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EKONOMICZNY MODEL BADAŃ NIEZAWODNOŚCIOWYCH GOI

ECONOMIC DESIGN FOR GOI RELIABILITY TESTS

Niniejsza praca analizuje metody i wytyczne dotyczące wyznaczania minimalnego rozmiaru próbki podane we wspólnej publikacji JEDEC/ FSA, wskazując na ich wady, niekonsekwencje i błędne wskazówki. W artykule podajemy dokładne i łatwe w użyciu rozwiązanie, które rozciąga wzór JEDEC na wszelką dozwoloną liczbę uszkodzeń, dopuszczalną gęstość defektów i poziom ufności. Przedstawiamy również ważne wytyczne dla specjalistów w zakresie niezawodności pozwalające zredukować możliwe błędy wynikające z niedoskonałych procedur próbkowania oraz uniknąć pomyłek w ocenie gęstości defektów względem dopuszczalnej gęstości defektów (D0). Proponowana przez nas metoda może być stosowana we wszelkich testach niezawodnościowych z rozkładem dwumianowym do wyznaczania minimalnego rozmiaru próbki przy oszczędnym użyciu płytek i środków badawczych.

Słowa kluczowe: *Minimalny rozmiar próbki, badanie V-Ramp, GOI (Nienaruszony Stan Tlenku Bramkowego), gęstość defektów, próbkowanie losowe, rozkład dwumianowy, granice przedziału ufności.*

This paper studies the methods and guidelines in minimum sample size determination provided by JEDEC/ FSA joint publication and points out their drawbacks, inconsistency, and misguidance. We provide an exact method and easy-to-use numerical solution by extending JEDEC's formula to any allowed failure number, target defect density, and confidence level. Important guidelines are also provided for reliability practitioners to reduce possible errors resulting from imperfect sampling procedures and to avoid mistakes in defect density evaluation against a target defect density (D_0). Our proposed method can be applied to any reliability tests with the binomial distribution to determine a minimum sample size to save wafers and testing resources.

Keywords: *Minimum sample size, V-Ramp test, GOI (Gate Oxide Integrity), defect density, random sampling, binomial distribution, confidence bounds.*

1. Introduction

Gate Oxide Integrity (GOI) of MOS devices has been a very important reliability concern [12]. The defects introduced during processing can significantly degrade oxide quality and lifetime [9]. The V-Ramp test is an important test for GOI [1]. Due to the defects randomly distributed in device sensitive area, an oxide stressed with a fixed electric field will wear out and break down eventually [8]. At a V-Ramp test, a pre-specified electric stress is applied on MOS structures and we measure the maximum electric field the structures can withstand before dielectric breakdown. The dielectric breakdown failure proportion (p) can be converted to a corresponding defect density (D) by [11]:

$$1 - p = \exp [- D A_{Test}] \quad (1)$$

where A_{Test} is the gate area per test structure.

The criterion for a product under GOI qualification is to meet the requirement that the defect density D be lower than a target defect density (also named acceptable defect density) D_0.

A sound process of V-Ramp GOI qualification involves the selection of appropriate stress conditions, an economic sample size for the device under test, and statistically sound data analysis approaches. The determination of economic sample size is a sophisticated topic in statistics. In order to facilitate reliability practitioners in sample size selection for V-Ramp qualification, JEDEC (the leading developer of standards for the world solid-state industry) provides guidelines in an international standard JEDEC/FSA Joint Publication (JP001.01, Feb 2004) [7]. In item 10 for "Gate Oxide Integrity" on page 16, the sample size (N) to demonstrate a target defect density (D_0) is given by [7]:

