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Investigation Into The Correct Statistical Distribution For Oxide Breakdown Versus The Oxide Thickness Used In Integrated Circuit Manufacture

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Abstract

A critical aspect of integrated circuit manufacturing is the reliability of the components, in particular the gate oxide of transistors and capacitors. Accelerated stress tests are used for reliability predictions of gate oxides. There are two statistical distributions, which can be applied to stress test failure data, namely the Lognormal or the Weibull distributions. The failure data can fit each distribution equally well. However the use of either distribution will give vastly different lifetime predictions and their correct use is crucial for accurate lifetime prediction. A statistical based test, developed with Monte Carlo data, which is designed to decide if a failure data set has an underlying Lognormal or Weibull distribution is applied to empirical Time Dependent Dielectric Breakdown (TDDB) failure tests. The TDDB tests are carried out on 7nm and 15nm thick gate oxides. The results generated show the necessity of making the correct choice between the two distributions for accurate lifetime prediction and validate the test for different oxide thickness.

I. Introduction

With increased scaling the reliability of thin gate oxides such as silicon dioxide (SiO₂) has become a very important issue in the microelectronics industry. The requirement for higher performance integrated circuits, has led to the necessity for continuous downscaling of gate oxide dimensions. Gate oxides thickness as small as 1.5 nm thick is being implemented in MOSFET's with gate lengths of only 4nm [1]. The industry often specifies that there is less than a 0.1% cumulative failure rate, for 10-years or greater, operational lifetime of semiconductors. Yet as gate oxides become thinner, the margin between the predicted lifetimes of the oxide versus this 10-year specification is decreasing rapidly [2].

II. TDDB Reliability Testing

TDDB tests are required for the determination of gate oxide reliability. These tests are typically performed on small sample sizes across multiple high temperatures and voltages. In many cases the sample size is approximately 16 units per test condition and they are generally tested to 100% failure. From these tests the failure times are generated and statistically analysed. The critical times are the T₅₀ and T_{0.1} percentiles. The T₅₀ percentile is used to generate the thermal and field acceleration factors while the T_{0.1} is used to predict the predicted lifetime based on the Arrhenius equation. The TDDB failure times have underlying statistical distributions, the two most common being the Lognormal and Weibull distributions.

The choice between the Lognormal and Weibull distribution can have major consequences on the determination of the predicted lifetime of the gate oxide. It has been reported that there is a significant difference between both distributions at lower percentiles, and that this difference increases as gate oxides get thinner [3][4][5].

Variations of the Arrhenius equation are used to extrapolate accelerated life data to operational life data. The basic form of the Arrhenius equation is given by:

$$r = A \exp\left(\frac{-E_a}{kT}\right) \dots\dots\dots(1)$$

Where; r = reaction rate, k = Boltzmann's Constant (8.63 x 10⁻⁵ eV/K), E_a = Activation Energy (eV), A = Frequency factor, T= Absolute temperature K.

Some of the variations of the Arrhenius equation are used to derive the thermal and field acceleration factors in TDDB experiments. These acceleration factors are used to extrapolate the TDDB test conditions, i.e. high temperature and voltage, to operating conditions. The acceleration factors due to voltage and temperature are expressed in equation 2 and 3 below:

$$AF_{voltage} = \exp\left\{\gamma (V_{stress} - V_{op})\right\} \dots\dots\dots(2)$$

Where: γ = field acceleration factor, V_{stress}= Voltage Stress, V_{op}= Operating voltage.

$$AF_{temp} = \exp\left[\frac{E_a}{kT_{op}} - \frac{E_a}{kT_{stress}}\right] \dots\dots\dots(3)$$

Where: E_a = Activation Energy (eV), k = Boltzman's constant (8.617 x 10⁻⁵), T_{stress} = Stress temperature, T_{op} = Operating temperature.

Both E_a and γ are derived using T₅₀ percentiles of TDDB failure data as variables.

