as

$$R_i^2 = \frac{[\sum_{k=1}^{n_i} x_{k,i} y_{k,i} - (\sum_{k=1}^{n_i} x_{k,i} \cdot \sum_{k=1}^{n_i} y_{k,i}) / n_i]^2}{[\sum_{k=1}^{n_i} x_{k,i}{}^2 - (\sum_{k=1}^{n_i} x_{k,i})^2 / n_i][\sum_{k=1}^{n_i} y_{k,i}{}^2 - (\sum_{k=1}^{n_i} y_{k,i})^2 / n_i]} \quad (12)$$

3.3. Life Estimation

If OLED life conforms to Weibull distribution, the calculation formula of OLED average life μ and median life $t_{0.5}$ are respectively expressed as

$$\mu = \eta_0 \Gamma(1 + \frac{1}{m}), \quad t_{0.5} = \eta_0 (\ln \frac{1}{0.5})^{\frac{1}{m}} \quad (13)$$

where $\Gamma(\cdot)$ is gamma function; η_0 is the scale parameter estimated at I_0.

According to Assumption 2 (Section 3.1), the shape parameter m is obtained as the weighted average of m_i, that is

$$m = \sum_{i=1}^{3} n_i m_i / \sum_{i=1}^{3} n_i \quad (14)$$

4. Test Data

For the M00071 white OLED mixed with red, green and blue colors, OLED CSALTs were carried out according to the accelerated test theory and plan. The failure time data of all white OLED samples at I_i $(i = 1, 2, 3)$ are listed in Table 1.

Table 1. The failure time of the tested sample under constant-stress at different currents.

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}
$I_1 = 9.64$	1691.50	2084.67	2100.32	2374.50	2421.50	2586.00	2621.50	2680.50	2868.00	2879.50
$I_2 = 17.09$	601.50	689.67	697.33	716.50	785.50	854.50	889.50	1115.67	1131.33	1251.50
$I_3 = 22.58$	406.00	440.50	463.50	532.50	555.50	643.67	651.33	716.50	762.50	—

5. OLED Life Prediction

Due to the calculation complexity in aspect of life estimation, a white OLED life test software developed by the authors was used to process and analyze the test data. The software has a series of advantages such as simplicity, speedy, accuracy and generality.

5.1. Data Processing for CSALT

The constant-stress test data listed in Table 1 are processed by self-developed software, and the statistics curves fitted by LSM are plotted in Figure 1. The shape parameter m_i, scale parameter η_i, and the determination coefficient

R_i^2 of fitting curve at each current stress level can be obtained by the Equations (10)-(12). These results are presented in Table 2. It is found that R_i^2 calculated at each current stress $I_i (i = 1, 2, 3)$ approaches to 1, which demonstrates that the degree of linear fitting is high.

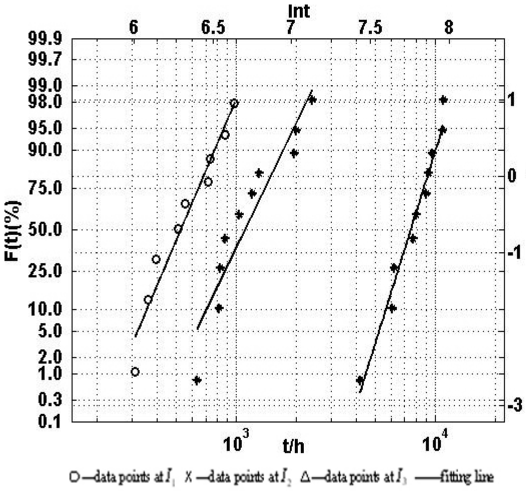

Figure 1. Statistical curves of constant-stress data

Table 2. m_i, η_i and R_i^2 at different current stress levels

Current Stress/*mA*	I_1 = 9.64	I_2 = 17.09	I_3 = 22.58
m_i	6.5764	4.2754	4.8350
η_i	2600.7568	959.9457	625.9725
R_i^2	0.9690	0.8909	0.9518

