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Reliability Prediction for Aerospace Electronics

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14. ABSTRACT

This project presents a method for predicting the failure rate, and thus the reliability of an electronic system by summing the failure rate of each known failure mechanism. The approach combines the physics of failure for each mechanism with their effects as observed by High/Low temperature, High/Low voltage, and current stresses. The method assumes that lifetime of each of its failure mechanisms follows constant rate distribution and each mechanism is independently accelerated by the stress factors that can be entered into a reliability model. The overall failure rate therefore follows an exponential distribution and is described in the standard FIT (Failure unIT or Failure In Time). The method combines mathematical models for known failure mechanism and solves them simultaneously at a multiplicity of accelerated life tests to find a consistent set of weighting factors for each mechanism. The result of solving the system of equations is a more accurate and a unique combination for each system model by proportional summation of each of the contributing failure mechanisms. Consequently, this matrix approach gives a very cost-effective way to predict reliability based on the Physics of Failure using only three tests as compared to the normal single-mechanism approach. Finally, this methodology can be extended to include radiation effects, frequency, and even packaging and solder joint effects to give a complete system reliability evaluation framework. Such efforts are being pursued in a follow-on project.

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Abstract

We present a method for predicting the failure rate, and thus the reliability of an electronic system by summing the failure rate of each known failure mechanism. We combine the physics of failure for each mechanism with their effects as observed by High/Low temperature and High/Low voltage and current stresses. Our method assumes that lifetime of each of its failure mechanisms follows constant rate distribution and each mechanism is independently accelerated by the stress factors that can be entered into a reliability model. The overall failure rate is thus, also follows an exponential distribution and is described in the standard FIT (Failure unIT or Failure In Time). The method combines mathematical models for known failure mechanism and solves them simultaneously at a multiplicity of accelerated life tests to find a consistent set of weighting factors for each mechanism. The result of solving the system of equations is a more accurate and a unique combination for each system model by proportional summation of each of the contributing failure mechanisms.

I. Introduction

To this day, the users of our most sophisticated electronic systems that include opto-electronic, photonic, Micro-ElectroMechancial Systems (MEMS) device, etc. are expected to rely on a simple reliability value for the Failure In Time (FIT) published by the supplier. The FIT is determined today in the product qualification process by use of High Temperature Over-voltage Life-test (HTOL) or other standardized test, depending on the product. The manufacturer reports a zero-failure result from the given conditions of the single-point test and uses a single-mechanism model to fit an expected Mean Time To Failure (MTTF) at the operator's use conditions. The zero-failure qualification is well known as a very expensive exercise that provides nearly no useful information. As a result, designers often rely on Highly Accelerated Life Test (HALT) testing and on handbooks such as Fides, Telecordia or Mil Handbook 217 to estimate the failure rate of their products, knowing full well that these approaches act as guidelines rather than as a reliable prediction tool. Furthermore, with zero failure required for the "pass" criterion as well as the poor correlation of expensive HTOL data to test and field failures, there is no way for the designers to utilize this knowledge in order to build in reliability or to trade it off with performance. Prediction is not really the goal of these tests, however current practice is to assign an expected failure rate, FIT, based only on this test even if the presumed acceleration factor is not correct.

This paradigm seems unfortunate since the manufacturers of our electronic equipment actually put a great deal of effort and spend so much money and excellent personnel resources to learn and study each failure mechanism. Today's approach to reliability takes the intimate knowledge of the failure mechanisms and then not communicate this knowledge downstream to the users, usually for fear that perhaps the models or the probabilistic interpretation will not be realized. Hence, known and already characterized mechanisms that could lead to failure are left out of the equation. This leaves the final, sterilized, accelerated test as the only available assessment on which the user can rely. Everyone recognizes that the resulting calculation is far from being a reliable value to predict anything about the life. Worse than that, it makes a joke of the reliability prediction process and has lead to confusion at all levels. It also makes a joke of the very excellent and hard work of the reliability engineers who evaluate the failure probabilities and the underlying physics.