III. Correct Distribution Test

Chi² and Kolmogorov-Smirnov tests are some general Goodness-of-fit tests. These have historically been used by Reliability Engineers to help choose the correct distribution, yet they are not specific to Lognormal and Weibull distributions.

A test was developed by Croes et al [5] to offer reliability engineers an objective tool, which would make a distinction between Lognormal and Weibull distributions. The test is based on Pearson's correlation coefficient;

$$\rho = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2 (y_i - \bar{y})^2}} \dots\dots\dots(4)$$

Where; \bar{x}, \bar{y} are the respective means of x, y.

The test involves calculating the ratio between the correlation coefficient of a Weibull distribution (ρ_{wei}) for a certain failure data set, and the correlation coefficient of the Lognormal distribution (ρ_{logn}) for the same failure data set. The ratio is written as ρ_{wei} / ρ_{logn} . This ratio is shown to have the ability to be used as a test statistic. Using ρ_{wei} / ρ_{logn} as a test statistic, Croes et al [5] devised a hypothesis test that chooses the correct statistical distribution to a certain significance level.

This test was subsequently further developed by Cain [6] for useful applications. ρ_{wei} / ρ_{logn} is compared to a critical value (W_{crit}). The critical value is dependent on the size of the TDDB data set, and is tailored such that the test makes a choice given no *a priori* information on the data. If ρ_{wei} / ρ_{logn} is greater than W_{crit} then the underlying distribution of the TDDB data is a Weibull distribution, and if ρ_{wei} / ρ_{logn} is less than W_{crit} then the underlying distribution of the TDDB data is a Lognormal distribution. Cain [6] also calculates the probability of making a correct decision in relation to the size of the data set, as seen in *Figure 1*, assuming that all the gate oxide test structures fail during the TDDB test.

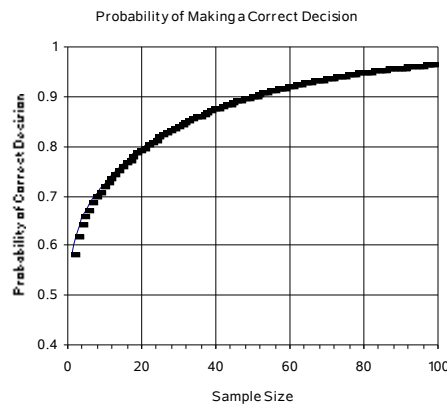


Figure 1 Probability of Correct Decision with Increasing Sample Size up to N=100.

The above tests were developed based on Monte Carlo data sets. The following sections apply empirical data to the theoretical work and points to the inconsistencies that arise if the incorrect statistical distributions are used.

IV. Experimental Details

TDDDB tests were carried out on n-type MOS capacitors with gate oxide thickness (t_{ox}) of 7nm and 15nm. The number of capacitors used and stress conditions are in Table 1 below.

Table 1.

t_{ox} (nm)	No. of Caps.	E-field Stress (MV/cm)	Temp.Stress (°C)
7	170	9	225
15	110	8	225

All capacitors were stressed till failure occurred, i.e. hard breakdown of gate oxide [7].

V. Application of Test for Correct Distribution

Figures 2 and 3 are the TDDDB failure data of the 7nm gate oxide, given a Lognormal and Weibull distribution respectively.