5.2. Kolmogorov-Smirnov Test

According to K-S theory [15], greater significance level (a = 0.2) was selected due to limited samples. K-S test was employed to verify whether the OLED life follows Weibull distribution at each current stress level $I_i (i = 1, 2, 3)$ or not. The values of the K-S test at three accelerated stresses are calculated by the self-developed software as follows: $a_1 = 0.142 < D_{0.2,10} = 0.323$, $a_2 = 0.186 < D_{0.2,10} = 0.323$, $a_3 = 0.126 < D_{0.2,9} = 0.339$.

Hence, it is verified that the K-S tests at each stress $I_i (i = 1, 2, 3)$ pass.

5.3. Accelerated life equation

Data points $(\ln I_i, \ln \eta_i)$ $(i = 1, 2, 3)$ can be plotted and fitted into a linear curve by LSM, as shown in Figure 2. The accelerated parameters obtained by LSM are $\alpha = -1.6834$, $\beta = 11.6699$. As such, the accelerated life equation is expressed as

$$\ln \eta = -1.6834 \ln I + 11.6699 \qquad (15)$$

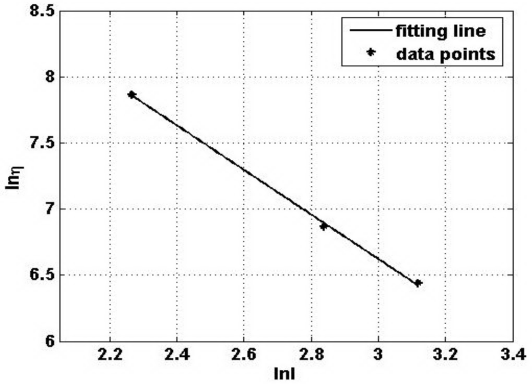

Figure 2. Curve of OLED life characteristic pattern

The determination coefficient R^2 in Figure 2 is 0.9991 that is very close to 1, which shows that the degree of linear fitting is high. The result also confirms that the accelerated model fully obeys the inverse power law.

5.4. OLED Life Prediction at the Normal Working Stress

After substituting $I_0 = 3.2mA$ into Equation (15), OLED scale parameter at normal working stress can be obtained as: $\eta_0 = 16511.9541\text{h}$. Combining $m_i (i = 1, 2, 3)$ in Table 2 with Equation (14), one can get OLED shape parameter at normal working stress $m_0 = 5.2425$. Therefore, according to Equation (13), the average life μ and the median life $t_{0.5}$ of white OLED can be calculated as follows: μ =15202.2h, $t_{0.5} = 15397\text{h}$.

The market performance demonstrates that the life of white OLED, which was selected as samples in the accelerated test, is about 16 thousand hours. Therefore, white OLED life estimated by constant stress accelerated life tests (CSALT) in this work is very close to the client feedback data with the difference in structure, material and techniques between OLED samples and products excluded.

6. Conclusions

From three CSALTs and statistical analysis for OLED, the following main conclusions can be drawn.

1) The results of test statistic analysis verify that white OLED life satisfies Weibull distribution and the accelerated life model follows inverse power law.

2) The self-developed software could be used to simplify statistical analysis of OLED accelerated life test and predict white OLED life precisely.

3) The acquired life information can provide engineers with important guidelines to improve reliability and quality of OLED products.

Acknowledgment

This study was financially sponsored by the Program of Shanghai Subject Chief Scientist (B type) (13XD1425200); the Foundation of Shanghai Committee of Science and Technology, China (11160500600, 11dz2281700, 09DJ1400204); the Innovation Program of Shanghai Municipal Education Commission (14ZZ154, 13ZZ130); the Key Fund of Shanghai Science Technology Committee (13160501000); the National Natural Science Foundation of China (50706025, 51201097).

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