We have found that a practical means of separating electronic device failure mechanisms at the system level. We tested Field Programmable Gate-Arrays (FPGA's) with a large range of frequency operation and tested them at extremely high and low temperatures with voltages ranging from nominal to more than 2 times nominal voltages. The result is the ability to completely distinguish the influences of hot carrier injection (HCI), Electromigration (EM), Bias temperature instability (BTI) and time dependent dielectric breakdown (TDDB). Our result shows that a meaningful reliability prediction can be made by a summation of distinct intrinsic failure mechanisms as measured at the system level. The result of our work will be a system qualification protocol that can actually predict the FIT with a much greater accuracy than a standard high temperature or low temperature overstress life qualification.

Chip and packaged system reliability is still measured by a failure unit, FIT. The FIT is a rate, defined as the number of expected device failures per billion part hours. A FIT is assigned for each component multiplied by the number of devices in a system for an approximation of the expected system reliability. The semiconductor industry provides an expected FIT for every product that is sold based on operation within the specified conditions of voltage, frequency, heat dissipation and etc. Hence, a system reliability model is a prediction of the expected mean time between failures (MTBF) for an entire system as the sum of the FIT rates for every component.

A FIT is defined in terms of an acceleration factor, A_F, as:

$$FIT = \frac{\#\, failures}{\#\, tested * hours * A_F} \cdot 10^9 \tag{1}$$

where #failures and #tested are the number of actual failures that occurred as a fraction of the total number of units subjected to an accelerated test. Therefore, the failure rate,

$$FIT \;=\; 10^9 / \mathrm{MTBF} \quad . \tag{2}$$

The acceleration factor, A_F, must be supplied by the manufacturer since only they know the failure mechanisms that are being accelerated in the High Temperature Operating Life (HTOL) and it is generally based on a company proprietary variant of the MIL-HDBK-217 approach for accelerated life testing. The true task of reliability modeling, therefore, is to choose an appropriate value for A_F based on the physics of the dominant failure mechanisms that would occur in the field for the device.

II. Standard HTOL

The standard HTOL qualification test is usually performed as the final qualification step of a semiconductor manufacturing process. The test consists of stressing some number of parts, usually about 100, for an extended time, usually 1000 hours, at an accelerated voltage and temperature. Two features shed doubt on the accuracy of this procedure. One feature is lack of sufficient statistical data and the second is that companies generally present zero failures results for their qualification tests and hence stress their parts under relatively low stress levels to guarantee zero failures during qualification testing.

Unfortunately, with zero failures no statistical data is acquired. Another feature is their calculation of the acceleration factor A_F. If the qualification test results in zero failures, which allows the assumption (with only 60% confidence!) that no more than ½ a failure occurred during the accelerated test. This would result, based on the example parameters, in a reported FIT = 5000/AF, which can be almost any value from less than 1 FIT to more than 500 FIT, depending on the conditions and model used for the voltage and temperature acceleration.

The accepted approach for measuring FIT would be reasonably correct if there were only a single dominant failure mechanism that is excited equally by either voltage or temperature. Additionally, this same mechanism is the only one that is accelerated by the burn-in or accelerated test. For example, electromigration is known to follow Black's equation and is accelerated by increased stress current in a wire or by increased temperature of the device. If, however, multiple failure mechanisms are responsible for device failures, each failure mechanism should be modeled as an individual "element" in the system and the component survival is modeled as the survival probability of all the "elements" as a function of time [1].

