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A Canary Design to Monitor Electromigration of Solder Joints

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Electromigration-induced failure has become one of the most serious problems in solder joints. In this paper, a canary device has been designed to monitor the eletromigration of solder joints. Then the current of the canary device is calculated. The canary solder joints are identical to those used in the host circuit but suffered properly larger environmental stress to accelerate aging so they are supposed to fail before those in the host circuit. For this reason the canary device are designed to be sacrificial, and are not used in the circuit. Instead it is packaged separately in order not to influence the normal operation of the host circuit. How to apply sufficient, but not overly large, stress current to the canary device to enhance its electromigration failure without stressing other part of the circuit becomes one of the problems we need to solve. In this paper a canary circuit is designed to solve this problem. Also the increased stress we need was calculated. With the help of the canary device , we can be warned before the solder joints fail to ensure the system health.

1. Introduction

With the development of fault detection and diagnosis techniques, the safety and reliability of a integrated circuit(IC) component is significantly enhanced by the ability to identify performance degradation and failure modes of the component. Particularly, the corrective actions to avert a catastrophic event are facilitated by the capability to monitor electronic aging at the board level, and to detect an impending IC failure. On the strength of the application of a board-level premonitory monitor design, we can extract precise predictions of electronic aging and end-of-life failure modes. We name the premonitory monitor chip the canary device.

In advanced electronic products, the design rule in devices which requires high current density through small solder joints for high performance and miniaturization lead to a result that electromigration-induced failure becomes one of the most severe problems in fine pitch solder joints (Jae-Woong Nah, 2007). It is unique that the failure mode is induced by electromigration in the solder joint, owing to the loss of under bump metallurgy (UBM) and the interfacial void formation at the cathode contact interface. When electromigration is applied to the solder joints, as a result of the special line-to-bump geometry of the solder joints, a rapid dissolution of UBM is caused by the current crowding at the entrance point of the Al trace into the bump and the joint becomes unreliable.

A canary device is designed in this paper aimed at monitoring the eletromigration of solder joints. In order to make sure that the extracted data matches the condition of the key components of the IC, the monitored solder joints and those used in the host IC are identical. The premonitory circuitry biases the solder joints to accelerate aging under certain environmental conditions. For this reason, the sensor devices which are designed to be sacrificial in the premonitory chip are not applied in the host application. Instead they are packaged separately, mounted, and biased at the board level. The design challenge for the canary is to apply sufficient, but not overly large, stress current to the test chip to enhance its electromigration failure without stressing other chips. A circuit can be designed to enlarge the current of the canary device. With the aid of the canary chip, we can make premonitory decisions on a continuous basis to avert that the solder joints fail to assess system health.

2. Prognostics and health management

Traditional reliability prediction methods for electronic products are usually based on prediction handbooks, which stem from the field failure data and list failure information of all kinds of components, including Mil-Hdbk-21, TelcordiaSR-332 (formerly Bellcore), PRISM, FIDES,CNET/RDF (European), and the Chinese GJB-299 (Jie GU, 2009).These methods assumed that the failure rate of an electronic component is constant and composed of different elements which represent various quality, environmental and other operating conditions.

However, more and more researches and engineering practices indicate that there are many mathematical and physical fallacies in this handbook prediction approach, leading to incorrect prediction results. Today it is widely considered that these methods are inaccurate and misleading and shouldn't be used any more in research and production.

A new alternative way is put into practice and called prognostics and health management (PHM).PHM is the process of monitoring the health of a product, and predicting the remaining useful life of the product by assessing the extent of deviation or degradation from its expected state of health and its expected usage conditions (Gang Niu, 2010). PHM has the following advantages: (1) providing advance warning of failures; (2) minimizing unplanned maintenance, extending maintenance cycles, and maintaining effectiveness through timely repair actions; (3) reducing the life cycle cost of equipment by decreasing inspection costs, downtime, and inventory; (4) improving qualification and assisting in the design and logistical support of fielded and future systems. In 2003, the U.S. Department of Defence claimed that the prognostics capability has become an important requirement for any U.S. military system.

PHM is a very popular research project in the reliability area. It evaluates the reliability of a system in its life cycle, and determines the advent of failure, and reduces dysfunctional system risks. A whole PHM system is a high-tech integrated system with hardware and software. Generally, the process of PHM includes data acquisition, data transmission, data preprocessing, health monitoring, fault diagnosis, fault prognosis and decision support for maintenance, and each part concerns many key techniques and methods (Hyunseok Oh, 2010).

Prognostics are technologies of predicting a product's remaining useful life based on a predefined confidence level and specified environmental stress. Many diagnosis methods can also be used in fault prognostics. Now prognosis methods mainly include physics of failure (POF) or reliability physics, data driven, canary methods and fusion method (Jie GU, 2008).

