Reliability and failure behavior model of optoelectronic devices

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***Abstract*—Recent dramatic development of science and technology has made optoelectronic devices, a crucial pole in many sophisticated systems, more powerful, accurate and complicated than ever. As a result, the development of these optoelectronic products not only increases the complexity of their structures, but leads to increasing challenge to predict the reliability of them. Based on this situation, this paper provides an engineering method to obtain the reliability prediction of optoelectronic products. In addition, several kinds of software have to be utilized to assist with computation in the method. Pspice is used to simulate the electrical stress, Calce FAST mainly resolve life prediction problems correlating electro-mechanism individually, and MATLAB is utilized to fit the degradation curves according to enough data which have been obtained above. Finally, a system failure mechanism tree which considering each failure mechanism is established. The result of lifetime prediction of sun sensor would be obtained according to the failure mechanism tree.**

Keywords—failure behavior;nonlinear sequence accumulation; failure mechanism tree

I. INTRODUCTION

With the development of the science and technology , optoelectronic products plays an increasingly important role, therefore, the life prediction of optoelectronic products is also expected to become urgent. However, the mechanism of damage caused by different environmental stress is different, and they couldn't be seen equivalently. How to use a systematic approach to accumulate the damage caused by various stresses becomes a popular research area. At present, there are two ways to estimate lifetime of products. One is based on the estimated statistics method, typical manual are GJB Z299C-2006 and MIL-HDBK-217F US. Predicting the reliability of electromechanical products is usually based on historical data. The second method is based on the physical of failure by choosing failure mechanism according to the physical model, obtaining the relevant parameters and calculating the prediction life of the product. Correlations among the failure mechanisms have already been studied by some scholars. Keedy and Feng [1,2] study a medical stents which be accompanied with degradation and a failure mechanisms of random vibration. Two probability model of failure process are given by them , based on the assumption that the failure process is unrelated, the reliability of system can be obtained., The reliability of the binary system have already been studied by Wang and Xing [3]. Huang and Askin [4] studied the reliability analysis method of electronic equipments, many failure models that they studied is competitive. Ying Chen [5] proposed five basic failure mechanisms relationship, they are competition, triggering, promotion, suppression and damage accumulation. And a failure mechanism tree which considering the correlation of failure mechanism is used to predict and simulate the life of the product. According to the type of injury, damage accumulation can be divided into destructive accumulation and parameters joint cumulative. Based on Crack Growth Model ,Mason [6] professor in Case Western Reserve University and NASA Lewis Research Center in Cleveland reaserched the bilinear damage rule when the stress is same and loading sequence is different. Advanced Life Cycle Engineering at the University of Maryland [7] use Coffin-Manson model to calculate system cumulative damage when the temperature cycling and vibration are exist simultaneously. There are also a number of scholars research damage accumulate in domestic, Yuan Wei, Nanjing University of Aeronautics and Astronautics [8] published a study of metal fatigue life prediction under multiaxial random loading conditions. Fei Chai and Michael Pecht [9] proposed the Miner linear rule which be widely used in engineering, but it is conservative so that the results is larger than the standard values. For optoelectronic products, the failure mechanism is diverse and the failure behavior of system is complex, it is necessary to consider the relationship of the fault mechanism if you want to assess the reliability of the system. Ying Chen [5] proposed failure mechanism tree which could describe failure mechanisms that have a complex relationships.

In this paper, A nonlinear sequence accumulation model [10] was proposed when the different stress affect the system in sequence. Finally, we use failure mechanism tree to calculate the life of a system, and this method considers the correlation of all failure mechanisms.

II. THE FAILURE BEHAVIOR AND FAILURE CORRELATION

The concept of failure behavior is the variation which could be observed from the surface of product and appear along with time. It includs the appearance, development, coupling of failure mechanism and the process which results in system failure.

The logical relationship of failure mechanisms refers to that each component contains a variety of failure mechanisms, and they are independent or mutual influence . There are five relationships among the failure mechanisms

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and they are competition, triggering, promotion, suppression and damage accumulation. After analysis, the sun sensor's main logical relationships are damage accumulation and parameters joint accumulation. It is competition that the system has some failure mechanisms and they are independent, meanwhile, each of them would lead to the system invalid. Similarly, if two or more failure mechanisms cause the same type damage in the same position, the relationship be called as damage accumulation. There are many different kinds of damage accumulations, they are linear accumulation under the same stress condition, bilinear cumulative when the same stress operates in order and nonlinear accumulation when thermal and vibration operate together.

