Research on the physics-of-the failure model for corrosion damage accumulation under a multi-level stress profile based on the acceleration factor

L. Wang[1*], B. Wan[2]

[1]School of Computer and Information Engineering, Beijing Technology and Business University, Beijing, 100048, PR China
[2]School of Reliability and Systems Engineering, Beihang University, Beijing, 100191, PR China

Attention is paid in this paper to the problem that the existing physics-of-failure model cannot input and calculate a complex multi-level stress environmental profile when conducting simulation calculations of microelectronic devices' studing reliability. A physical model of corrosion failure is analyzed as an example. We carry out cumulative calculation and improvement using the theory of the accelerated factor, the theory of fatigue damage accumulation and the general function of physics-of-failure model for corrosion damage accumulation under a multi-level stress profile. This model can achieve simulation and prediction of cycle time before failure under a multi-level stress profile. At the end of this paper, an instance of a multi-level stress profile's calculation is provided.

Keywords: Corrosion, Multi-level stress, PoF model

INTRODUCTION

At present, using the technical means of reliability simulation to establish the virtual prototype and calculate the user reliability of microelectronic devices through the simulation of the physics-of-failure model, is one of the most important branches and the future development trend in the field researching the methods of electronic products' reliability design. However, most of the environmental stress parameters of the common physics-of-failure model are becoming uniform. Only a single stress value can be input during calculation. Actually, complex multi-level stress environmental profiles always exist. In this case, the physics-of-failure model cannot be input and calculated. Because of the limitation brought about by this defect, a technical problem appears when simulating and calculating microelectronic devices' for their reliability.

This paper uses a physical model of corrosion failure as an example, predicts a model of multi-level stress damage accumulation and improves the theory, according to the basic theories of accelerated test and factor and theory of fatigue damage accumulation. Meanwhile, the general functional physics-of-failure model for corrosion damage accumulation under a multi-level stress profile and its corresponding mathematical expressions are set up. The model can input complex multi-level stress profiles and calculate the cycle index of damage accumulation as well as time to failure under multi-temperature stress.

PHYSICS-OF-FAILURE MODEL FOR CORROSION

Corrosion failure mechanism

Moisture and impurities can cause the corrosion of the aluminum, aluminum copper alloy or silico aluminum interconnect of the microelectronics components. Due to the low cost and ease of mass production, microelectronic components use a lot of resin for encapsulation, which is moisture permeable and absorptive. Impurities such as a variety of positive and negative ions like Na^+ ions are introduced during the resin material manufacturing process. The ions along with the penetration and absorption in vapour continue to infiltrate into the surface of aluminum or the aluminum alloy interconnects and traverse through the surface passivation film of tiny defects into the metal interconnects inside and cause the interconnects to electrochemically react and then the metal interconnects open or the interconnect resistance increases. The process describes corrosion. In microelectronic components, corrosion of aluminum has two mechanisms: chemical corrosion and electrochemical corrosion [1]~[6].
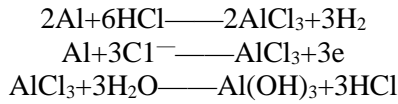
Chemical corrosion

Corrosion of aluminum happens when the microelectronic components are stored in a high temperature and high humidity environment. When exposed to dry air, aluminum forms a layer of Al_2O_3 on the surface and the film will prevent aluminum from being oxidized and the chemical etched. But during the presence of moisture,

* To whom all correspondence should be sent:
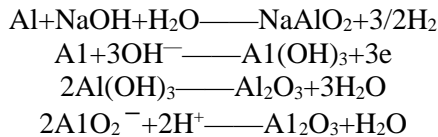E-mail: wangli@th.btbu.edu.cn

aluminum can form $Al(OH)_3$ and $Al(OH)_3$ is soluble in alkali as well as acid.

When the external substances reach the surface of the aluminum material, the chemical reactions are as listed below:

Reactions with an acid substance:

$$2Al+6HCl——2AlCl_3+3H_2$$
$$Al+3Cl^-——AlCl_3+3e$$
$$AlCl_3+3H_2O——Al(OH)_3+3HCl$$

Reactions with an alkaline substance:

$$Al+NaOH+H_2O——NaAlO_2+3/2H_2$$
$$Al+3OH^-——Al(OH)_3+3e$$
$$2Al(OH)_3——Al_2O_3+3H_2O$$
$$2AlO_2^-+2H^+——Al_2O_3+H_2O$$