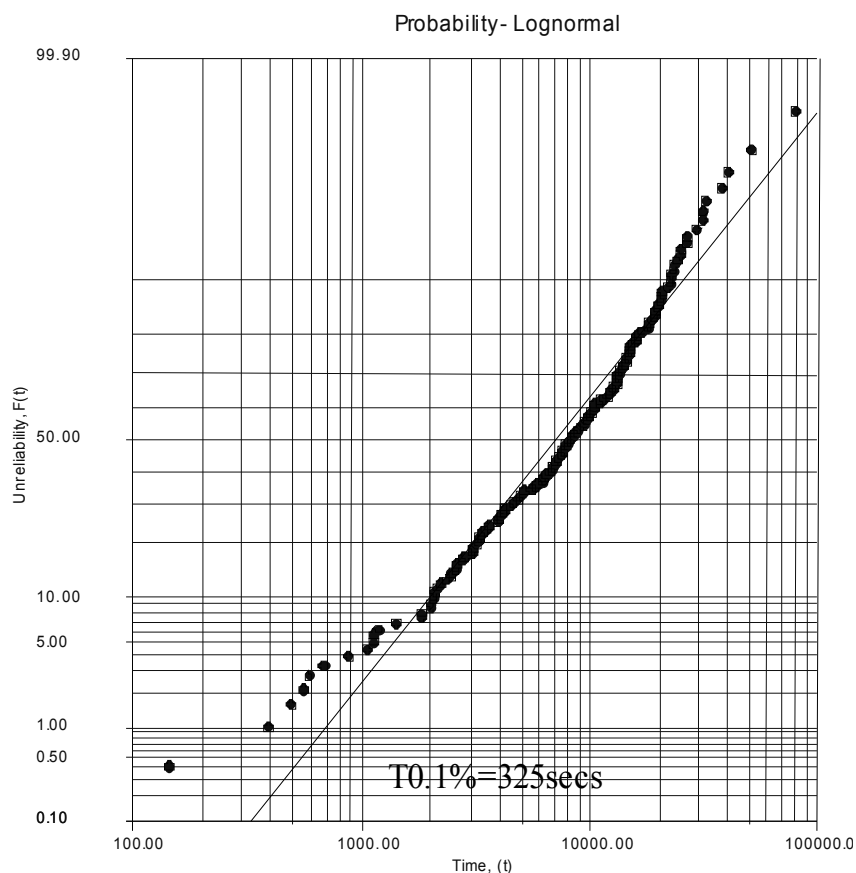


Figure 2 Lognormal distribution of 7nm TDDDB Data

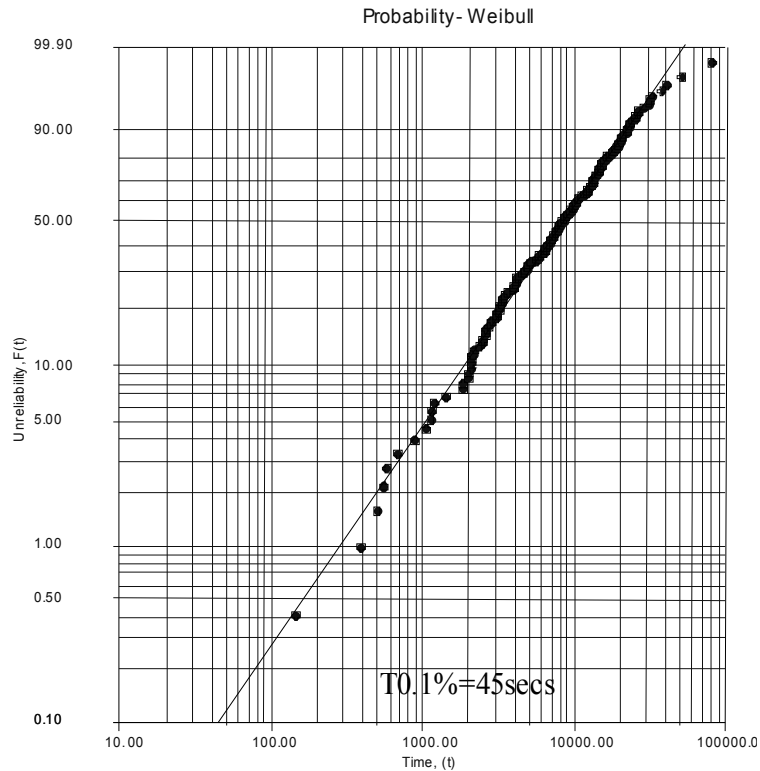


Figure 3 Weibull distribution of 7nm TDDB Data

The correlation coefficient for the Lognormal distribution ($\rho_{\log n}$) = 0.9807, and the correlation coefficient for the Weibull distribution (ρ_{wei}) = 0.9970. The ratio $\rho_{\text{wei}} / \rho_{\log n} = 1.017$. The critical value of a data set of 170 = 0.9958. $\rho_{\text{wei}} / \rho_{\log n}$ is greater than the critical value which implies that the TDDB failure times has an underlying Weibull distribution. The $t_{0.1}$ (time taken for 0.1% of population to fail) of the Lognormal is 325 seconds, and the $t_{0.1}$ of the Weibull distribution is 45 seconds. This is a difference of a factor 7.

Figures 4 and 5 are the TDDB failure data of the 15nm gate oxide, given a Lognormal and Weibull distribution respectively

Using the test as for the 7nm gate oxide, the underlying distribution for the 15nm gate oxide is found to be a Lognormal distribution. The $t_{0.1}$ of the Lognormal distribution is 850 seconds, and the $t_{0.1}$ of the Weibull distribution is 195 seconds. This is a difference of a factor 4. This difference is less than 7 nm gate oxide difference, which is in agreement with previous findings [4]. The results imply that with 93% confidence the lognormal distribution is the most suitable for the 15 nm oxide. For the 7 nm oxide there is a 95 % chance that the Weibull distribution is the correct one to use. As a result the correct statistical distribution to use depends on the oxide thickness.

