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Empirical Study on the Burn-in Time of SDRAM Products

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Abstract: The burn-in can be used to reduce warranty costs, particularly for products with an initially high failure rate that are sold under warranty. Because previous studies seldom account for burn-in error factors, this study consider such factors in our model to obtain an optimal burn-in time that corresponds more closely with reality. This study focuses on a burn-in test carried out on SDRAM products for the purpose of obtaining reliability and optimal burn-in time and test costs. This study will analyze and validate the data acquired from a life test to determine the types of distributions. The empirical analysis results of this study show that the lifetime of SDRAM products conforms to a Weibull distribution. If the lifetime of an SDRAM product is estimated under such a distribution, a cumulative failure of about 6799 ppm is acquired when the product is operated for one year under normal conditions which is much higher than goal of 100 ppm; thus for the SDRAM products used in this study, the execution of a burn-in is necessary.

Key words: Accelerated Life Testing (ALT), burn-in test, burn-in error, reliability test, reliability objective model

INTRODUCTION

The semi-conductor industry has developed quickly in recent years, leading to investment and construction of new wafer factories in nations across the globe, including China. With a constant increase in new productivity but with no obvious growth in demand, an excess supply of new wafers appears imminent. A key point in the competitive environment for the semi-conductor industry is that the customer must be at the center of any business strategy. Deregulation has made it possible for consumers to select their suppliers based on cost effectiveness (Ahmadi-Khatira *et al*., 2009). Due to a limited demand for their products, wafer factories will be forced to reduce their prices in order to survive, a phenomenon that is quite apparent in the SDRAM industry. Therefore, becoming the highest-ranking manufacturer requires not only improving the quality and reliability of the products produced but also reducing their manufacturing costs. Improvements in quality and reliability can be achieved by redesigning the product and using improved processes based on the Plan-Do-Check-Action (PDCA) cycle. Reliability is one of the most important quality attributes of commercial software since it quantifies software failures during the development process (Huang and Lo, 2006). In order to increase the reliability, Semiconductor manufacturer should have a comprehensive test plan that ensures all requirements are included and tested.

Semiconductor manufacturing consists of two major steps: fabrication of integrated circuits onto wafers to form dies and assembly of each die into a finished product. While burn-in is beneficial to improving the reliability of products shipped to customers, it is costly since burn-in test equipment is highly expensive and burn-in boards are expendable materials that should be replaced regularly (Tong and Yum, 2008). One method to reduce overall costs, other than through a reduction in processing and material costs, is through a reduction in test costs. Test costs in SDRAM products are of two types, those due to functional tests and those due to burn-in tests. In the former type, the duration of the functional test is usually related to the contents and complexity of the test procedures. The content and complexity of the test procedures are dependent on the product specifications. Therefore, if the specifications are fixed, the time needed for an electrical performance test is also be fixed and the test cost can only be slightly reduced. The burn-in test cost depends on the duration of a burn-in test which is in turn related to the guaranteed level of reliability and burn-in strategy used. The

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determination of different reliability levels and burn-in strategies depends on burn-in time.

By conducting a burn-in test for all manufactured devices, most semiconductor manufacturing companies typically screen out semiconductor devices with early field failures. Moreover, they evaluate their long-term reliability by conducting accelerated life tests for sample devices for an extended duration (Lee and Park, 2008). A burn-in test is used to improve product quality and reliability. A burn-in can be used to reduce warranty costs, particularly for products with an initially high failure rate that are sold under warranty. Since a burn-in is usually expensive and adds directly to a product's manufacturing cost, optimizing the duration of the burn-in procedure is a major concern (Sheu and Chien, 2005). However, a burn-in is beneficial for improving the reliability of products shipped to customers. An efficient burn-in can be achieved by establishing a rational policy for factors such as burn-in duration and burn-in conditions, such that the required in-field reliability is assured and the related costs are minimized (Tong and Yum, 2008).