Usually, a passivation film on the surface of the chip protects the aluminum. However, in the pad of the wire bonding area, the aluminum metal is exposed on the surface and chemical corrosion frequently occurs in these parts. The corrosion situation of the chip pad is shown in Figure 1.
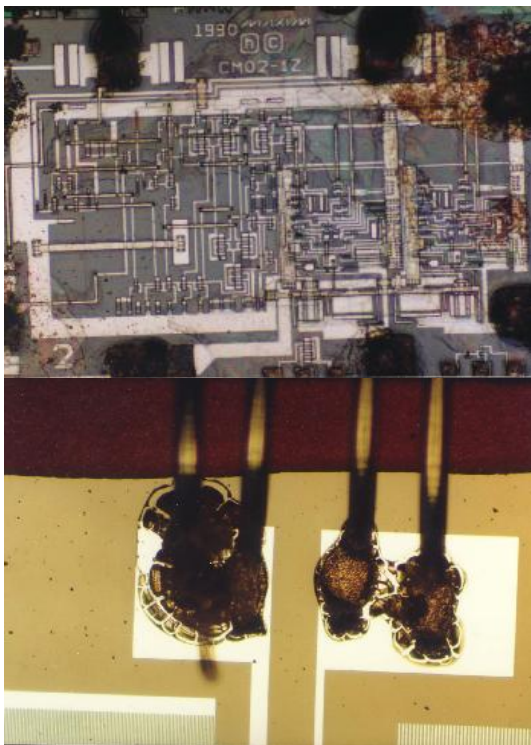

Fig. 1. PAD on the chip is corroded
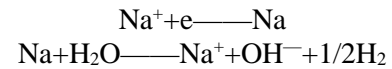
Electrochemical corrosion

Electrochemical corrosion occurs when the microelectronic components are under exploitation under a high temperature and high humidity environment. According to the positive or negative potential of the aluminum electrode, the electrochemical corrosion is divided into anodic corrosion and cathodic corrosion [7]~[10]. When the anodic corrosion happens, the aluminum electrode has a positive potential, which attracts negative ions such as Cl to start the chemical reactions as follows:

$$Al(OH)_3+Cl^-——Al(OH)_2Cl+OH^-$$
$$Al+4Cl^-——AlCl_4^-+3e$$
$$AlCl_4^-+3H_2O——Al^{(OH)}_3+3H^++4Cl^-$$
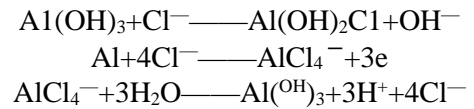
The reaction above reduces the Cl—absorbed on the anode and the results of the reaction furthers the corrosion of the small amount of Cl⁻.

For the cathodic corrosion, due to the negative potential of aluminum, positive ions such as Na^+, K^+ are attracted to produce chemical reactions as follows:

$$Na^++e——Na$$
$$Na+H_2O——Na^++OH^-+1/2H_2$$

After the reaction, the concentration of the OH⁻ increases, the aluminum hydroxide forms and the aluminum is corroded. The electrochemical corrosion of the cathode of the microelectronic components is shown in Figure 2 and Figure 3.
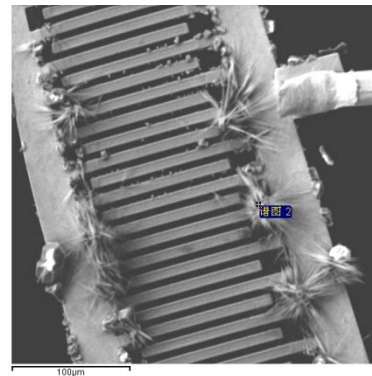

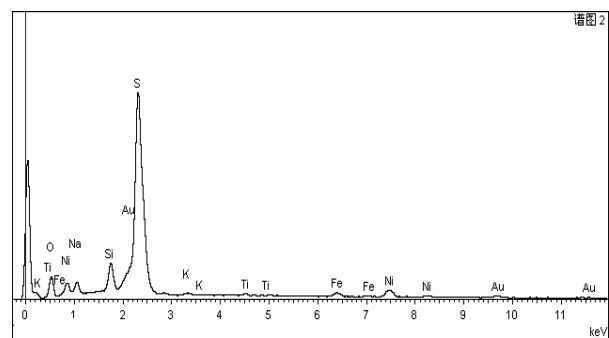**Fig. 2.** The electrochemical corrosion of cathode.

Fig. 3. The ESD of the electrochemical corrosion of the cathode.