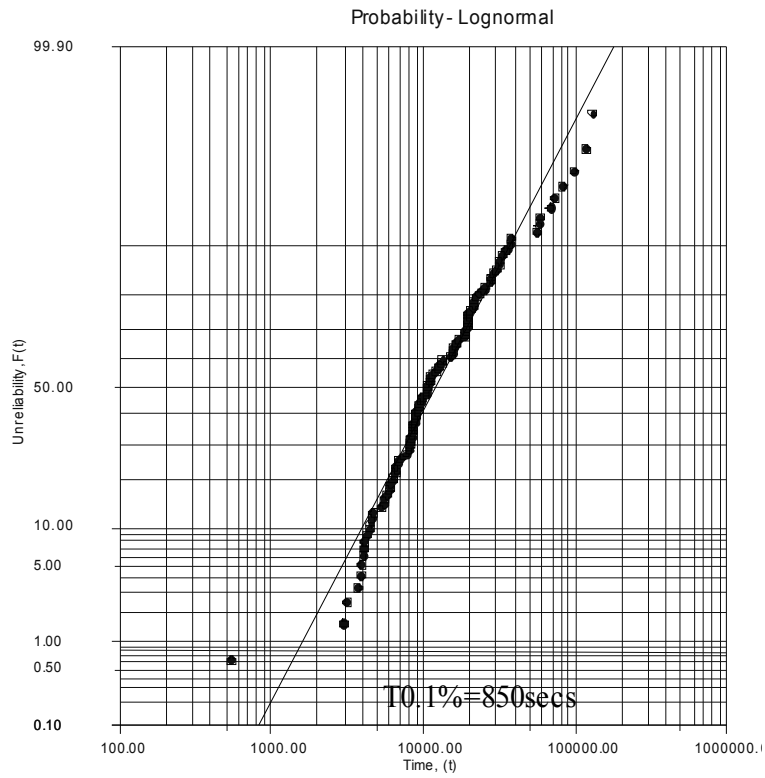


Figure 4 Lognormal distribution of 15nm TDDB Data

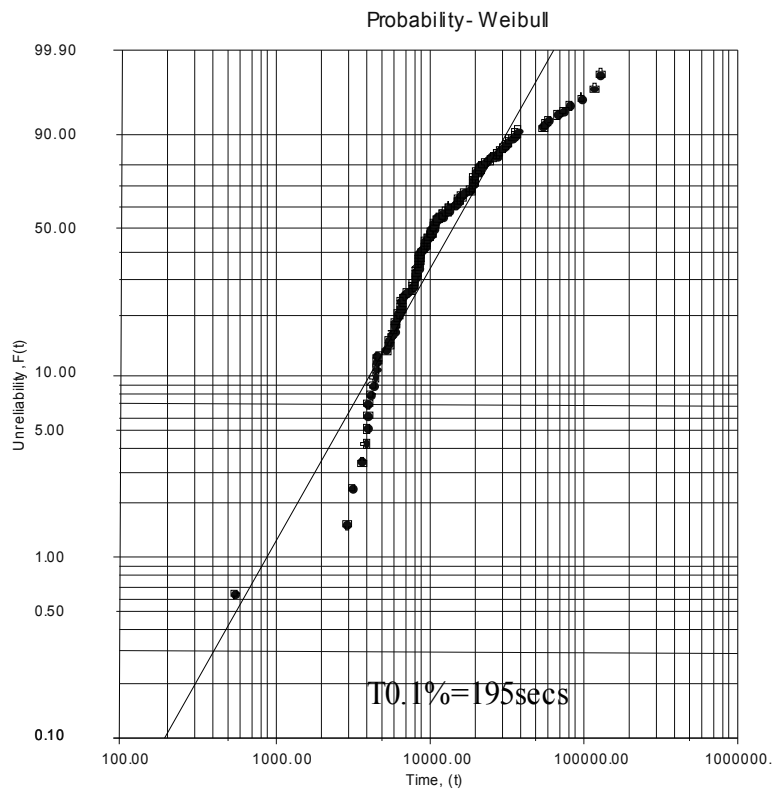


Figure 5 Weibull distribution of 15nm TDDB Data

Equation 2 and 3 can be combined and rewritten as can be rewritten such that:

$$TTF_{op} = Exp [-E_a/k (1/T_{test} - 1/T_{op})] \times Exp \gamma (V_{test} - V_{op}) \times TTF_{test} \dots \dots (5)$$

where: TTF_{op} represents the time for 0.1% fails at operating temperature and voltage conditions, e.g. 55°C and 3V, extrapolated from stress conditions. TTF_{test} is the $t_{0.1}$ percentile of the TDDB failure data. Using this equation with E_a and γ values derived from experiment, $t_{0.1}$ for operating temperature conditions are calculated for 7nm and 15nm gate oxides, using both the Lognormal and Weibull conditions, as seen in Table 2.

Table 2

t_{ox}	Distribution	T0.1% test	T0.1% use
7 nm	Weibull	45 sec	16yrs
	Lognormal	325 sec	65yrs
7 nm	Weibull	195 sec	5552yrs
	Lognormal	850 sec	9005yrs

For the 7nm gate oxide, the $t_{0.1}$ at operating temperature and field conditions is 65 years using the Lognormal distribution, and 16 years using the Weibull distribution. As the underlying distribution for the 7nm TDDB data is found to be Weibull, the use of a Lognormal distribution would give an over-optimistic evaluation of the reliability of the gate oxide.

For the 15nm gate oxide, the $t_{0.1}$ at operating temperature and field conditions is 9005 years using the Lognormal distribution, and 5552 years using the Weibull distribution. As the underlying distribution for the 15nm TDDB data is found to be Lognormal, the use of a Weibull distribution would give an over- pessimistic evaluation of the reliability of the gate oxide.

VI. Conclusion

In this paper empirical data has been presented to support the theoretical model proposed by Croes and further developed by Cain to distinguish between Lognormal and Weibull distributions. The results show how choosing the wrong distribution can lead to erroneous reliability projection. Choosing distributions arbitrarily may no longer be sufficient and care needs to be taken before reliability characterisation to determine the correct statistical

distribution. This is crucial for the microelectronics industry as gate oxides become thinner and customer's reliability expectations increase.

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