This study focuses on a burn-in test carried out on SDRAM products for the purpose of obtaining reliability and optimal burn-in time and test costs. When analyzing data obtained from a burn-in test, one should first know the statistical distribution of the product life data determined during the test. This study will analyze and validate the data acquired from a life test to determine the types of distributions. Additionally, the burn-in strategy is an important factor that affects the burn-in time. In this study, we will establish a model for achieving good reliability and minimum cost. Because previous studies seldom account for burn-in error factors, we consider such factors in our model to obtain an optimal burn-in time that corresponds more closely with reality.

A burn-in is used to eliminate products with early failures at the proper time by utilizing accelerated stress environments in order to increase the reliability of product use. Kar and Nachlas (1997) found that the execution of a burn-in test is only meaningful for products with gradually decreasing failure rates. Lawrence (1966) also showed that when an electronic product starts being used after its market introduction, a gradual decrease is often observed in its failure rate. Therefore, SDRAM products that belong to the semi-conductor industry are prime candidates for burn-in tests, using which their reliability can be improved.

Accelerated life testing: Accelerated Life Testing (ALT) has been widely applied in modern manufacturing industries. However, as products are becoming more reliable, a challenge faced in both ALT planning and inference is that failures can be elusive at low stress levels within a reasonable timeframe (Liu and Tang, 2010). ALT is a common way to determine the reliability of parts for operating conditions. Typically, parts age at different (high) temperatures and their resulting failure times are used to predict the time-to-failure at usage (low) temperatures (Whitman, 2003). ALT exposes products to stress levels that are higher than normal; the stress is in terms of temperature, voltage and usage rates. In this manner, data of a product's expected lifetime can be quickly obtained. On account of time and resource constraints, ALT provides an economical way of obtaining lifetime data (Pascual, 2010). The purpose of executing a life test is to obtain information pertaining to the life of a product. However, if a general life test is carried out on products having a long life expectancy, obtaining the appropriate data will consume a large amount of time. A life test cannot reveal the required information for the process and production departments in a timely manner for continual quality improvement. However, an ALT aims at improving product defects and obtaining product life expectancy data more quickly. Peiravi and Dehqanmongabadi (2008) proposed an ALT that applies higher stress on a product than is generally expected (e.g., higher voltage, temperature, humidity, corrosion, magnetic field and vibration), creating a faster deterioration of the product's material or parts in order to obtain the required information more quickly. Ke (2002) classified ALT tests into different types: stress-accelerated life test, time-accelerated life test and analyzing-accelerated life test. This study conducts an accelerated life test through the use of stress. A stress-accelerated life test is a hybrid type of accelerated life test that involves constant temperature and voltage stresses.

Acceleration test factor: Inferring the expected lifetime of a product under normal use on the basis of an accelerated life test must be made through the conversion of one acceleration factor. This factor can be acquired by properly selecting the stress mode. This study adopts a hybrid stress accelerated life test. Therefore, the acceleration test factor can be acquired using the Eyring model. Ke (2002) proposed the following version of the Eyring model:

The relation among the lifetime η, temperature T (absolute temperature K) and temperature outer stress u is as follows:

$$\eta = C \times \exp(\frac{E}{KT}) \times (\frac{1}{\mu^m}) \qquad (1)$$

where, C and m are constants, E is the activation energy, K is Boltzmann's constant and the acceleration factor $A\eta$ is presented as:

$$A_{\eta} = (\frac{\mu_a}{\mu_n})^m \times \exp\left[(\frac{E}{K}) \times (\frac{1}{T_u} - \frac{1}{T_a}) \right] \quad (2)$$

where, T_n and μ_n and T_a and μ_a are the temperature and stress under normal operation and accelerated test conditions, respectively. SDRAMs were researched in this study. Through an Eyring model calculation, an acceleration factor of 91865.28 was acquired; this indicates that an accelerated life test carried out over a 1-h period equals 91865.28 h of operation under normal conditions.

