Accelerated Life Test Technology Based on Unilateral Confidence Estimation

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Abstract. The test principle, test type and test model of accelerated life test, as well as the data processing method of unilateral confidence estimation are introduced. Taking the enhanced field effect transistor as an example, a reasonable accelerated life test scheme is formulated by selecting the appropriate accelerated test model and stress conditions. After the test, the life characteristic value of the device under normal stress level is calculated according to Arrhenius equation and unilateral confidence estimation method. Through research, an accelerated life test method for processing non failure data is provided.

1. Introduction

With the rapid development of science and technology, the complexity of electronic system is higher and higher, and its use environment is more and more diversified. As an important part of the electronic system, the failure of any component will have a serious impact on the operation of the whole system. Therefore, it is required to continuously improve the quality and reliability of components. In practical engineering applications, it often takes a long time to predict the reliability level of highly reliable products by using normal life test. Too long test cycle will affect the development and use of products. In terms of reliability test, new methods that can shorten the test time and quickly evaluate the reliability level of products must be studied, so as to meet the demand of model development for the continuous improvement of product life and reliability [1].

The accelerated life test method developed from the traditional test method can quickly predict the life and reliability of products under normal working conditions by increasing the stress to make the test samples fail in a short time. As one of the most important research contents in the field of reliability test, accelerated life test technology can quickly evaluate the reliability level of products with high reliability and long life requirements, and finally determine the ultimate tolerance of products. It has been widely used in aerospace, aviation, weapon electronics and other fields [2-4].

In the accelerated life test, the test method of fixed number censoring or fixed time censoring is often used. When the test time is strictly limited, the products are often subjected to fixed time censoring test. However, with the progress of science and technology, high reliability products have developed rapidly. The data obtained in the fixed time censoring test is sometimes no failure data, that is, there is no sample failure within the specified test time. At present, there are mature methods for data analysis of accelerated life test with failure data. Therefore, it is necessary to further study the accelerated life test without failure data. This paper studies the accelerated life test method without failure data based on unilateral confidence estimation.
2. Test method

2.1. Principle of accelerated test
On the basis of reasonable engineering and statistical assumptions, the accelerated life test is a test method to convert the reliability information obtained in the accelerated environment beyond the normal stress level by using the statistical model related to the physical failure law, and obtain the reproducible numerical estimation of the reliability characteristics of the specimen under the rated stress level [5]. The accelerated life test shall meet the following three principles: ① consistency of failure mechanism; ② regularity of failure process; ③ identity of failure distribution [6-8].

Accelerated life test is to accelerate the failure of the tested product by increasing the stress and strengthening the test conditions without changing the product failure mechanism, so as to obtain the necessary information in a short time to evaluate the reliability or life index of the product under normal conditions.

In the accelerated life test, the ideal failure should have a regular process with the increase of stress level, that is, the characteristics of the tested product under short time high stress are consistent with those of the product under long time low stress [9].

Product life is a random variable, and its regularity can be described by life distribution function. Given the life distribution, the relevant reliability parameters can be obtained. In reliability engineering, life distribution includes exponential distribution, normal distribution, lognormal distribution and Weibull distribution. Accelerated life test can be carried out only when the life distribution under accelerated conditions is consistent with that under normal conditions.

2.2. Types of accelerated test
According to the different ways of stress application, accelerated life test can be divided into three basic test types: constant stress test, step stress test and progressive stress test. Take a certain number of samples and divide them into several groups, apply a fixed stress greater than the rated value to each group, and stop when the specified failure number or specified failure time occurs, which is called constant stress accelerated life test (as shown in Figure 1(a)); the test that the stress increases with time is called step stress accelerated life test (as shown in Figure 1(b)); the test with increasing stress over time is called progressive stress accelerated life test (as shown in Figure 1(c)).

Among the above three types of accelerated life tests, the most widely used accelerated life test is the constant stress accelerated life test. The theory of constant stress accelerated life test has been very mature and has been adopted by IEC 62506-2013 standard. The failure factor caused by the constant stress accelerated life test method is relatively single and the accuracy is high, so this paper adopts the constant stress to carry out the accelerated life test.