The metal in a high humidity environment will obviously corrode. One solution is to use the ceramic sealing packaging which can prevent the corrosion, if the structure is not hermeticaly sealed, the residue remaining after the plasma or reactive ion sputter etching occurs (such as chlorine) along

with the moisture will corrode the aluminum and attain erosion, even in the absence of an applied electric field:

$$2Al+6HCl\text{——}2AlCl_3+3H_2$$
$$AlCl_3+3H_2O\text{——}Al(OH)_3+3HCl$$
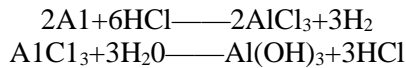
It is clear that after the formation of Al $(OH)_3$, the chlorine is not bound, which leads to further corrosion of the exposed aluminum. In the VLSI structure, the metal wires are very close to each other and the electric field between them causes the problem to become complicated.

External lead corrosion

The lead material of a micro electronic device is usually kovar alloy, it is the iron-nickel-cobalt alloy, the linear expansion coefficient of which is similar to that of molybdenum. In addition to the introduction of stress in the mechanical processing and the production of stress corrosion, there is also an electrochemical corrosion reaction during the presence of Cl⁻ and other impurities, thus the corrosion rate speeds up.

When the water vapor condenses around the external leads and the potential difference exists (such as discrete devices inserted in the printed circuit board), the leakage current travels through the leads continuously, and materials (such as iron) with a high ionization tendency (standard electrode potential to negative) will produce electrochemical corrosion.

As for the silver plating on the external lead, the silver anode will have Ag⁺ ions, migrating in the electric field and precipitating at the cathode. Then these will grow like resin on the anode, causing a deterioration in performance, or short circuits.

PoF model of Corrosion

The degradation process of the chemical or electrochemical properties of materials is known as corrosion, which is a time dependent wear-out failure mechanism. From a macroscopic point of view, corrosion will lead to brittle fracture caused by stress, or fatigue crack extension caused by the wear-out; from the microscopic point of view, corrosion can change the electrical properties of the material and its thermal properties. The corrosion rate correlates with the type and dimensions of the materials and the ionic contaminants[11].

The corrosion failure physical model is given by:

$$MTTF = A(RH)^{-n}\exp(\frac{Ea}{kT}) \qquad (1)$$

In the formulation,

A is the constant related to the corrosion area;
RH is the relative humidity;
N is the empirical constant, and generally have values of 3;
Ea is the activation energy, measured by the test;
K is the Pohl Seidman constant;
T is the ambient temperature and the units are degrees Kelvin.

ACCELERATED FACTOR MODEL

The rate of physical and chemical change varies with the temperature, leading to various lifetimes of the products. In the general case, there is a more rapid rate of physical and chemical change under high stress levels, which means a shorter life of the products. Hence, the process of change at a high stress level can be regarded as acceleration of that at a low stress level. The idea of an Accelerated Factor (AF) needs to be put forward, in order to describe the acceleration extent of high stress levels relative to low levels. The accelerated factor, from the accelerated test [12][13][14], is the ratio of the product's lifetime characteristic under different stress levels. It is a parameter used to present the extent of acceleration. While the value of AF is greater than 1, it means that the device's lifetime can be shortened by increasing the stress S. The definition formula is as follows [15][16]:

$$AF = \frac{TF_{op}}{TF_{stree}} \quad , \qquad (2)$$

Here, TF_{op} is the expected failure time under stress S (normal working conditions) and TF_{stree} under stress S_0 (accelerating stress conditions).

The method of AF damage accumulation converts the multi-level stress of the actual profile to single stress before evaluation with the help of the AF concept. Afterwards, the cycle index of the actual profile will be solved through time to failure under the single failure mechanism and single stress level. Finally, a time to failure for practical working conditions is obtained.

ESTABLISHMENT OF A PHYSICS-OF-FAILURE MODEL FOR CORROSION DAMAGE ACCUMULATION BASED ON THE ACCELERATED FACTOR MODEL

Method for establishing a physics-of-failure model based on an accelerated factor model

The stress θ_0 is selected as a datum plane and the duration of every phase is converted to duration under a datum plane. The overview flow is shown in Figure 4.
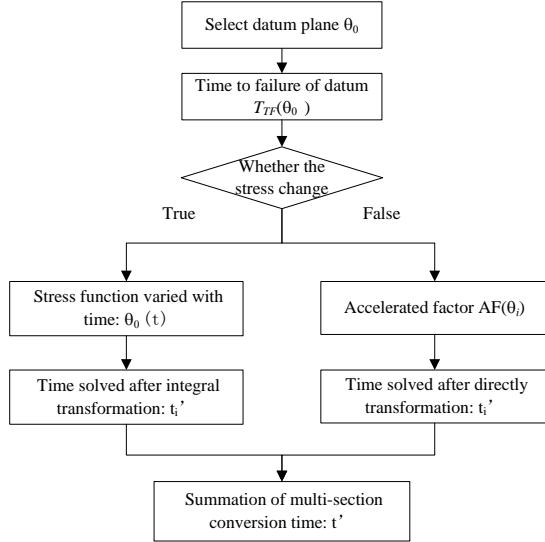
Fig.2. Multi-level stress damage accumulation based on the accelerated factor model.