Optimal burn-in time analysis method: Determining the optimal burn-in time depends on the analysis method adopted. Common methods can be divided into four types:

Average residual life maximization method: The average residual life acquired from a failure constant is maximal after a burn-in test is carried out and the required burn-in time is then determined. Whitbeck and Leemis (1989), Mi (1995) and Chang (2000) adopted this method of optimal burn-in time acquisition. This method usually focuses on whether the mean lifetime increases after a burn-in test is conducted which often neglects costs and profit and thus a burn-in time acquired using this method is not economical.

Reliability objective model: To acquire the burn-in time, the reliability objective to be achieved needs to be clarified and then the value of the reliability objective needs to be added to the cumulative failure function. Lawrence (1966) and Ebeling (1997) based this method of application on articles.

Minimizing cost model: This method is based on research articles by Nguyen and Murthy (1982), Chou and Tang (1992), Wu and Su (2002) and Yun *et al.* (2002), who determined the optimal burn-in time by considering the manufacturing costs, burn-in costs and assurance costs in order to minimize the total average costs.

Baye's method: Baye's method is usually applied to an estimation of conversion points in a hybrid distribution. For example, a Weibull distribution is used to describe early failures and an exponential distribution is used to describe a normal phase. Conversion points used in Weibull and Exponential distributions are acquired using Baye's method and the optimal burn-in time is thus acquired. This method of application is based on articles by Boukai (1987) and Chou and Tang (1992). Chien and Kuo (1997) addressed Baye's non-parametric method to determine the burn-in time of a system by targeting the average residual life of the system as its goal. This study adopted the reliability objective model and minimizing cost model to study the optimal burn-in time and considered the effects that burn-in errors have on a product. The model proposed in the study was modified using the reliability objective model and minimizing cost model in order to acquire an optimal burn-in time that conforms more closely to an actual burn-in situation.

RESEARCH METHOD

Life test: A life test aims at obtaining the life data of a product and is carried out using the following steps:

Step 1: The life test is carried out in a burn-in furnace using 10,000 DDR SDRAM ICs

Step 2: Eleven test points are set (1, 2, 4, 6, 8, 10, 15, 20, 30, 45 and 60 h) on the basis of the test points of the life test machine which are provided by the SDRAM manufacturer

Step 3: When the test moves to a particular test point, the SDRAM IC is removed and subjected to a functional test in order to verify whether it failed

Step 4: After the time and occurrence of failure are recorded, if an SDRAM IC is determined to be qualified, it is put into the burn-in furnace and a test to obtain the next reading is carried out until the test point of 60 h is reached

Analysis of product life distribution: Data acquired during a life test requires validation based on statistical distribution. Data are added into the adopted analysis method to calculate the proper burn-in time only when the estimated parameter value is acquired. This study conducts a parameter analysis using four types of distribution, e.g., normal distribution, lognormal distribution, exponential distribution and Weibull distribution. Next, the estimated values are used to conduct normal and Kolmogorov-Smirnov goodness-of-fit tests in order to find a statistical distribution conforming to the lifetime test data.

Establishment of burn-in model: When the statistical distribution of a product's lifetime is validated, the optimal burn-in time can be calculated using the reliability objective model and minimizing cost model under general conditions with the appropriate burn-in errors added.

If the reliability objective function or cumulative failure objective function Fe is known, the reliability objective model is established under general conditions using the following equation:

$$\tilde{F}(t_0) = F(T + t_0) - F(T) = F_e \tag{3}$$

where, T is the burn-in time, t_0 is the operation time, $\tilde{F}(t_0)$ is the cumulative failure function after operation for time t_0 and F $(T+t_0)$ is the cumulative failure function including the burn-in test and operation time.