2.3. Accelerated test model
The key of accelerated life test is to establish the relationship between life characteristics and stress level, which is commonly referred to as accelerated model, also known as accelerated equation. When
selecting the model, the key criterion is that the selected model can accurately simulate the life under accelerated conditions into that under normal service conditions. The most commonly used acceleration models include Arrhenius model, inverse power law model and generalized Erin model. Arrhenius model is widely used to predict the life of electronic products.

When studying temperature excited chemical processes in 1880, Arrhenius found that the reaction rate was inversely proportional to the index of activation energy and inversely proportional to the index of the reciprocal of temperature. Based on a large amount of data, the famous Arrhenius acceleration model is proposed, namely:

$$\xi = Ae^{Ea/kT}$$

(1)

Where:
- $\xi$ is a life characteristic (such as median life, average life, etc.),
- $A$ is acceleration factor,
- $E_a$ represents activation energy of failure mechanism,
- $k$ represents Boltzmann constant, and
- $T$ is absolute temperature.

The faster the reaction rate, the faster the degradation rate and the shorter the lifetime. Taking logarithms on both sides of equation (1) can deform the Arrhenius model into a linearized $(1/T)$ form:

$$\ln\xi = a + b/T$$

(2)

Where: $a = \ln A$, $b = E_a/k$.

2.4. Unilateral confidence estimation

The processing of accelerated life test data is the key to component life evaluation. According to the method specified in GB 5080.4-85 for reliability accelerated test interval estimation, the average failure rate and life of components under accelerated test conditions can be estimated by using exponential distribution function [10]. For exponential distribution, the confidence limit specifies the confidence interval around the estimated value, which contains the true value of the estimated parameter with a determined probability (that is, the confidence level). The confidence interval can be unilateral or bilateral. For the unilateral confidence interval, the lower or upper confidence limit is given. For bilateral confidence intervals, both lower and upper limits should be given. For the fixed time test, the confidence limit expression of the failure rate with a confidence level of 90% is as follows:

Unilateral confidence interval, upper limit:

$$\lambda < \frac{x^2_{0.95}(2r+2)}{2T^*}$$

(3)

Bilateral confidence interval:

$$\frac{x^2_{0.05}(2r)}{2T^*} < \lambda < \frac{x^2_{0.95}(2r+2)}{2T^*}$$

(4)

Where: $\lambda$ is the failure rate, $x^2_p(v)$ represents the theoretical value of $p$ quantile of $x^2$ distribution with degree of freedom $v$, $r$ is the total number of relevant failures in the measurement test, and $T^*$ is the accumulated relevant test time to the specified deadline.

If no failure is observed, only the upper limit of unilateral confidence interval can be determined. For the accelerated life test without failure data, unilateral confidence estimation can be used for data processing.

3. Case analysis

Using the accelerated life test method, the failure rate and average life of a certain type of enhanced field effect transistor at an application temperature of 110°C are predicted, with a confidence level of 90%.
3.1. Formulation of test scheme

3.1.1. Stress selection. The selection of stress has a great impact on the acceleration efficiency of the test. Generally, the acceleration stress should be selected according to the failure mechanism and failure mode of the product. The stress usually referred to in accelerated life test mainly includes mechanical stress, thermal stress and electrical stress. The accelerated stress selected in the accelerated life test requires to accelerate product failure, but at the same time, it cannot change the failure mechanism. Once the failure mode is changed, the basis of accelerated life test will be lost. For field effect transistors, temperature stress and electrical stress are the main stresses causing failure, but the acceleration effect of electrical stress is not obvious. Therefore, temperature is taken as the main stress in this paper.