The specific steps are described below:

1) Calculating the time to failure $T_{TF}(\theta_0)$ under a datum plane θ_0 based on the corresponding physics-of-failure model;

2) According to a model of the failure time, calculating the time to failure under actual working conditions and marking it as $T_{TF}(\theta(t))$;

3) Calculating the acceleration factor according to the formula $AF\left(\theta(t)\right) = \dfrac{T_{TF}(\theta_0)}{T_{TF}\left(\theta(t)\right)}$;

4) The mission time for one mission cycle can be converted to that of the datum plane through FA.

That is
$$t' = \int_0^T AF\left(\theta(t)\right)dt \tag{3}$$

5) Calculating the mission cycle index $N = \dfrac{T_{TF}(\theta_0)}{t'}$, in accordance with the formula

$$N = \frac{T_{TF}(\theta_0)}{\int_0^T \dfrac{T_{TF}(\theta_0)}{T_{TF}\left(\theta(t)\right)}dt} = \frac{1}{\int_0^T \dfrac{1}{T_{TF}\left(\theta(t)\right)}dt} \tag{4}$$

Method of accelerating the damage accumulation at a constant stress stage

As shown in Figure 5:

The formula is calculated as:

$$AF(\theta_i) = \frac{T_{TF}(\theta_i)}{T_{TF}(\theta_0)}, \tag{5}$$

$$t_i' = AF(\theta_i) \times (t_{i+1} - t_i), \tag{6}$$

Here, t_i' is the duration that the stress θi translated into the datum plane θ_0 within the time

interval $[t_i, t_{i+1}]$; $T_{TF}(\theta_i)$ shows the expected failure time under stress θi (normal working conditions) and $T_{TF}(\theta_0)$ under θ_0 (accelerating stress conditions); $AF(\theta_i)$ is the accelerated factor of the stress θi and θ_0.

Method of accelerating damage accumulation at the slowly changing stress stage

The method process is shown in Figure 6.
The formula is calculated as:

$$AF\left(\theta(t)\right) = \frac{T_{TF}\left(\theta(t)\right)}{T_{TF}(\theta_0)} \tag{7}$$

$$t_j' = \int_{t_j}^{t_{j+1}} AF\left(\theta(t)\right)dt \tag{8}$$

Here, $\theta(t)$ is the function of stress θ and time t, which can be confirmed according to the known stress profile; $TTF(\theta(t))$ is the expected failure time under slowly changing stress $\theta(t)$; $TTF(\theta_0)$ is on behalf of the failure time under stress θ_0 (specific accelerating stress conditions); and t_i' is the duration that the slowly changing stress $\theta(t)$ translates into a given stress θ_0 within the time interval $[t_i, t_{i+1}]$.

The establishment of a corrosion damage accumulation model based on the accelerated factor

On the basis of a multi-level-stress failure model using the method of AF, the physics-of-failure model and the formula of corrosion PoF model is derived. The specific forms are as follows:

$$N = \frac{T_{TF}(\theta_0)}{\int_0^T \dfrac{T_{TF}(\theta_0)}{T_{TF}\left(\theta(t)\right)}dt} = \frac{1}{\int_0^T \dfrac{1}{T_{TF}\left(\theta(t)\right)}dt} \tag{9}$$

The final multi-level-stress failure model based on the method of AF can be described as:

$$N = \frac{1}{\int_0^T \dfrac{1}{A(RH)^{-n}\exp\left(\dfrac{Ea}{k\theta_H}\right)}dt} \tag{10}$$