3. Canary device

Originated from the use of canary birds that was to protect miners from poisonous gases by warning early because they were more sensitive to dangerous environment, the word canary today is an approach in PHM (Wenbin Wang, 2011). The environmental and operational conditions the canary device and the actual system experience are the same so that the canary can be a monitor of the actual system. The environmental and operational conditions may include the stresses that lead to the degradation of a circuit such as voltage, current, temperature, humidity, vibration, radiation and so on. However, prognostic canaries are not only fuses in which the damage rate of the canary and the system are supposed the same , bus also designed to break down ahead of the system by suffering increased stress(e.g., current density).

Canary devices for an actual system can be used to provide advance failure warning due to specific wear-out failure mechanisms. For example, by using canaries located on the same chip as the actual circuitry, the applicability of semiconductor-level health monitors was studied by Mishra and Pecht (2002). Han et al. (2007) came up with an idea that developing a "canary-containing" packet attached externally to weapon casings can be used to receive environmental loading what the weapons experienced. A 90-nm 128-Kb test chip, where canary cells track changes in temperature and data-retention voltage, was demonstrated by Wang and Calhoun (2007) in order to detect the minimal value of a supply voltage. Also, a closed-loop approach using canary flip-flops was proposed by Calhoun et al. (2004) to enable power savings of over 40 times in a 0.13-μ m dual-test chip. Anderson and Wilcoxon (2004) used low cycle-fatigue solder joints and corrosion-susceptible circuits as canaries of the host printed circuit board and distinguished potential failure mechanisms. A prognostic cell was used by Goodman et al. (2006) to monitor the time-dependent dielectric breakdown of metal–oxide–semiconductor field-effect transistors on integrated circuits. However many progresses have been made , a small amount of papers about canary devices are published even all over the world during the past several years.

4. Design description of the canary device

In the traditional research about the electromigration of AL and Cu interconnects , the Black equation is applied to do life evaluation successfully. It shows that log-normal distribution is a good approximation for the TTF distribution when concerning MTTF, which is defined as the 50% of failure probability. Then the famous Black's equation was discovered and proved by experiments (1983). The so-called Black's equation is given as follows:

$$MTTF = \frac{A}{j^n} \exp\left(\frac{\Delta H}{KT}\right) \tag{1}$$

Where:

A is a pre-constant ;

n is a current-independent exponent.

J is the current density.

Log(MTTF) should be linearly if we take logarithm of both sides of this equation and make A,KT and DH stay constant related with log(j). The simulated results show that log(MTTF) can be related linearly with log(j).

However, due to the maldistribution of the current density and the notable local thermal effect, the Black equation cannot be used to evaluate solder joints' life caused by electromigration. C.Basaran and his workmates (2008) set up a life evaluation equation of solder joints' electromigration based on law of mass conservation and the diffusion theory of atoms with the help of finite-element analysis. The equation is shown below.

$$MTTF = \frac{a}{j^3} \exp\left(\frac{b}{t}\right) \tag{2}$$

where a and b are parameters to be determined by the least square method and t is time to failure, j is the current density, and T is temperature(K).

From the equation it is informed that the TTF of solder joints' electromigration only concerns the current density of the solder joints. With other conditions remain unchanged , we control the current of the canary device to ensure it sufficient but not overly large so that the canary fails before the solder joints under test.

Since the TTF of solder joints' electromigration only concerns the current density of the solder joints and has nothing to do with the type of component, we design a canary to monitor the solder joint of a metalster for convenience as shown in *Figure 1*.

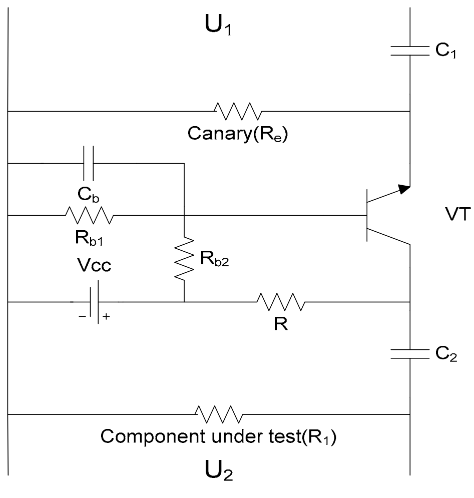

Figure 1: the Canary Design

In this design , the component under test is supposed to be a resistor R_1.R_1 is in a direct-current circuit. With the help of the canary design we can be warned before R_1 breaks down.

In the design , the reason we choose the metalster is that the reliability of solder joint only concerns the type of the solder joint itself and has nothing to do with the component .So in order to make the design easier , the metalster is applied. The key point of this canary circuit is to supply a larger current in proportion. So the idea of an amplifying circuit is come up with.