The acceleration of a single failure mechanism is a highly non-linear function of temperature and/or voltage. The temperature acceleration factor (AF_T) and voltage acceleration factor (AF_V) can be calculated separately and is the subject of most studies of reliability physics. The total acceleration factor of the different stress combinations will be the product of the acceleration factors of temperature and voltage,

$$AF = \frac{\lambda(T_2,V_2)}{\lambda(T_1,V_1)} = AF_T \cdot AF_V = \exp\left(\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right)\exp\left(\gamma_1(V_2-V_1)\right) \tag{3}$$

This acceleration factor model is widely used as the industry standard for device qualification. However, it only approximates a single dielectric breakdown type of failure mechanism and does not correctly predict the acceleration of other mechanisms.

To be even approximately accurate, however, electronic devices should be considered to have several failure modes degrading simultaneously. Each mechanism 'competes' with the others to cause an eventual failure. When more than one mechanism exists in a system, then the relative acceleration of each one must be defined and averaged at the applied condition. Every potential failure mechanism should be identified and its unique AF should then be calculated for each mechanism at a given temperature and voltage so the FIT rate can be approximated for each mechanism separately. Then the final FIT will be the sum of the failure rates per mechanism, as is described by:

$$\mathrm{FIT}_{\mathrm{total}} = \mathrm{FIT}_1 + \mathrm{FIT}_2 + \ldots + \mathrm{FIT}_i \tag{4}$$

whereby each mechanism leads to an expected failure unit per mechanism, FIT_i. Unfortunately again, individual failure mechanisms are not uniformly accelerated by a standard HTOL test, and the manufacturer is forced to model a single acceleration factor that cannot be combined with the known physics of failure models.

If multiple failure mechanisms, instead of a single mechanism, are assumed to be time-independent and independent of each other, FIT (constant failure rate approximation) should be a reasonable approximation for realistic field failures. Under the assumption of multiple failure mechanisms, each will be accelerated differently depending on the physics that is responsible for each mechanism. If, however, an HTOL test is performed at an arbitrary voltage and temperature for acceleration based only on a single failure mechanism, then only that mechanism will be accelerated. In that instance, which is generally true for most devices, the reported FIT (especially one based on zero failures) will be meaningless with respect to other failure mechanisms.

III. Acceleration Factor

The qualification of device reliability, as reported by a FIT rate, must be based on an acceleration factor, which represents the failure model for the tested device. If we assume that there is no failure analysis (FA) of the devices after the HTOL test, or that the manufacturer will not report FA results to the customer, then a model should be made for the acceleration factor, AF, based on a combination of competing mechanisms. This will be explained by way of example. Suppose there are two identifiable, constant rate competing failure modes (assume an exponential distribution). One failure mode is accelerated only by temperature. We denote its failure rate as $\lambda_1(T)$. The other failure mode is only accelerated by voltage, and the corresponding failure rate is denoted as $\lambda_2(V)$.

By performing the acceleration tests for temperature and voltage separately, we can get the failure rates of both failure modes at their corresponding stress conditions. Then we can calculate the acceleration factor of the mechanisms. If for the first failure mode we have $\lambda_1(T_1), \lambda_1(T_2)$ and for the second failure mode, we have $\lambda_2(V_2), \lambda_2(V_2)$ then the temperature acceleration factor is:

$$AF_T = \frac{\lambda_1(T_2)}{\lambda_1(T_1)},\ T_1 < T_2 \tag{5}$$

and the voltage acceleration factor is:

$$AF_V = \frac{\lambda_2(V_2)}{\lambda_2(V_1)}, V_1 < V_2 \tag{6}$$

The system acceleration factor between the stress conditions of $(T_1, V_1)$and $(T_2, V_2)$is:

$$AF = \frac{\lambda_1(T_2,V_2) + \lambda_2(T_2,V_2)}{\lambda_1(T_1,V_1) + \lambda_2(T_1,V_1)} = \frac{\lambda_1(T_2) + \lambda_2(V_2)}{\lambda_1(T_1) + \lambda_2(V_1)} \tag{7}$$