For constant stress accelerated life test, the test samples need to be divided into several groups, and each group of products shall be subject to life test under a certain constant stress level. Considering the test effect and input cost, three stress levels are selected in this paper. The specific conditions are shown in table 1.

| Test channel temperature | Electrical bias |
|--------------------------|-----------------|
| $T_{ch1}=245^\circ C$   | $V_{DS}=5V$, $I_{DS}=0.08A$ |
| $T_{ch1}=260^\circ C$   | $V_{DS}=5V$, $I_{DS}=0.08A$ |
| $T_{ch1}=275^\circ C$   | $V_{DS}=5V$, $I_{DS}=0.08A$ |

3.1.2. Sample selection. Due to the high cost of some electronic components, it is impossible to carry out accelerated life test on all components. Therefore, only through the reliability analysis, the electronic components which have low reliability index and cannot meet the application life can be found out for analysis and test. Under each stress level, the number of test samples can be equal or unequal. But generally, the number of samples under each stress level should not be less than 5. In this paper, the number of samples selected for each stress level is 6.

3.1.3. Determination of test time. In terms of improving the accuracy of life evaluation, it is best to end the accelerated life test only when all samples fail, which requires that the number of samples should be sufficient and the test time should be long enough. But in fact, it is generally difficult to meet these two requirements. Therefore, at present, the censoring method is usually used in accelerated life test. Compared with the fixed number censoring method, the fixed time censoring method has the advantages of simple operation and controllable time. Therefore, the fixed time censoring method is selected in this paper, and the test time is 1,000h.

3.1.4. Determination of test parameters and test time. During the test, as many parameters as possible should be measured. But considering the test cost, the parameters sensitive to the failure mechanism should be selected as the key test parameters. The test parameter selected in this paper is the saturated leakage current.

The test cycle shall be selected according to the life characteristics of the sample. If the parameters change greatly in the early stage of the test, the test cycle in the early stage of the test shall be as short as possible. The test was carried out at 48±8h, 168±24h, 336±24h, 504±24h and 1000±24h respectively in this paper.

3.1.5. Determination of failure criterion and data processing scheme. The failure criterion is the premise of judging whether a sample fails or not. It is used to determine the failure time and carry out statistical analysis of life characteristics. Generally, the change rate of easy drift parameters is selected, or fatal failure is selected as the failure criterion of the sample. The failure criterion selected in this paper is the change rate of saturated leakage current $\Delta I_{DSS}/I_{DSS0}$≥20%.
After the accelerated life test, failure analysis shall be carried out in case of device failure; if there is no device failure, the failure rate and life characteristics can be estimated according to the unilateral confidence estimation method.

3.2. Platform temperature calculation

The temperature of the test platform is determined by the channel thermal resistance at high temperature and the channel temperature at high temperature. The formula is as follows:

$$T_c = T_{ch} - R_{th} \times P \quad (5)$$

Where:
- $T_c$ is the test platform temperature,
- $T_{ch}$ is the channel temperature at high temperature,
- $R_{th}$ is the channel thermal resistance at high temperature, and
- $P$ is the DC power consumption.

Because the thermal conductivity of GaAs material decreases with the increase of temperature and is limited by the upper limit of heating platform temperature, the channel thermal resistance $R_{th}$ of the device cannot be measured directly at high temperature. Therefore, Fujitsu’s modified formula (6) is used to extrapolate the channel thermal resistance at high temperature, and then the heating platform temperature is calculated from formula (5).

$$R_{th} = (T_{ch}/T_{cho}) \times R_{tho} \quad (6)$$

Where $T_{cho}$ is the channel temperature at the test temperature and $R_{tho}$ is the channel thermal resistance at the test temperature.

When $T_{cho} = 115^\circ C$, $R_{tho} = 90^\circ C/W$, the DC power consumption $P$ of the test sample under different test channel temperatures is 0.4W. According to formula (5) and formula (6), the test platform temperatures corresponding to $T_{ch1} = 245^\circ C$, $T_{ch2} = 260^\circ C$ and $T_{ch3} = 275^\circ C$ are $T_{c1} = 197^\circ C$, $T_{c2} = 210.5^\circ C$ and $T_{c3} = 224^\circ C$.

3.3. Test results

The total time of accelerated life test is 1,000h. The changes of key parameter saturated leakage current $I_{DSS}$ are shown in figure 2 - figure 4, in which the change rate of $I_{DSS}$ is obtained by comparing with the initial value.