A. The linear cumulative damage model when stress is same.

The average injury caused by each cycle is 1 / N, this damage can be accumulated. n times damage caused by constant amplitude load is equal to its recycle ratio $C=n/N$. Damage D of variable amplitude loading is equal to the sum of the cycle radio,

$$D = \sum_{i=1}^{l} n_i / N_i \tag{1}$$

where i is the level number of the main load, n_i is the number of cycles of i th stress level. N_i is the life of i th stress level. The formula is as follows,

$$D=\sum_{i=1}^{l} n_i / N_i = D_f \tag{2}$$

When the accumulated damage amount reaches a critical value D_f ,the product is invalid.

B. Bilinear cumulative damage model of the same kind of stress effect in order

Based on Crack Growth Model ,Mason [6] professor in Case Western Reserve University and NASA Lewis Research Center in Cleveland reaserched the bilinear damage rule when the stress is same and loading sequence is different. Bilinear damage rule formula is as follows:

$$N_{II} = N_f - N_I = N_f\left[1 - \exp\left(ZN_f^{\phi}\right)\right] \tag{3}$$

Where,

$$\phi = \frac{1}{\ln(\frac{N_1}{N_2})}\ln\left\{\frac{\ln[0.35(\frac{N_1}{N_2})^{0.25}]}{\ln[1-0.65(\frac{N_1}{N_2})^{0.25}]}\right\} \tag{4}$$

$$Z = \frac{\ln[0.35(\frac{N_1}{N_2})^{0.25}]}{N_1^{\phi}} \tag{5}$$

Where N_1 and N_2 are respectively the number of faigure failure cycles under the different stress level conditions. N_I is the number of cycles that the product suffers in the first stage, N_{II} is the number of cycles that the product suffers from the first stage to failure.

C. Nonliner cumulative damage modle under heat and vibration operate in sequence

CASPaR center [11]of he University of Georgia have studied cumulative damage model respectively when the loading sequence is different. By doing experiments, they obtain the cumulative damage model as follows,

$$CDI = \sum_{i=1}^{\text{number.of.load.steps}} \frac{n_i}{N_i} \tag{6}$$

where CDI is the cumulative damage index, ni is actual number of applied cycles for the i th load step, and Ni is the number of cycles to failure for the i th load step. CDI ranges from 0 to 1.0 with 0 being the undamaged state and 1.0 being the fully damaged state. Failure is typically defined when the CDI exceeds a critical value of 0.7.

When the first stress is vibration and the last is temperature cycle, the cumulative damage model is as follows,

$$CDI = \left(\frac{n_T}{N_T}\right)^{m_T} + \left(\frac{n_V}{N_V}\right)^{m_V} \tag{7}$$

where CDI is the cumulative damage index, its value is 0.7. When the first stress is vibration and the last is temperature cycle, mT and mV are the fitting parameters according to the experimental results.

III. The Process Of Failure Behavior Of Optoelectric Products

The structure of the optoelectric product is composed of both the circuit part and the optical part. Common failure mechanisms of the circuit part is consist of thermal fatigue, vibration fatigue, electromigration, TDDB and hot carrier. Failure mechanisms of the optical part mainly include the coloring effect of quartz glass, the aging of silicon rubber and the degradation of silicon photo cell.

IV. Case Analysis

A sun sensor could obtain its vector of the orientation in the celestial coordinate system, Which mainly includes the optical probe and a signal processing circuit section.

A. The structure and composition of the sun sensor

The structure of sun sensor are shown in Fig 1, and the basic principle and composition of sun sensor are shown in Fig 4. The incident light through the cylindrical mirror, plate glass, flat glass disc, the silicon photocell, and finally get into the signal processing circuit board.

B. Environmental and working stress in life cycle

In the process of rocket launching, the sun sensor is mainly affected by vibration, and the vibration is random vibration. After entering the track, it is no longer affected by vibration, but mainly affected by the spatial temperature cycle, the temperature range from -50 to 50 degrees, so the life cycle of the sun sensor integrated section is shown in Fig. 2. Vibrational spectra are shown in Fig. 3.