The above equation can be transformed to the following two expressions:

$$AF = \frac{\lambda_1(T_2) + \lambda_2(V_2)}{\frac{\lambda_1(T_2)}{AF_T} + \frac{\lambda_2(V_2)}{AF_V}} \tag{8}$$

or

$$AF = \frac{\lambda_1(T_1)\,AF_T + \lambda_2(V_1)\,AF_V}{\lambda_1(T_1) + \lambda_2(V_1)} \tag{9}$$

Due to the exponential nature of acceleration factor as a function of V or T, if only a single parameter is changed, then it is not likely for more than one mechanism to be accelerated significantly compared to the others for any given V and T. As we will see in the next section, at least 4 mechanisms should be considered. Also, the various voltage and temperature dependencies must be considered in order to make a reasonable reliability model for electron devices. Until now, the assumption of equal failure probability at-use conditions is used since it is the most conservative approach assuming the correct proportionality cannot be determined.

IV. Proportionality Matrix Solution

The basic method for solving the system of equations is described in the paper from Bernstein [2] and using the suggestion of a Sum-of-failure-rate method as described in JEDEC Standard JEP122G [1] as published in a more recent paper by Bernstein [3]. The matrix method forms the basis for this work. It is clear that the manufacturers of electronic components recognize the importance of combining failure mechanisms in a sum-of-failure-rates method. Also, the formula for each mechanism is well studied and published.

Thus, we describe here, the prediction of a system reliability using a linear matrix solution. Although until today, we have only verified the methodology on verifiable microelectronic device failure mechanism, our methodology will apply directly to additional mechanisms including thermal and mechanical stresses due to wafer bonding and any failure mechanism that can be modelled by physics of failure; including wide bandgap semiconductors and even packaging failures.

This approach allows accelerated testing to be performed at increased voltages, temperature, frequency and power levels and even mechanical stresses and thermal cycles to increase the separation of individual mechanisms in order to calibrate this matrix to actual components in a system. The matrix is then solved using input from multiple accelerated tests as compared to the relative contribution of each assumed mechanism. This approach requires multiple, High Temperature Overstress Life-tests (M-HTOL) in order to accelerate different mechanisms in the same set of accelerated tests. This M-HTOL test allows calculations that consider all conditions simultaneously. Thus, an appropriate failure rate calculation will determine the failure rate during actual operating conditions. Furthermore, a system can be de-rated for increased robust design and prolonged failure-free operation. This is accomplished by solving the matrix assuming any desired stress condition using the same proportionality factors as determined by the M-HTOL test. We will add thermo-mechanical and additional stresses related to packaging failures using this same methodology.

As part of calibrating the proportionality factors, accelerated test results can be used as input to calculated failure rates for all the failure mechanisms. The output of accelerated life test determines the proportional acceleration factors for each of the various mechanisms. We assume the circuit itself is what determines the relative contribution of each mechanism, so a matrix is constructed based on the physics models (JEDEC [1] or manufacturer based) solved for the experimental results. We assume that any test is performed with a specific set of conditions, which determines a specific failure rate that would lead to a failure.

This matrix, when solved for relative contributions at each set of conditions, becomes a forecasting tool that allows determining the dominance of each failure mechanism and its relative contribution to the chance occurrence of a system failure. By solving a system of equations whose information can be obtained from the matrix, one can make an assessment and prediction of acceleration for each combination of failure mechanism and its proportion in the circuit. This model assumes a constant total failure rate so the time at which a given percentage will fail can be used to calculate the duration of the warranty period and the approximate lifetime of the component. The matrix is described in Table 1.