Ebeling (1997) proposed that if n products are manufactured and the reliability function of the products is R(t), the expected number of failures during the burn-in will be n[1-R(T)]. During operation, the expected number of failures is:

$$\begin{aligned} nR(T)\left[1 - R(t_0|T)\right] &= nR(T)\left[1 - \frac{R(t_0 + T)}{R(T)}\right] \\ &= n\left[R(T) - R(t_0 + T)\right] \end{aligned} \tag{4}$$

When the unit cost of a burn-in test is C_b, the unit cost of a failure during the burn-in is C_f and the unit cost of failure during operation is C_0, the expected total cost is:

$$\begin{aligned} E(C_T) = nC_b \times T + C_f \times n[1 - R(T)] \\ + C_0 \times n\left[R(T) - R(t_0 + T)\right] \end{aligned} \tag{5}$$

The total cost of an average unit can be presented as follows:

$$\begin{aligned} E(C) = \frac{E(C_T)}{n} = C_b \times T + C_f \times [1 - R(T)] \\ + C_0 \times \left[R(T) - R(t_0 + T)\right] \end{aligned} \tag{6}$$

Thus, the model used for the total cost of an average unit can be presented as follows:

$$E(C) = C_b \times T + C_f \times F(T) + C_0 \times \tilde{F}(t_0) \tag{7}$$

When the burn-in error factors are included in the above two models, the necessary correction is made on the basis of the probability distribution situation.

ESTABLISH OF MODEL

The establishment of a burn-in test model involves general and burn-in error conditions which are described in the following section.

General conditions

Reliability objective model conditions: Reliability objective model conditions are acquired from $\tilde{F}(t_0) = F(T + t_0) - F(T) = F_e$, such that:

$$F(T + t_0) - F(T) - F_e = 0$$

and

$$F(t) = 1 - \exp\left[-(\frac{t}{\theta})^\beta\right] \tag{8}$$

By adding the Weibull cumulative distribution function t = 0 into the above equation, it can be inferred that:

$$\exp\left[-(\frac{T}{\theta})^\beta\right] - \exp\left[-\left(\frac{T + t_0}{\theta}\right)^\beta\right] - F_e = 0 \tag{9}$$

The parameters θ and β have estimated values of θ = 2.3514E+22 and β = 0.0926.

If an accelerated life test is used for the burn-in test, the acceleration test factor becomes 91865.28. Therefore, if the product is used for one year (8760 h) under normal operation conditions, it equals an operation of 8760/9186.28 = 0.09536 h in an accelerated-life-test environment, namely t_0 = 0.09536. If the product is required to operate under normal conditions for one year, Fe becomes 100 ppm (i.e., 0.0001) and T = 0.6378 h is obtained through a value analysis.

Minimizing cost model conditions: If we add a Weibull distribution into the model of total cost for an average unit, then the following equation is obtained:

$$\begin{aligned} E(C) &= C_b \times T + C_f \times F(T) + C_0 \times \tilde{F}(t_0) \\ E(C) &= C_b \times T + C_f \times \left\{1 - \exp\left[-(\frac{T}{\theta})^\beta\right]\right\} \\ &+ C_0 \times \left\{\exp\left[-(\frac{T}{\theta})^\beta\right] - \exp\left[-\left(\frac{T + t_0}{\theta}\right)^\beta\right]\right\} \end{aligned} \tag{10}$$

When C_b = 0.4, C_f = 105, C_0 = 2800 and t = 0.09536, the minimal total cost of an average unit becomes T = 0.5274.

Burn-in error conditions: Kim (1998) proposed a burn-in probability model. As listed in Table 1, probability PP_B refers to a burn-in error and indicates the probability of bad products still surviving after a burn-in test.

Table 1: Probability model of burn-in tests

Burn-in results	Good population	Bad population
Survivorship	$(1-p)\ (1-p_G)$	pp_B
Failure	$(1-p)\ p_G$	$p(1-p_B)$

Resources: Kim (1998)

Table 2: Modify probability model of burn-in tests

Burn-in results	Good population	Bad population
Survivorship	[1-F(T)] (1-p_R)	[1-F(T)] p_R
Failure	F(T)	

p_R is the probability that parts found within a bad population survive after a burn-in, namely, the probability of a burn-in error

The term p4 refers to the probability that the parts belong to a bad population, p_G refers to the probability that the parts belong to a good population and fail after a burn-in test and p_B refers to the probability that the parts belong to a bad population and survive after a burn-in test.