$$N > -\ln(1-0.95)/D_0 A_{Test} \quad (2)$$

However, no guideline in defect density evaluation is given in this joint publication. This leads to disagreement in defect density evaluation among reliability practitioners in IC industries. Most users adopt the recommended sample size but use a point estimate to do defect density calculation and evaluation against the target defect density D_0. When the calculated point estimate defect density D through Eq. (1) is lower than D_0, they conclude that the product under test meets the requirement that the defect density be lower than the target defect density, D_0. For example, assume the test area A_{Test} = 3 mm^2 = 0.03cm^2, and D_0 = 1/cm^2. By Eq. (2), the calculated sample size, N> -ln(1-0.95)/(0.03cm^2*1/cm^2)≅100. If only one test structure breaks down (i.e., the failure number, f, is 1), $p = f/N$ = 1/100=0.01. The determined defect density D = 0.335/cm^2 by Eq. (1) is smaller than the required D_0 (= 1/cm^2). The engineer then concludes this product meets the criterion. However, as will be illustrated later in this paper, the confidence level for such conclusion is very low and should be claimed as failing to meet the requirement under 95% confidence level.

On the other hand, JEDEC/FSA (item 10.1, page 17) provides a different guideline for the sample size besides Eq. (2). This guideline suggests the minimum total area to be 10cm^2 for both NMOS and PMOS capacitor test structures [7]. Based on this, the minimum sample size for either NMOS or PMOS devices will be 10cm^2 /0.03cm^2 /2= 167 if we use the same test area of 0.03cm^2 as in the earlier example. This sample size is much larger than the 100 determined by Eq. (2) and is therefore inconsistent with the first guideline by the same JEDEC/FSA Joint Publication. Assume that there are 4 failures ($f = 4$), then $p = f/N = 4/167=0.024$ and the calculated defect density will be $D = 0.81/cm^2$, also lower than target defect density $D_0 = 1/cm^2$. Again, as will be illustrated later in this paper, the confidence level for this conclusion is also very low and it should be claimed as failing to meet the requirement under 95% confidence level. Besides, this second sample size determination using the area method does not require the pre-specified target defect density D_0! This does not make sense since the required sample size should depend on the magnitude of the pre-specified D_0 (which will be illustrated later).

We employ binomial statistics and derive exact and generic equations for determining the minimum sample size under any allowed failure number (f), target defect density (D_0), and confidence level 100(1-α)%. Besides, we provide important guidelines for practitioners to avoid mistakes in defect density evaluation against a target defect density D_0 and also caution practitioners the hidden uncertainty resulting from the realistic non-randomness of the chips selected in the imperfect sampling procedures.

2. Statistical comparison for defect density

The success/failure testing describes a situation where a product (a component or system) is subjected to a test for a specified duration T (or stress intervals, distance or cycles, etc). The product either survives (i.e., survives the test) or fails prior to T [5, 6]. The probability model for this kind of testing situation is the binomial probability distribution given by [10]

$$P(f;N,p) = \frac{N!}{f!(N-f)!} p^f (1-p)^{N-f} \quad (3)$$

where N is the sample size of products under test; f is the number of failed products after the reliability test; and p is the probability of failure (which is usually named as population failure proportion or percentage). This probability of failure (p) is different from the point estimator of failure proportion $\hat{p} = \frac{f}{N}$.

Using the beta distribution, Grosh derived the exact expression for the confidence limits for the point estimate of failure proportion p [4]. The one-sided upper 100(1-α)% confidence limit for the point estimator $\hat{p}$ is:

$$p_{ucl} = \frac{(f+1)F_a[2(f+1), 2(N-f)]}{(N-f)+(f+1)F_a[2(f+1), 2(N-f)]} \quad (4)$$

where $F_\alpha[2(f+1), 2(N-f)]$ is the upper α percentage point of the F distribution with DOF (degrees of freedom) of $2(f+1)$ and $2N(N-f)$ [3].

From Eq. (1), we can obtain the one-sided 100(1-α)% upper confidence limit (D_{UCL}) for the calculated defect density D:

$$D_{UCL} = \frac{-\ln(1-p_{UCL})}{A_{test}} \quad (5)$$

D_{UCL} should be the one to be compared with the target D_0. When D_{UCL} is less than D_0, we conclude that the products under qualification pass the requirement with 100(1-α)% confidence. The widely accepted confidence level is 95% (i.e., $\alpha = 0.05$).