	TDDB	HCI	NBTI	EM	Results
V_1, T_1	$W{\cdot}A_1$	$X{\cdot}B_1$	$Y{\cdot}C_1$	$Z{\cdot}D_1$	$\frac{1}{MTTF_1}$
V_2, T_2	$W{\cdot}A_2$	$X{\cdot}B_2$	$Y{\cdot}C_2$	$Z{\cdot}D_2$	$\frac{1}{MTTF_2}$
V_3, T_3	$W{\cdot}A_3$	$X{\cdot}B_3$	$Y{\cdot}C_3$	$Z{\cdot}D_3$	$\frac{1}{MTTF_3}$
V_4, T_4	$W{\cdot}A_4$	$X{\cdot}B_4$	$Y{\cdot}C_4$	$Z{\cdot}D_4$	$\frac{1}{MTTF_4}$

Table 1. ***M-HTOL Matrix used to solve models with measured times to fail.***

Each row describes various operating conditions under which the system is tested. Each experiment, i, is operated with its unique voltage and temperature. The 'results' column, $MTTF_i$ is the average time when the failure occurs under the experimental condition, which is associated with a pre-determined failure point. Our example will use 5% performance degradation as the failure point, however any reasonable value will work as long as it is consistent with the application. The result, $1/MTTF_i$ is a failure rate l and measured as the FIT, reported as 10^9/MTTF. This approach assumes that each mechanism follows a constant failure rate that is time independent. That is to say that the FIT or MTTF completely describes the reliability of each failure mechanism as well as the whole system. A full justification is beyond the scope of this paper, but is well explained in the book by Bernstein [4]. In short, since the whole system is regarded as having a constant failure rate, we may treat each mechanism as having an average constant rate that is accelerated by the applied conditions.

The left hand side of the matrix, then, specifies the acceleration of each mechanism at the tested operating conditions while measured experimental results comprise the right hand side as seen in Table 2. Each column in the matrix represents a different failure mechanism while the row represents the relative acceleration for each V, T and frequency. We assume that each mechanism (A-D) affects the system linearly with its own acceleration factor (AF) at the given test conditions. The Acceleration factor formulae are calculated as the solution that fit the experimental condition of each result on the right hand side. Thus, any failure mechanism will have a different value for each experiment, depending on the test conditions. We then solve the matrix to find a set of constants, P_i, shown here as W-Z, across the whole matrix that matches the experimental results with calculated acceleration factors.

$$\overbrace{\begin{bmatrix} A_1 & B_1 & C_1 & D_1 \\ A_2 & B_2 & C_2 & D_2 \\ A_3 & B_3 & C_3 & D_3 \\ A_4 & B_4 & C_4 & D_4 \end{bmatrix}}^{AF} \cdot \overbrace{\begin{bmatrix} W \\ X \\ Y \\ Z \end{bmatrix}}^{P_i} = \overbrace{\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix}}^{\lambda}$$

$$(AF) \cdot (P_i) = (\lambda) \rightarrow (P_i) = (AF)^{-1} \cdot (\lambda)$$

Table 2: ***Demonstration of the Matrix Solution Method.***

Knowledge of these coefficients allows prediction of the MTTF or the FIT for any other work conditions that were not tested and give an accurate prediction of the reliability of the device under different conditions. The multiple life-tests performed are what comprise the multiple-HTOL (M-HTOL) testing and provides actual data to calibrate the expected reliability. The result is a meaningful value for the failure rate as measured in FIT.

When designing the M-HTOL test, it is important that each individual mechanism is accelerated more than the others in at least one of the tests so that there is a reasonable calibration between the mechanisms. For example, if within the testing extremes, the relative contribution of one mechanism is never seen, then the inclusion of that mechanism may confuse the result and it would be best not to include that as part of the model. For our example, we found that within the parameters of Voltage, Temperature and Frequency, we were unsuccessful to accelerate time-dependent dielectric breakdown (TDDB) beyond NBTI or any other mechanism. Hence, we solved the full matrix as 3X3 including only the mechanisms that included significant contribution within the testing parameters.

In order to apply this methodology to packaging, where electrical considerations may be less important than the thermo-mechanical or environmental stresses, we will determine final tests that will cause intentional failures due to each of the studied mechanisms. The goal of an accelerated test will be to study the potential failure mechanisms that would occur due to each new technology that is developed and model those physics of failure so that a final test matrix can be developed to include at least one failure during final test so that a minimum design of experiments will allow our matrix solution to predict the expected failure rate under user defined conditions.