Considering the practice used in the SDRAM industry, after a burn-in failed parts are often cannot be easily identified as qualified or disqualified material and thus the failure probability of two materials can be integrated into a cumulative failure probability during burn-in F(T). Additionally, a nonzero pp_B probability may lead to complaints or the return of goods by customers; this may greatly affect the operation and brand image of a company. Thus, this study corrects the burn-in probability after considering the burn-in error factor, as provided in Table 2.

Reliability objective model conditions: Considering the burn-in error probability, the reliability objective model is corrected as follows:

$$(1-p_R)\times[F(T+t_0)-F(T)]+p_R\times F(t_0)-F_e=0 \tag{11}$$

After a Weibull cumulative distribution is added into the above equation, the following equation is obtained:

$$\begin{aligned}&(1-p_R)\times\left\{\exp\left[-(\frac{T}{\theta})^{\beta}\right]-\exp\left[-\left(\frac{T+t_0}{\theta}\right)^{\beta}\right]\right\}\\&+p_R\times\left\{1-\exp\left[-(\frac{t_0}{\theta})^{\beta}\right]\right\}-F_e=0\end{aligned} \tag{12}$$

If p_R = 0.2%, t_0 = 0.09536 and F_e = 100 ppm, the optimal burn-in time determined through a value analysis is T = 0.7976 h.

Minimizing cost model conditions: Considering the probability of a burn-in error, the total cost of an average unit is corrected as follows:

$$\begin{aligned}&E(C)=C_b\times T+C_f\times F(T)\\&+C_0\times\{(1-p_R)\times[F(T+t_0)-F(T)]+p_R\times F(t_0)\}\end{aligned} \tag{13}$$

After a Weibull distribution is added into the above equation, the following equation is obtained:

$$\begin{aligned}E(C)=&C_b\times T+C_f\times\left\{1-\exp\left[-(\frac{T}{\theta})^{\beta}\right]\right\}\\&+C_0\times\left\{(1-p_R)\times\left\{\exp\left[-\left(\frac{T}{\theta}\right)^{\beta}\right]-\exp\left[-\left(\frac{T+t_0}{\theta}\right)^{\beta}\right]\right\}\right\}\\&+p_R\times\left\{1-\exp\left[-\left(\frac{t_0}{\theta}\right)^{\beta}\right]\right\}\end{aligned} \tag{14}$$

When C_b = 0.4, C_f = 105, C_0 = 2800, t = 0.09536 and p_R = 0.2%, the obtained minimum total cost of an average unit is T = 0.5267 h.

EMPIRICAL STUDY

The accelerated life testing goal is penetrates strengthens the environmental factor to obtain the experimental result earlier. Therefore, this study was used to conduct a life test on 10,000 DDR SDRAM ICs in a burn-in furnace; the results are provided in Table 3. From Table 3 demonstrated that f (t) in the 1st h is 0.82, f (t) along with this testing time to become stable in the 4th h. Its h (t) in previous 2 h highest is getting more and more low to the 4th h. It can be noted from Table 3 that the failure rate of SDRAM ICs tends to gradually decrease over time and therefore products showing early deterioration can be removed by means of a burn-in test which increases their reliability:

$$h(t)=\frac{f(t)}{[1-F(t)]\times\Delta t} \tag{15}$$

where, h (t) is the failure function, f (t) is the probability density distribution, F (t) is the cumulative distribution function and Δt is the time interval.

Thus, the following equation is obtained:

$$h(1)=\frac{f(1)}{[1-F(t)]\times 1}=\frac{0.82}{1-0.82}=0.827$$

The rest can be inferred using the above equation.

