Solid-State Electronics 75 (2012) 102–106

Contents lists available at SciVerse ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

# Life prediction for white OLED based on LSM under lognormal distribution

Jianping Zhang [a,*], Fang Liu [a], Yu Liu [b,c], Helen Wu [c], Wenqing Zhu [d], Wenli Wu [a], Liang Wu [a]

[a] School of Thermal Power and Environmental Engineering, Shanghai University of Electric Power, Shanghai 200090, China
[b] Chinese Academy of Sciences, Shanghai Institute of Ceramics, Shanghai 200050, China
[c] School of Engineering, University of Western Sydney, Penrith, NSW 2751, Australia
[d] Key Laboratory of Advanced Display and System Applications of EMC, Shanghai University, Shanghai 200072, China

ARTICLE INFO

*Article history:*
Received 20 May 2011
Received in revised form 31 October 2011
Accepted 4 December 2011
Available online 18 May 2012

The review of this paper was arranged by Y. Kuk

*Keywords:*
Life prediction
White OLED
Accelerated life test
Lognormal distribution
LSM

ABSTRACT

In order to acquire the reliability information of White Organic Light Emitting Display (OLED), three groups of OLED constant stress accelerated life tests (CSALTs) were carried out to obtain failure data of samples. Lognormal distribution function was applied to describe OLED life distribution, and the accelerated life equation was determined by Least square method (LSM). The Kolmogorov–Smirnov test was performed to verify whether the white OLED life meets lognormal distribution or not. Author-developed software was employed to predict the average life and the median life. The numerical results indicate that the white OLED life submits to lognormal distribution, and that the accelerated life equation meets inverse power law completely. The estimated life information of the white OLED provides manufacturers and customers with important guidelines.

Published by Elsevier Ltd.

## 1. Introduction

With the continuous development and maturity in luminescent material and device technology, Organic Light Display (OLED) has shown high efficiency and brightness, wide viewing angle, low power consumption, self-luminous, low driving voltage, fast response time and full-color. It has received extensive attention from the international communities, in particular from industry and academic circle, and has got into the various display fields gradually [1]. At present, OLED is widely used in many applications, such as television, MP3 players, mobile phones, automotive display [2]. The double-light-emitting devices (OLEDs) were reported in 1987, a considerable progress on the OLED research, whether theoretically or experimentally, has been achieved. However, OLED working stability and lifetime prediction still remains an issue.

For the input market of the organic EL devices (OLEDs), service life and storage life under continuous operation condition are required to exceed 10,000 h and 5 years, respectively. For the time being, the green organic EL device has reached the practical requirements at the constant current and initial brightness of 100 cd/m$^2$ [3]. In July 2006, Konica Minolta technology center successfully developed the white OLED device, whose brightness half-life was about 10,000 h at the initial brightness of 1000 cd/m$^2$ with the luminous efficiency being 64 lm/W. Further, a brightness half-life of 16,000 h was realized at the initial brightness of 300 cd/m$^2$ [4]. The half-life of the light-emitting device in green, yellow and blue also surpassed 80,000, 30,000 and 8000 h, respectively [5]. In 2007 SID exhibition, Japan developed a white light device, whose efficiency reached 16.8 lm/W, and life exceeded 40,000 h [4]. In the same year, Seiko Epson Company released the latest research achievement—"the ultimate black" OLED display system. They solved the problem of plaguing OLED life all along, and extended the product life to over 50,000 h successfully [6]. In lighting area, the life of white OLED at the initial luminance 1000 cd/m$^2$ was more than 10,000 h, and OLED decoration lighting products have been launched in recent years [7].

From passive to active, OLED products have dominated certain markets after 30 years' development. However, they have to be improved further in order to compete with LCD all over the large, medium and small size display fields. Relatively short life of the OLED remains one of the biggest technical challenges. As OLED technology continues to progress, the general life test under normal working conditions needs more than 1 year, which has become a heavy burden of enterprises in terms of time and cost. Moreover, when the test results come out, products might have been updated already,

* Corresponding author at: School of Thermal Power and Environmental Engineering, Shanghai University of Electric Power, Shanghai 200090, China. Tel.: +86 21 35303752.
*E-mail address:* jpzhanglzu@163.com (J. Zhang).

0038-1101/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.sse.2011.12.004

and hence the significance of the test disappears. As we know, life is an important index of device performance, and product life span is the key factor deciding whether a product can survive on the market. Therefore, in order to estimate the OLED life accurately and quickly, accelerated life test (ALT) is needed urgently. A series of automatic measurement systems were designed and built to measure the OLED current density–voltage-brightness and attenuation curve (the brightness attenuation with time) [8,9]. The factors affecting the primary failure mechanism were defined and characterized, and a general method for accelerated stress testing of TFT pixel circuits was developed, but the application of the method was limited to some certain device types [10].