The matrix approach we use to model useful life failure rate (FIT) for components in electronic assemblies by assuming each component is composed of multiple sub-components, for example; a certain percentage is effectively ring-oscillator, static or dynamic random-access memory (SRAM or DRAM). Each type of circuit, based on its operation, can be seen to affect the potential steady-state (defect related) failure mechanisms differently based on the accelerated environment, for example; Electromigration, Hot-Carrier, NBTI, etc. Hence, the standard system reliability FIT can be modeled using traditional MIL-handbook-217 type of algorithms and adapted to known system reliability tools, however, instead of treating each component as individuals, we propose treating each complex component as a series system of sub-components, each with its own reliability matrix. This matrix can then be solved at any given set of conditions, i.e. voltage, temperature and frequency, as a percentages at each stressed operating condition, there is a unique proportion of each mechanism for a given set of stressed conditions that will result in the given time to fail.

In order to find a relative failure rate for each mechanism, we take the accelerated life test at various voltages and temperatures and extrapolate to an end-of-life time at each temperature and voltage condition. For each condition, a consistent failure criterion must be chosen and the times to reach that degraded state yields "Time To Fail" (TTF) for that set of voltage and temperature. Since the relative degradation is measured as the percentage change in ring-oscillator frequency, the time to fail is recorded as time to 5% degradation, giving the results as seen in Table 3.

Volt	T °C	Freq (MHz)	EM	HCI	NBTI	Measured FIT	Calculated FIT
2.4	-20	500	0.00%	100.00%	0.00%	8.00E+04	8.00E+04
1.2	140	500	100.00%	0.00%	0.00%	5.40E-01	5.40E-01
2.4	160	0.02	0.58%	3.40%	96.02%	1.78E-02	1.78E-02
3	0	500	0.00%	81.16%	18.84%	3.45E+07	3.43E+07
2.4	173	500	35.19%	61.50%	3.31%	1.76E+01	1.73E+01
2.4	160	500	14.56%	85.34%	0.10%	1.50E+01	1.77E+01
3	0	0.20	0.00%	0.02%	99.98%	6.37E+06	6.47E+06

Table 3. ***Test Results showing proportions of failure mechanisms for given V,T and F compared with the calculated as well as the measured failure rate (FIT).***

An absolute FIT value is determined in the next row based on the mean time to fail. This allows calibration of the final results in operation. The column line is the expected FIT (failures per billion part-hours) at those conditions. By substituting these percentages into the matrix, the true acceleration factors are determined for not only the tested condition but also for any extrapolated condition. A calculated reliability curve is shown in Figure 1 showing the full range of expected FIT versus Temperature for any set of operational conditions shown in Table 4.

Volt	T °C	F (MHz)	EM	HCI	NBTI	Calculated FIT
1.1	30	0.02	99.76%	0.24%	0.00%	2.87E-10
1.2	70	500	100.00%	0.00%	0.00%	9.88E-04
1.5	80	500	98.58%	1.42%	0.00%	3.00E-03
2	-50	500	0.00%	100.00%	0.00%	3.12E+03
1.8	125	500	98.23%	1.77%	0.00%	1.86E-01
2	150	0.02	96.20%	3.80%	0.00%	5.16E-05

Table 4. ***Calculated FIT based on the solved matrix for typical use conditions.***

A calculated reliability curve is shown in Figure 1 showing the full range of expected FIT versus Temperature for any set of operational conditions based on the matrix of Table 4. A full range of temperatures, frequencies and core voltage is substituted into the appropriate equations based on the proportionality solution from the results of Table 3.