On the basis of the above test data, the parameters are estimated using the minimal square method under normal distribution, lognormal normal distribution, exponential distribution and Weibull distribution (Ramakumar, 1993). Then, under a significant level of α = 0.05, the Chi-square and Kolmogorov-Smirnov goodness-of-fit tests are carried out (Ramakumar, 1993), the results of which are given in Table 4. By Chi-square test understood whether the above four kind of distribution function does conform to which probability distribution function, discovered that only has Weibull and lognormal distribution accepts null hypothesis. Next,

Table 3: Results of life test experiment

t (h)	Failed count	Failed count (cum.)	f (t)	F(t)	h (t)
1	82	82	0.82	0.82	0.827
2	11	93	0.11	0.93	0.111
4	4	97	0.04	0.97	0.020
6	2	99	0.02	0.99	0.010
8	4	103	0.04	1.03	0.020
10	2	105	0.02	1.05	0.010
15	3	108	0.03	1.08	0.006
20	1	109	0.01	1.09	0.002
30	6	115	0.06	1.15	0.006
45	5	120	0.05	1.20	0.003
60	4	124	0.04	1.24	0.003

Failed count (cum.): Failed count cumulative value

Table 4: Results of goodness-of-fit tests

Dstribution	χ^{2-} test value	χ^{2-} test determination	K-S test value value	K-S test determination value
Normal distrobution	5.71070*	3.84	0.00131$^{\#}$	0.0136
Lognormal distribution	0.33849$^{\#}$		0.000298$^{\#}$	
Weibull distribution	0.28298$^{\#}$		0.000298$^{\#}$	
Exponential distribution	913.943$^{\#}$		0.0098$^{\#}$	

*Reject hypothesis. $^{\#}$Accept hypothesis

penetrates Kolmogorov-Smirnov test again, discovered that four kinds of distribution functions all accept null hypothesis; Expressed that SDRAM products burn-in time only has Weibull distribution and lognormal distribution is tallies. Through a comparison of these results, it can be seen that when a Weibull distribution is defined, the fitness is optimal, followed by lognormal distribution; thus this study has discussed the optimal burn-in time by means of a Weibull distribution.

CONCLUSIONS

Two major questions must be answered when conducting research on the use of burn-in tests: the first question is whether it is necessary to execute a burn-in test at all. If the answer is yes, the second question is, how long does the burn-in test need to be? For the first question, the answer is usually related with the goals specified by the manufacturers. For SDRAM products, the goal is usually stipulated as a cumulative failure smaller than 100 ppm when operating for one year under normal conditions. Given the current reliability levels of products, if this goal is achieved without the execution of a burn-in test, then a burn-in test is not necessary. The empirical analysis results of this study show that the lifetime of SDRAM products conforms to a Weibull distribution. If the lifetime of an SDRAM product is estimated under such a distribution, a cumulative failure of about 6799 ppm is acquired when the product is operated for one year under normal conditions which is much higher than goal of 100 ppm; thus for the SDRAM products used in this study, the execution of a burn-in is necessary. The answer to the second question depends on the burn-in model adopted. Four burn-in models were proposed in this study. These four burn-in models conform to an actual industry environment because they take the burn-in error condition into account. Because no operator can ensure that a burn-in error did not occur in a product being practically used, the probability of a burn-in error can be acquired by analyzing the data of customer complaints.

Within the burn-in error condition, the choice of using the reliability objective model or minimizing cost model depends on the choice made by the enterprise. According to the results obtained in this study, if operation time $t_0 = 1$ y, the difference in optimal burn-in time between the reliability objective model and minimizing cost model is 0.2709 h and the difference in the total cost of an average unit is NT$ 1.4680-1.4285 = 0.0395. If an analysis conducted using this case study reveals a small difference, then the reliability objective model should be executed to guarantee proper quality commitment to customers. Therefore, upon operating for one year under normal conditions after conducting a burn-in, if the cumulative failure objective value is 100 ppm and the burn-in error probability is 0.2%, the optimal burn-in time for an SDRAM IC is 0.7976 h.

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