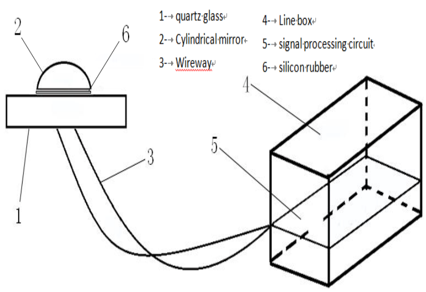

Fig. 1. Structure of sun sensor

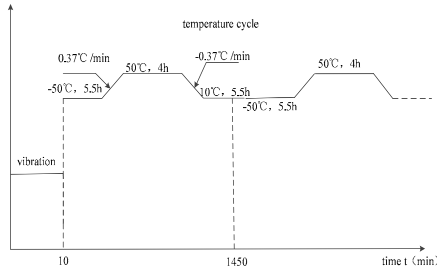

Fig. 2. Sun sensor's comprehensive stress profile of simulation analysis

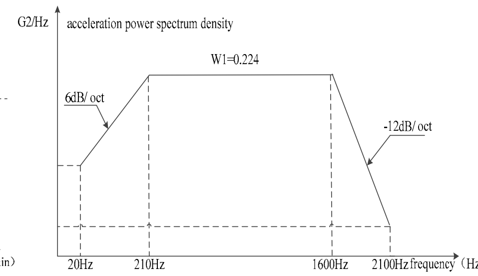

Fig. 3. Vibration spectrum

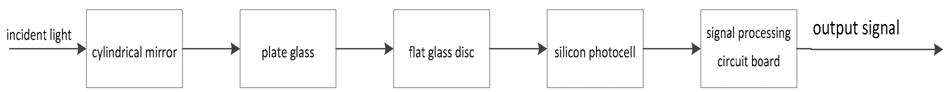

Fig. 4. The basic principle and composition of the sun sensor

In the space, there are ionospheric plasma, magnetospheric plasma and auroral plasma and other low-energy charged ion. There are also solar cosmic rays, galactic cosmic rays, earth radiation belt and other Energetic charged particles. In the space, circuit portion of the sun sensor will appear thermal fatigue, vibration fatigue and electrical stress injuries. The glass coloring effect, surface sputtering erosion, charge and discharge effects and radiation-induced pollution effects will appear in the optical portion of the sun sensor.

C. Single Stress Analysis and Damage Calculation

1) Using Calce SARA Software to simulate emperature stress distribution of the sun sensor.

The sun sensor circuit board model could be established by the Calce SARA software. Entering the board boundary temperature, the thermal simulation results for each temperature couldn't been obtained. Finally, the temperature profile was entered into the life sectional bar. As seen from Table 6 , the thermal prediction life results of the circuit portion when running the procedure would been obtained.

2) Using Calce SARA Software to simulate vibration stress distribution of the sun sensor.

Using the model established in the last step, the vibration results could been obtained by inputing the vibration power spectral density. Finally , the vibration profile was entered into the life sectional bar, and the vibration prediction life results of the circuit portion when running the procedure was obtained.

3) Using Pspice, Cadence, Cyber and other software to simulate the electric stress of the sun sensor.

Establishing Pspice circuit model of the signal processing circuit board which is normal state. Making a transient circuit simulation for it. Finally, the output parameters of the circuit could be obtained, such as voltage and current curves change over the time.

According to the electrical stress simulation results, the damage which is cased by electromigration could been calculated , TDDB and hot carrier. then, inputing some important parameters as shown in Table II, the prediction life calculated by the Calce FAST software are presented in table III.

4) Silicone rubber life expectancy of the optical part.

The prediction life of the silicone rubber according to the selected aging failure model was calculated.

The failure physical model of silicon rubber is,

$$y = Be^{-Kt^{a}},\ K = Ae^{-E/RT} \tag{8}$$

Where , B is the constant, K is the velocity constant, α is empirical constant, τ is the ageing time , y is index which indicates the degree of degeneration. E is the activation energy, R is gas constant, T is absolute temperature, A is the frequency factor. In this paper, the value of α, E, A and B are 0.38,27.03,623.45and 1.0208 respectively.

Firstly, the constant K could been obtained according to the formula. Among them, A=623.45，E=27.03 KJ/mol-1，R=8.314 $J \cdot mol^{-1} \cdot K^{-1}$, the absolute temperature which could obtained according to the thermal analysis of the probe is 72.249 ℃ (345.409K). $K = Ae^{-E/RT}$ =0.0509. The silicon rubber compression permanent deformation model could been obtained according to $y = Be^{-Kt^{a}}$ and $y = 1 - \varepsilon$,the formulate is as follows,

$$\varepsilon = 1 - y = Be^{-Kt^{a}} \tag{9}$$

$$t = \sqrt[\alpha]{\frac{ln\frac{B}{1-\varepsilon}}{K}} \tag{10}$$

The threshold value of silicone rubber deformation is 20%, and then the prediction life could been obtained, namely, t =82.698years.