EXAMPLE

Figure 7 is a typical profile and the parameters of temperature and time are shown in Table 1.
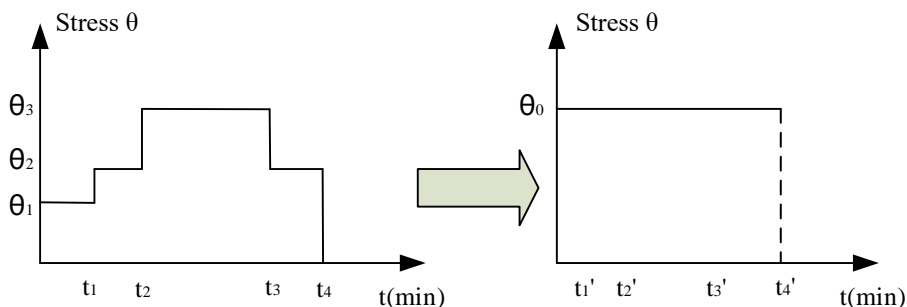
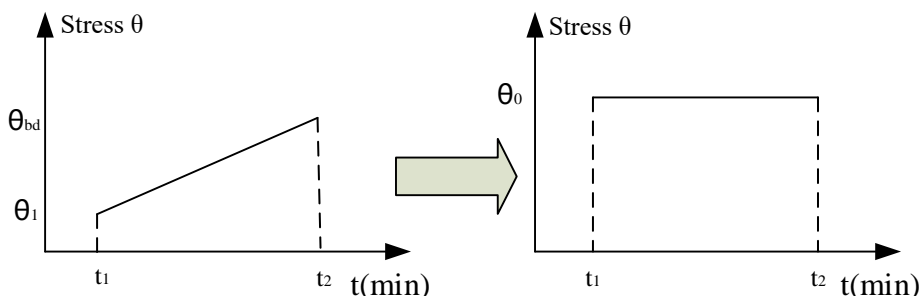**Fig. 3.** The condition for the parameter value of stress to remain unchanged.

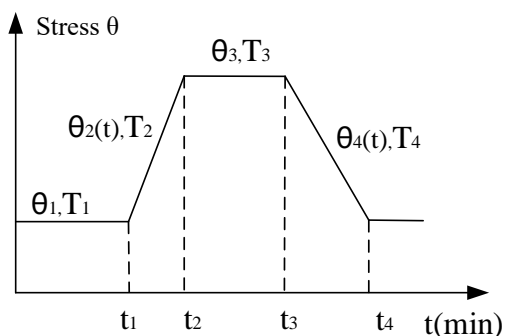**Fig. 4.** The condition that the parameter value of stress is slowly changing

Fig. 7. A typical sectional multi-level stress profile.

Table 1. The parameters of temperature stress

No.	T	t
1	25°C	30min
2	(2t-35) °C	25min
3	75°C	30min
4	(-2t+245) °C	25min

Table 2. Technological parameters

Parameter	value
A	1.3
RH	80%
n	3
k	1.381×10^{-23} J/K
Ea	0.7eV

A certain type of microelectronic device is taken as an example. In accordance with the corrosion PoF model and formula (1), the device's internal process parameter values can be obsrved in Table 2.

In accordance with formula (11) and under the profile stipulated in Figure 7 and Table 1, the total cyclic index of damage accumulation of this certain type of microelectronic device in which corrosion failure occurred is N=5043. While the time to failure isTTF=20153h.

CONCLUISIONS

In this paper, the accelerated factor model is applied and the damage accumulation under a multi-level stress profile is calculated based on the physics-of-failure model of corrosion. Meanwhile, the method of accelerating damage accumulation at the constant and slowly changing stress stage is respectively provided. The generalized corrosion damage accumulation model based on the AF is also established. Finally, for the case of a certain type of microelectronic device, the applicability of this model is demonstrated and the total cyclic index before failure and the time to failure of the physics-of-failure model for corrosion damage accumulation under the multi-level stress profile are solved. This paper provides a new theoretical method and solution for more scientific and rational applications of the corrosion failure model in the evaluation of microelectronic devices' reliability and emulation ability.

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ИЗСЛЕДВАНЕ НА НАТРУПВАНЕТО НА КОРОЗИОННИ ДЕФЕКТИ ПРИ МНОГО-СТЕПЕННО НАПРЕЖЕНИЕ С УСКОРЕНИЕ С МОДЕЛА „PHYSICS-OF-FAILURE

Ли Уан[1]*, Бо Уан[2]

[1]Училище по компютърно и информационно инженерство, Технологичен и бизнес- университет в Пекин, Пекин 100048, Китайска НР
[2]Училище по системно инженерство, Университет Бейхан, Пекин, Китайска НР

(Резюме)

В настоящата работа се обръща внимание на факта, че съществуващия „physics-of-failure" – модел не дава възможност да се изчислят сложни много-степенни напрежения при симулирането на надеждността на микро-електронни уреди. Като пример е анализиран физичен модел за корозионни дефекти. Извършени са кумулативни пресмятания и подобрения с помощта на теорията на ускоряващия фактор и теорията на натрупване на умора в материалите, заедно с модела „physics-of-failure". Този модел може да постигне симулиране и предсказване на цикъла от време преди разрушаване под многостепенно напрежение. В края на работата е даден илюстративен пример.