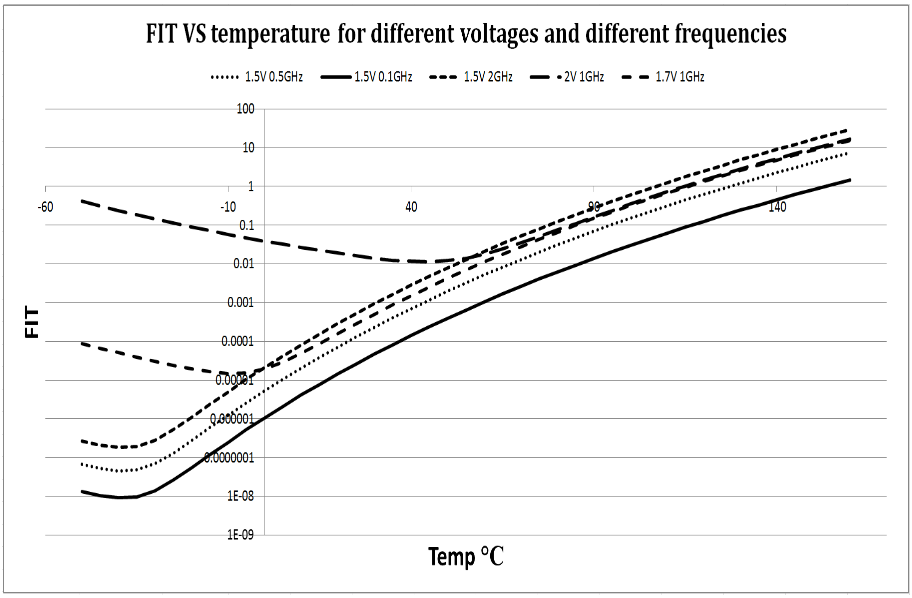

Figure 1. ***Failure Rate (FIT) calculations versus Temp. for a variety of Voltages and Frequencies.***

The unique solution that solves all the equations with the extrapolated acceleration factors gives a percentage contribution for each of the failure mechanisms. We report the reliability as FIT, which is 10^9/MTTF for each condition. The percentages for each mechanism are shown, based on the relative contributions that were extrapolated from the physics of failure equations normalized to the measured FIT of each test.

The most important result from our study is that Electromigration and HCI are the most dominant failure mechanisms throughout the useful range of device operation. This is surprising since the standard HTOL test emphasizes only TDDB and BTI since those are most accelerated by high voltage and temperature, however under use conditions, the other two are most important. Furthermore, it is important to see that at very low temperature and high frequency, HCI is the most important failure mechanism and this could have very important implications for satellite and low-temperature military applications. Fortunately, very low FIT values are found and reliability is predicted confidently.

V. Summary

We present here a simple and accurate way to combine the physics of failure equations for reliability prediction from accelerated life testing. We show that a matrix approach allows the reliability physics equations to be fit proportionally to the results of monitored accelerated life testing in order to extrapolate failure rate one would expect given actual operating parameters. This methodology can be extended to include radiation effects, frequency and even packaging and solder joint effects to give a complete system reliability evaluation framework. This matrix gives a very cost-effective way to predict reliability based on the Physics of Failure using only 3 tests as compared to the normal single-mechanism approach.

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***Professor Joseph B. Bernstein** specializes in several areas of nano-scale micro-electronic device reliability and physics of failure research including packaging, system reliability modeling, gate oxide integrity, radiation effects, Flash NAND and NOR memory, SRAM and DRAM, MEMS and laser programmable metal interconnect. He has licensed his technology and consulted for RFID and SRAM applications related to fuse and redundancy and for programmable gate arrays and system-on-chip. He directs the Laboratory for Failure Analysis and Reliability of Electronic Systems, teaches VLSI design courses and heads the VLSI program at Ariel University. He has developed a method for predicting device failure rates based on new JEDEC standards for multiple failure rate based prediction. Professor Bernstein was a Fulbright Senior Researcher/Lecturer at Tel Aviv University in the Department of Electrical Engineering, Physical Electronics. Professor Bernstein is a senior member of IEEE.*

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