In the first example in Section I, the point estimate of p is $\hat{p} = \frac{f}{N} = \frac{1}{100} = 0.01$, and the point estimate of D is then $\hat{D} = \frac{-\ln(1-\hat{p})}{A_{test}} = \frac{-\ln(1-0.01)}{0.03cm^2} = 0.335cm^2$. However, the one-sided 95% confidence limit for the failure proportion is $p_{ucl} = 0.0466$, and its corresponding $D_{UCL} = \frac{-\ln(1-p_{UCL})}{A_{test}} = \frac{-\ln(1-0.0466)}{0.03cm^2} = 1.59/cm^2$, which is larger than the target D_0 (= $1/cm^2$). The conclusion here is contradictory to the previous one in Section I using the simple point estimate for comparison.

For the second example in Section I, the point estimate of p is $\hat{p} = \frac{f}{N} = \frac{4}{167} = 0.024$ and $\hat{D} = \frac{-\ln(1-\hat{p})}{A_{test}} = \frac{-\ln(1-0.024)}{0.03cm^2} = 0.808cm^2$.

However, the one-sided 95% confidence limit for the failure proportion is p_{ucl}=0.0530, and its corresponding $D_{UCL} = \frac{-\ln(1-p_{UCL})}{A_{test}} = \frac{-\ln(1-0.808)}{0.03cm^2} = 55.0/cm^2$, which is much larger than the target defect density $D_0 = 1/cm^2$! The conclusion here is also contradictory to the previous conclusion in Section I using the simple point estimate for comparison.

3. Economic design with minimum sample size

We propose to use the exact and conservative one-sided binomial hypothesis test [2]. Assume that the samples tested have constant failure percentage p, which requires uniform samples and selecting samples with good randomness.

Let $B(f; N, p)$ be a binomial CDF (Cumulative Distribution Function). Then a conservative size α test of H_0: $p \geq p_0$ against H_1: $p < p_0$ is to reject H_0 if $B(f; N, p_0) \leq$ That is,

$$B(f;N,p_0) = \sum_{i=0}^{f} \frac{N!}{i!*(N-i)!} p_0^i (1-p_0)^{N-i} \leq \alpha \quad (6)$$

The p_0 in Eq. (6) is actually the p_{UCL} determined from D_{UCL} (equivalently the given target defect density D_0) and test area A_{Test} through Eq. (5). Namely,

$$p_{UCL} = 1 - \exp(-D_0 * A_{Test}) \quad (7)$$

For pre specified $f = 0$, we can obtain an analytical solution for the minimum sample size N using Eq. (6) with f=0.

$$B(f;N,p_0) = (1-p_0)^N = [\exp(-D_0 * A_{test})]^N = \exp(-N * D_0 * A_{test}) \leq \alpha$$

Thus, we have the minimum sample size when the pre specified allowable failure number $f = 0$:

$$N \geq \frac{-\ln(\alpha)}{D_0 A_{test}} \quad (8)$$

When $\alpha = 0.05$, Eq. (8) becomes Eq. (2). However, JEDEC/ FSA Joint Publication [6] did not mention how to use this obtained sample size, not to mention that it is for $f = 0$ only. Therefore, most practitioners have been misusing the sample size that JEDEC/ FSA Joint Publication provides in Eq. (2). People who use this calculated sample size evaluate their product's defect density by estimated defect density, as illustrated with examples in Section I. The correct usage of Eq. (8) should be as follows.

When the minimum sample size obtained using Eq. (8) is used for V-ramp testing and zero device is found failed (i.e. f=0) after all devices finish testing, we conclude that the product under test shall pass, with 100 (1-α)% confidence level, the requirement that its defect density be lower than target defect density D_0. If the number of failed devices is larger than zero, the product under test fails the defect density requirement. This makes the statistical comparison much easier than using Eq. (4) and at the same time, the chosen sample size is most economic comparing cases if a larger sample size is used, such as the second guideline using total test area from JEDEC/ FSA (item 10.1, page 17) [7].