![Figure 2. Parameter changes of $T_{ch1}$ test conditions](image-url)
3.4. Life analysis

From the results of accelerated life test, only one sample fails at 275°C in the three test temperatures of 245°C, 260°C and 275°C, which can be considered as early failure and is not included in the number of failures of accelerated life test samples. Since the number of failures is not enough, the failure rate and average life can be calculated according to the unilateral confidence interval estimation method of reliability measurement test.

The failure rate and life of samples at an application temperature of 110°C are estimated by the results of 275°C stress temperature test. According to formula (1), the acceleration factor is:

$$A = \frac{x_{110}}{x_{275}} = e^{\frac{E_a}{k} \left(\frac{1}{T_{110}} - \frac{1}{T_{275}}\right)}$$  \hspace{1cm} (7)

According to the typical activation energy value given in ESA standard ESCC-Q-30-1 (2002), the activation energy of GaAs of semiconductor devices is 1.4eV. Considering the process level and device complexity, and referring to the research results of other devices of the same process, the activation energy is calculated as 1.2eV. $k$ is a constant of 8.63×10⁻⁵eV, then $A=56,833.05$.

Since there is no device failure, the failure rate is calculated according to the upper limit of unilateral confidence interval. The degree of freedom of $x^2$ distribution corresponding to non-failure is 2, and the quantile corresponding to 90% confidence level is 4.605 from the lookup table. The cumulative device test time of accelerated life test is 5,000h. The maximum normal failure rate of the device can be calculated by substituting into formula (3): $\lambda=4.605/(2\times5000)/56833.05=8.10\times10^{-9}$/h, then the minimum average life is: $MTTF=1/\lambda=1.23\times10^8$h.
3.5. Failure mode and failure mechanism analysis

After 1000h accelerated life test of enhanced field effect transistor, except one sample fails at 275°C for 48h, there are no failure of other samples. $T_{ch1}$ is 245°C, $T_{ch2}$ is 260°C and $T_{ch3}$ is 275°C. It can be seen from figure 2 - figure 4 that the change trend of sample parameters at the three test temperatures is basically the same, and the higher the test temperature, the greater the degradation degree of the sample, indicating that the degradation degree of the sample is related to the size of temperature stress. Therefore, it is considered that the failure mode and failure mechanism of the sample at the three test temperatures are the same.

The failure mode of accelerated life test of enhanced field effect transistor is the decrease of saturated leakage current. The quality of Schottky gate metal semiconductor contact surface of GaAs devices directly affects the electrical parameters of GaAs devices. For GaAs devices, the mutual diffusion of gate metal and GaAs will lead to the reduction of active channel depth and the change of effective channel doping. This effect is called "gate sinking". This failure mechanism usually occurs when the device is subjected to accelerated life test or works at high temperature. The inducement of this mechanism is the thermal accelerated diffusion of gate metal (Au) into GaAs. This process is affected by the surface condition of GaAs material during gate metal deposition, deposition parameters and selected deposition materials. Through the test and analysis of various parameters of the accelerated life test samples, it is found that in addition to the decrease of saturated leakage current, other parameters have the following trends: the gate source diode on voltage ($V_f$) decreases and the source drain resistance ($R_{DS}$) increases. The decrease of gate source diode on voltage ($V_f$) shows that the contact potential of metal semiconductor decreases, which is one of the manifestations of Schottky barrier degradation; the increase of source drain resistance ($R_{DS}$) is caused by the decrease of active channel depth after accelerated life test. Therefore, the failure mechanism of accelerated life test of enhanced field effect transistor is gate sinking.

4. Conclusion

Taking temperature as the main stress, the constant stress accelerated life test of enhanced field effect transistor at three stress levels is carried out. After 1,000h of test, there was no sample failure except for the early failure of one sample. According to Arrhenius equation and unilateral confidence estimation method, the failure rate and life eigenvalues of devices with 90% confidence level under 110°C normal stress level are calculated. It is found that unilateral confidence estimation is an effective way to deal with accelerated life test without failure data.

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