The degradation of the light transmittance of silicone rubber in the space radiation environment was calculated.

In order to predict the degradation of the light transmittance of silicone rubber, the least square fitting bar in MATLAB software was used according to the experimental data. The formula which was selected is as follows,

$$Tr = a \cdot e^{bt} + c \cdot e^{dt} \qquad (11)$$

Where, t is time, a，b，c，d are the fitting parameters, Tr is the light transmittance.

Fitting the degradation data of light transmission of silicone rubber ,the curve equation is

$$Tr = 6.35e^{-0.3635t} + 75.9e^{-0.01287t} \qquad (12)$$

If the threshold of degradation of silicone rubber is 60%, and then y = 60% * 82.45 = 49.47, the failure life of silicone rubber was 33.259 years according to the formulate model.

5) life expectedncy of Quartz glass and Silicon photovoltaic cells under space radiation environment

Similarly, the degradation formula of quartz glass and silicon photovoltaic cells were obtained respectively,

$$Tr = 14.07e^{-8.47t} + 78.18e^{-0.02809t} \qquad (13)$$

$$Tr = 402e^{-0.01196t} \qquad (14)$$

The light transmittance degradation threshold of quartz glass and silicon photovoltaic cells is 60% , Similarly, the prediction of quartz glass and silicon photovoltaic cells by calculating are 12.29years and 24.47years respectively.

TABLE I. THE CALCULATION RESULTS OF THE FAILURE TIME OF THE CIRCUIT MODULE UNDER THE CONDITION OF TEMPERATURE CYCLE AND VIBRATION

fault location	**type**	**（vibration） failure mode**	**(temperature cycles） failure mode**	**（vibration） Mean time to failure**	**（temperature cycles） Mean time to failure**
U3	4051	Solder joint cracking	Solder joint cracking	11.32 years	12.33 years
U22	80C32E	Interconnection site cracking	Solder joint cracking	12.60 years	13.11 years
U4	4051	Interconnection site cracking	Solder joint cracking	18.92 years	13.86 years
U24	6664RH	Interconnection site cracking	Solder joint cracking	19.13 years	14.31 years
R2F4	resistance	Interconnection site cracking	Solder joint cracking	19.56 years	14.77 years
R103	resistance	Interconnection site cracking	Solder joint cracking	19.98 years	15.16 years
R102	resistance	Interconnection site cracking	Solder joint cracking	20.54 years	16.73 years
R2C4	resistance	Interconnection site cracking	Solder joint cracking	21.35 years	17.23 years
U23	54AC373	Interconnection site cracking	Solder joint cracking	21.91 years	17.83 years
U1	4051	Interconnection site cracking	Solder joint cracking	22.31 years	18.14 years

TABLE II. SOME IMPORTANT PARAMETERS OF ELECTRO MIGRATION, TDDB AND HOT CARRIERS

electromigration	**W is Width of the chip metallization layer (m)**	**T is thickness of the metal layer of the chip (m)**	**J is Metal layer current density**	**T is chip operating temperature （K）**
TDDB	1/E modle V_{ox} is voltage of oxide layer (V)	1/E modle Xox(off) is effective oxide thickness (m)	E modle E_{ox} is gate oxide field acceleration factor (m/v)	T is chip operating temperature（K）
hot carrier	Id is leakage current (A)	W is channel width（m）	Isub is substrate current (A)	-

TABLE III. ELECTROMIGRATION, TDDB AND HOT CARRIER MECHANISM -- THE RESULTS OF FAILURE TIME (25℃)

fault location (Chip code)	**type**	**T chip operating temperature （K）**	**Mean time to failure of electromigration (year)**	**Mean time to failure of TDDB (year)**	**Mean time to failure of hot carrier (year)**
U1	4051	339.15	23.20	25.38	15.82
U10	AD574	317.95	19.75	26.54	15.17
U11	LM108A	312.15	22.11	26.38	17.48
U17	DS26F32M	330.19	22.55	29.59	16.88
U18	DS26F31M	329.99	22.73	28.37	17.49
U22	80C32E	318.75	21.72	30.53	16.51
U23	54AC373	319.75	21.71	27.32	17.66
U24	6664RH	317.35	20.24	27.11	15.35
U26	4060	316.45	24.24	29.35	15.14
U28	CC4011	316.55	18.74	26.93	17.26
U32	HS-565BH	307.55	>30	27.88	21.43
U39	54AC02	319.35	22.29	28.69	16.49
U40	54AC138	320.45	26.20	29.65	15.61

D. More stress damage accumulation of the sun sensor

Equation (1) shows the accumulation formula. In this paper, where n is the actual number of applied cycles, N is the number of cycles to failure, and the subscripts T and V refer to thermal and vibration loading respectively. Meanwhile, m_T=0.91,m_V=0.93. U3 was took as an example to calculate. CDI=0.7, n_V=0.166h, N_V=11.32, N_T=12.33, So, n_T=8.07. Similarly, the accumulation life of the rest components could be got.