Currently, the most widely used ALT is constant stress accelerated life test (CSALT), which has been also adopted by IEC (International Electrotechnical Commission) standard. CSALT shows many merits: mature theory, simple test procedures and accurate test data [11,12]. In view of these advantages, we carried out the accelerated life test of constant stress on the M00071 type OLEDs manufactured by Visionox Company. The test data statistics and analysis were achieved by using logarithmic normal distribution function and LSM. Rapidly and accurately predicted OLED life provides users and manufacturers with the key reference.

## 2. Test plan

The OLED life is briefly affected by two common kinds of accelerated stresses: current and temperature [13]. As current can be changed and controlled easily, it is selected as accelerated stress to study the light attenuation of high-power white OLED in this paper [14].

### 2.1. Accelerated stress level and stress number

In order to ensure high test accuracy, the stress interval between the maximum stress and the minimum stress should be large. Further, the maximum stress should not be larger than the limit stress that the product can bear, so as not to bring new failure mechanisms. According to reliability theory, the number of accelerated stress levels should not be less than 3; the number of samples under each stress should not be less than 10; the number of special product should not be less than 5. Therefore, we selected three stress levels [15], namely, $I_1$ = 9.64 mA, $I_2$ = 17.09 mA, $I_3$ = 22.58 mA. In addition, the current in the test samples during the normal working hours is $I_0$ = 3.20 mA.

### 2.2. Failure standard and termination time

Time-to-failure of each test sample was recorded based on the failure criteria of OLED (test brightness is less than 50% of the initial intensity) [14,16]. The test was terminated when all the test samples at each current stress level failed.

## 3. Mathematical model of CSALT

### 3.1. Basic assumption

**Assumption 1.** At the current stress $I$, the white OLED life satisfies lognormal distribution and the distribution function is expressed as follows:

$$F(t) = \Phi(z) = \int_{\infty}^{z} \frac{1}{\sqrt{2\pi}} \exp\left[\frac{z^2}{2}\right] dz \tag{1}$$

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

**Assumption 2.** At the normal working stress $I_0$ and each accelerate stress $I_i$ ($i$ = 1,2,3), the failure mechanism of white OLED remains unchanged. If the estimated values of logarithmic standard deviation at each stress level are $\sigma_1$, $\sigma_2$, $\sigma_3$, respectively, the logarithmic standard deviation $\sigma$ is the weighted average

$$\sigma = \frac{\sum_{i=1}^{3} n_i \sigma_i}{\sum_{i=1}^{3} n_i} \tag{2}$$

where $n_i$ is the total number of the samples at each stress $I_i$ ($i$ = 1,2,3), and $n_1 = n_2$ = 10, $n_3$ = 9 are used in this study.

**Assumption 3.** For white OLED, the accelerated life equation conforms to inverse power law completely, that is to say, the logarithmic mean value and the current stress level meet the following equation:

$$\mu = \alpha + \beta \ln I \tag{3}$$

where $\alpha$ and $\beta$ are the unknown acceleration parameters to be determined.

**Assumption 4.** In 1980, the famous theory was put forward [17]: The remaining life of a sample is only determined by the accumulated failure parts and the stress level just at that time, but is not related to the cumulative way. Therefore, the failure probability is $F_i\,(t_i)$ when the product is working for time $t_i$ at the stress $I_i$. Correspondingly, the failure probability is $F_j\,(t_j)$ with time $t_j$ at the stress $I_j$. Then we have

$$F_i(t_i) = F_j(t_j) \tag{4}$$

### 3.2. Least square method

Making the transformation of the distribution function (1), one gets

$$\Phi^{-1}[F(t)] = \frac{1}{\sigma} \ln t - \frac{\mu}{\sigma} \tag{5}$$

Let

$$x = \ln t, y = \Phi^{-1}[F(t)] \tag{6}$$

$$a = \frac{1}{\sigma}, \quad b = -\frac{\mu}{\sigma} \tag{7}$$

Linear equation is rewritten as

$$y = ax + b \tag{8}$$

After sorting the failure times from small to large numbers, the following median rank formulae is used to calculate the cumulative failure probability $F(t_k)$ at each failure time $t_k$

$$F(t_k) = \frac{k - 0.3}{n_i + 0.4}, k = 1, 2, \ldots, n_i \tag{9}$$

Thus, a group of experimental data can be obtained

$$(t_k, F(t_k)), k = 1, 2, \ldots, n_i \tag{10}$$

Least square method (LSM) is employed to estimate the parameters of lognormal distribution. Based on Eq. (6), the test data (10) are transformed into the following form

$$(\ln t_k, \Phi^{-1}F[t_k]) = (x_k, y_k) \tag{11}$$

For lognormal distribution linear model using LSM regressing line, the coefficient expressions are