However, the minimum sample size using pre-specified f=0 using Eq. (8) has a potential drawback when the sampling of devices to test is not perfectly randomized. The randomization of sampling is the premise for statistical hypothesis testing. However, the impact extent of imperfect sampling could be alleviated significantly by choosing pre-specified failure numbers f larger than zero. The larger the f chosen, the less impact on the conclusion from statistical hypothesis test. Therefore there is a need to use $f>0$.

For a pre-specified f>0 (and also given D_0, α, f and A_{Test}), we can determine the minimum sample size N using the equation below.

$$\frac{(f+1)F_{a}[2(f+1),2(N-f)]}{(N-f)+(f+1)F_{a}[2(f+1),2(N-f)]}=1-\exp(-D_0 * A_{Test}) \quad (9)$$

This equation is obtained by combining Eq. (4) and Eq. (7). Since the F function in Eq. (9) is a very complicated integral involving the Gamma functions, the numerical solution of N is quite difficult. Fortunately, we have easy access to the numerical tabulation of the F function from the popular Microsoft Excel, which has $FINV[\alpha,n_1,n_2]=F_{\alpha}[n_1,n_2]$. In Excel, we establish two columns using the left and right sides of Eq. (9) respectively with different possible N. The solution of N can be easily obtained by finding the row which assures the matching left and right sides of Eq. (9). The above operations only take a couple of minutes. This greatly facilitates reliability practitioners to determine the minimum sample size for any pre-specified failure number f, target defect density D_0, test area A_{Test}, and confidence level 100(1-α)%; this is not available yet in any current JEDEC standard and reliability literature.

After the V-ramp testing with the minimum sample size determined hereinabove, if the actual failure number is less than or equal to the pre-specified allowed f, we conclude that the defect density D meets the requirement that the product under test be lower than target D_0 with 100(1-α)% confidence.

4. Economic test with earlier decision employing the minimum sample size method

The result or the actual defect density level of the V-ramp test is usually unknown in advance. The conventional practice is that all prepared devices finish the V-ramp test before the calculation of estimated defect density. Therefore, if the number of devices of more than the minimum sample size is used in testing such as the planned sample size determined by the second guideline in JEDEC/ FAS joint publication, it will certainly result in big waste of time and resources.

With the method of the minimum sample size discussed earlier, we could make early conclusion that the product under test fails the defect density requirement if larger than or equal to one device is found failed during testing before the number of devices tested reaches the minimum sample size for pre specified f=0. This could save time and resources. However this requires us to assure good randomness of the sampling process. If the realistic imperfect sampling requires us to use pre specified f>0, such as f=2, we still could terminate the testing earlier to save time and resources if more than 2 devices failed already during the testing before the sample size of devices finishing testing reaches the minimum sample size corresponding the pre specified f=2.

5. Conclusions

The drawbacks and inconsistency of two guidelines in JEDEC/ FAS joint publication for the minimum sample size to be used in V-Ramp GOI tests have been pointed out and discussed in details. An exact method for any allowed failure number, target defect density, test area and confidence level is proposed based on the conservative binomial hypothesis test. The minimum sample size has been extended to any pre-specified allowed failure number. This has realistic and practical applications considering the difficulty to maintain the pure randomness during sampling procedures in some circumstances. An easy-to-use method using a spreadsheet software package like Excel has made it possible for reliability practitioners to determine the minimum sample size from the complex equation for f>0. This exact method is not available yet from any current JEDEC standard and reliability literature. Additional benefit can be obtained to make earlier conclusions for an economic test by employing the minimum sample size method for some circumstances if the actual defect density is higher than the specified. Furthermore the minimum sample size method can also be applied in many other reliability tests requiring the determination of a minimum sample size to save wafers and testing resources as long as the binomial distribution is applicable.

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