E. Using the failure mechanism tree to establish system model and predicte life.

Failure mechanism tree describes the correlation of the respective failure mechanism. Fig. 7 is the failure mechanism tree of output signal degradation of the sun sensor.

There are two kinds of failure mechanism correlations. they are Joint parameter and damage accumulation, the former is represented by APA, the latter is represented by UMACO. Fig. 5 shows the symbol of joint parameter and damage accumulation.

Fig. 5a) illustrates failure mechanism accumulation correlation, where M1,…,Mn are failure mechanisms and F is their common consequence. According to the destructive type, If M1,… Mn have damage accumulation correlation, the threshold of system due to this kind of damage is X_{th}, then

$$\Delta X_i = \frac{X_{th}}{t_i} \tag{15}$$

a) parameter joint b) Damage accumulation

Fig. 5. The symble of failure mechanism.

Where ΔX_i is the damage in unit time due to Mi, it is the failure time due to Mi when it works alone. Then lifetime of system is

$$\begin{aligned}\varsigma &= \frac{X_{th}}{\Delta X} = \frac{X_{th}}{\lambda_1 \Delta X_1 + \ldots + \lambda_i \Delta X_i} \\ &= \frac{X_{th}}{\lambda_1 \frac{X_{th}}{t_1} + \ldots + \lambda_i \frac{X_{th}}{t_i}} \\ &= \frac{1}{\frac{\lambda_1}{t_1} + \ldots + \frac{\lambda_n}{t_n}} = \frac{1}{\sum_{i=1}^{n} \frac{\lambda_i}{t_i}}\end{aligned} \tag{16}$$

Where ΔX is the accumulated damage in unit time. And λi is a scaling factor of Mi, i=1,2,…,n.

System failure probability F(t) is,

$$F(\mathrm{t}) = P(\varsigma \le \mathrm{t}) = P\left(\frac{1}{\sum_{i=1}^{n} \frac{\lambda_i}{t_i}} \le \mathrm{t}\right) \tag{17}$$

Assume $X_{Mi}(t)$ indicates some kind of damage that Mi brings to the system and varies with time t, and X_{Mith} is the threshold of damage caused by Mi. When damage X_{Mi} increases to the threshold X_{Mith}, mechanism Mi will result in system failure. So system lifetime ς is,

$$\varsigma = \min\left\{\arg_t \left\{X_{Mi}(t) = X_{Mith}\right\}\right\} \tag{18}$$

Based on the lifetime data of the failure mechanisms calculated in the above steps, we can obtain the output paramenters and the distribution of failure life according to Monte Carlo simulation method and the failure mechanism tree as shown in Fig. 6 . And then results of lifetime prediction of sun sensor are obtained in the table 4.

V. CONCLUTIONS

The paper describes the life prediction method of the general optoelectronic products, and establishs a life prediction method which based on nonlinear damage accumulation and integrate multiple failure mechanisms. Meanwhile the paper proposes a non-linear formula when the stresses is different but operating in order, and then proposes a new method using failure mechanism tree to calculate life of the system which has more failure mechanisms.

TABLE IV. THE PREDICTION LIFE RESULTS OF THE SUN SENSOR

equipment	**distribution Type**	**distributed parameter**		**Average life（year）**
		mean value	***standard deviation***	
sun senor	normal distribution	12.26	2.55	12.113

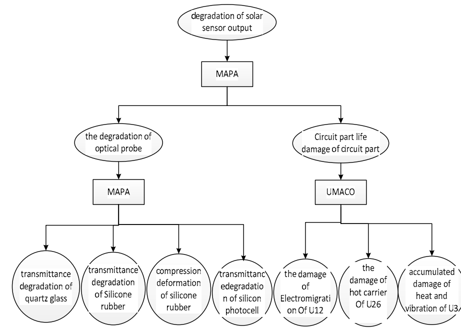

Fig. 6. The failure mechanism tree.

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