5. Calculation Of Current

A canary device must fail before the host circuit fails, which means that the cumulative failure probability of the canary must be close to unity before the cumulative failure probability of the circuit becomes appreciable. Goodman et al. (2006) suggested that the current design attempts to achieve a prognostic distance of 10% which means that before 90% of the time has elapsed at which 1% of the circuits have failed, 99% of the canary must have failed , and they gave the reliability requirement in terms of time-to-fail of the circuit and the canary device as below:

$$\frac{9}{10} t_{01\text{ , }circuit} = t_{99.canary} \tag{3}$$

R. E. HUMMEL and his workmates (1976) did lots of experiments and at last found that the resistance change rate caused by electromigration meets the equation below:

$$\frac{\Delta R}{R_0} = \frac{t}{l} v_B \tag{4}$$

Where V_B and l are parameters related with the environment and the material itself , R_0 is the initial resistance and △ R is the change rate. From the equation we are informed that the change of the resistance is linear. So combined formula (2) with formula (3) we have the equation:

$$\frac{9}{10} \frac{a}{j^3_{01\text{ , }circuit}} \exp\left(\frac{b}{T}\right) \times 0.01 = \frac{a}{j^3_{99\text{ , }canary}} \exp\left(\frac{b}{T}\right) \times 0.99 \tag{5}$$

From formula (5) it is easily obtained that:

$$\frac{j_{99\text{ , }canary}}{j_{01\text{ , }circuit}} = 4.7914 \tag{6}$$

Since the canary device is the same with the circuit under test in essence, so:

$$\frac{i_{99\text{ , }canary}}{i_{01\text{ , }circuit}} = \frac{j_{99\text{ , }canary}}{j_{01\text{ , }circuit}} = 4.7914 \tag{7}$$

The circuit in figure 1 is a functional common-base amplification circuit in fact , so it meets the equation shown below :

$$\frac{i_{99\text{ , }canary}}{i_{01\text{ , }circuit}} = \frac{1+\beta}{\frac{R_C}{R_L + R_C}\beta} = \frac{1+\beta}{\beta} \frac{R_L + R}{R} \tag{8}$$

Where : β =the current amplification coefficient

Hence the resistance value of R can be controlled to meet the requirements in formula (8) and (9) so that the current ratio can reach 4.7914. Assumed that the failure criteria is that the resistance value increases by 20% , we can detect the failure of the canary device by measure the value of the input resistance R_{in} of this circuit in real time. We have :

$$R_{in} = \frac{R_e \frac{r_{be}}{1+\beta}}{R_e + \frac{r_{be}}{1+\beta}} = \frac{R_e r_{be}}{(1+\beta) R_e + r_{be}} \quad (9)$$

With the calculation above , we can obtain the resistance change of both R1 and Re as shown below :

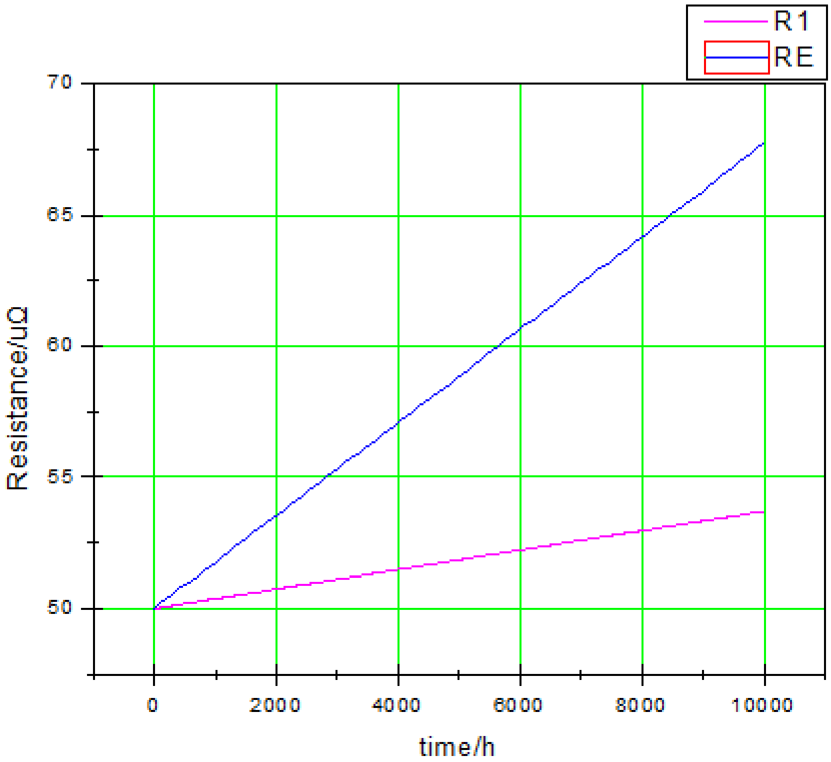

Figure 2: the resistance change of R1 and Re

6. Conclusions

In this paper , a canary device was designed to monitor the electromigration of the solder joint. The purpose to design the canary device is to monitor the operation of key devices which are in severe environment or are of high failure rate. Before the key device breaks down , the canary device fails. In order to achieve this goal , the canary device is designed independent with the key device and suffered properly increased environmental stress. Also the increased current we need was calculated. However there is still a long way to go to improve and perfect the canary device to make the prognosis of system health more convenient.

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