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Physics-of-Failure Based Approach for Predicting Life and Reliability of Electronics Components

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Abstract

Enhancing functional performance while at the same time continuing with the miniaturization of electronic systems are the main drivers for electronic industries world over. The phenomenal growth of VLSIs and embedded systems is testimony to these developments. Development of complex embedded systems using components like FPGA, CPLD, etc, where not only the transistor densities but current densities of interconnects have almost been optimized to the limits, pose reliability issues that need to be addressed. Even though the material properties, design and construction features are better understood than ever before, further research is required to understand root causes of failure so that failure in the field conditions can be further minimized.

The traditional method of reliability prediction, Like MIL-217 approach, have some inherent limitations which include, a) it does not allow simulations with projected component load profiles, b) no provisions to assess the root cause(s) of component failure, c) basis and science behind the considerations of base failure rate and other modifying factors are not clear.

The physics-of-failure approach is based on first principles of science and technology and provides the insight into not only life and reliability aspects of the component, but also provides details about the various degradation mechanism(s) and thereby improved understand of the associated root cause(s) of the failure. This approach extends Accelerated Life Testing philosophy to investigate the basic failure mechanism. The role of statistics in this methodology is to predict the uncertainty in the estimates of life and reliability. This paper brings out the salient feature of this approach.

1. Introduction

In the last more than four decades, electronics systems and their applications have revolutionised the industrial and domestic scene. It all started with application of vacuum tube-based systems in fifties and solid state systems in sixties to the present VLSI (Very Large Scale Integration) based digital systems. Even though the embedded technology has entered the market and finding wider applications; there are reliability issues primarily due to higher current densities of the order of 106 A/cm^2 in the interconnects and new modes of failure viz, Electromigration, gate oxide breakdown and hot carrier effects. These developments posed a challenge to reliability specialists to devise new methods for reliability prediction which should be effective in estimating not only the likelihood of the failure but also provide adequate understanding of associated failure mechanisms, such that, the

re-engineering / root cause analysis can be done to avoid recurrence of such failures.

Reliability of a component, system or structure has two components. The first one is probabilistic, where the likelihood of failure and uncertainty in parameters is estimated, while the second one is deterministic and deals with finding various modes and causes of failure. These two aspects together make reliability prediction more accurate and complete.

Traditionally, the reliability estimates for electronics components are obtained by one of the three approaches, viz., one, using standard handbook; two, statistical analysis of operating & maintenance data and third, by performing life testing experiments. Generally, the reliability of electronics components is estimated using standard handbooks, the most prominent among these include MIL-HDBK-217 (American Military Handbook 217), TELCORDIA (or Bellcore, developed for Telecommunication applications), PRISM (Developed by Reliability Analysis Center, USA for US Air force), etc. These handbooks are based on data and model derived from simulated engineering tests of the individual components. Amongst these the American Military Handbook 217 is being most widely used for predicting reliability of electronic components [1]. In MIL-217 approach the individual component failure rate is estimated using the base failure rate of the component. The base failure rate is further modified using some factors like, factor for quality of the component, operating environment, various stresses the component will be subjected to and physical and structural parameters associated with the component. The second approach for reliability estimation involves statistical analysis of the operational and maintenance experience data collected from plant records. One more approach that is used for assessing the life / reliability of the component is through accelerated life testing of the components. It is a well established fact, that stress has influence on the life and reliability of the component. As the stress, which may include operating stress or the environmental stress, increases; the failure rate also increases. This principle forms the basic tenet of the life prediction through accelerated life testing methods.

The MIL-217 approach is most widely used while the plant specific statistical modelling and Life testing methods have limited applications. The major limitation of the MIL-217 approach includes, a) it provides assessment of only one aspect of reliability, i.e. likelihood of the failure and cannot indicate basic failure mechanisms, b) relatively large uncertainties that are associated with various parameters and hence, in the final results; c) often this method tends to provide very optimistic estimates of reliability as it does not take into account the life cycle loads particularly modelling of wearing phenomenon, d) MIL217 approach is based on constant failure rate assumptions which may not reflect the true life cycle failure trends, and e) no reference to the basic material properties or constructional features for predicting the reliability, f) it is not effective in predicting reliability of new components, like, embedded electronics, FPGA / CPLD, or new design of conventional components like control connectors, etc.

2. The Component Life Cycle

Reliability prediction includes both the likelihood estimates for Mean Time To Failure and the competing root causes of the failure. Hence, it is important that the life cycle model should address both probabilistic and deterministic aspects of component life cycle. Probabilistic aspect is required to predict the life with acceptable level of uncertainty and deterministic approach to analyze the competing failure mechanisms and identify the dominant failure mechanism that limits the functional capability of the component. Fig. 1 can be interpreted as modified form of traditional bath tub curve depicting three regions, viz, early failure, useful life and ageing end of life along with the competing failure mechanisms.

3. Competing Failure Mechanisms

As shown in Fig. 1, there could be more than one failure mechanism associated for a given mode of failure. As shown, the failure of type one could be due to failure mechanism 1a or 1b etc. Similarly, for other modes of component failure can also have more than one failure mechanisms. For example, consider life testing of electrical connectors. In an electrical connector the increase in contact resistance beyond threshold can be considered as failure criteria.

The mechanism for increase in contact resistance could be due to deposition of oxide layer due to environmental corrosion, particularly under the influence of temperature and humidity. The mechanical relaxation of connectors pins due to prolonged usage may also contribute to increase in contact resistance. Hence, it is important to understand the root cause of each failure and identify amongst the competing failure mechanisms the dominating failure mechanism(s). To model the competing failure mechanisms in life testing, it is important to create synergy of operational and environmental stresses, by defining appropriate acceleration factors for each stress. Testing / experiments performed under such condition will facilitate proper modelling of not only individual effect but also the net effect of the synergy, created by combining stresses on component life. The dominant failure mechanism plays decisive role in naming the life of the component. The physics-of-failure approach incorporates this theory of competing failure mechanisms, towards assessing the root cause of failure and mean time to failure (MTTF), as part of reliability assessment of not only electronic but mechanical and electrical components too.

4. The Approach

The physics-of-failure approach is based on the fundamental principles of science and engineering.

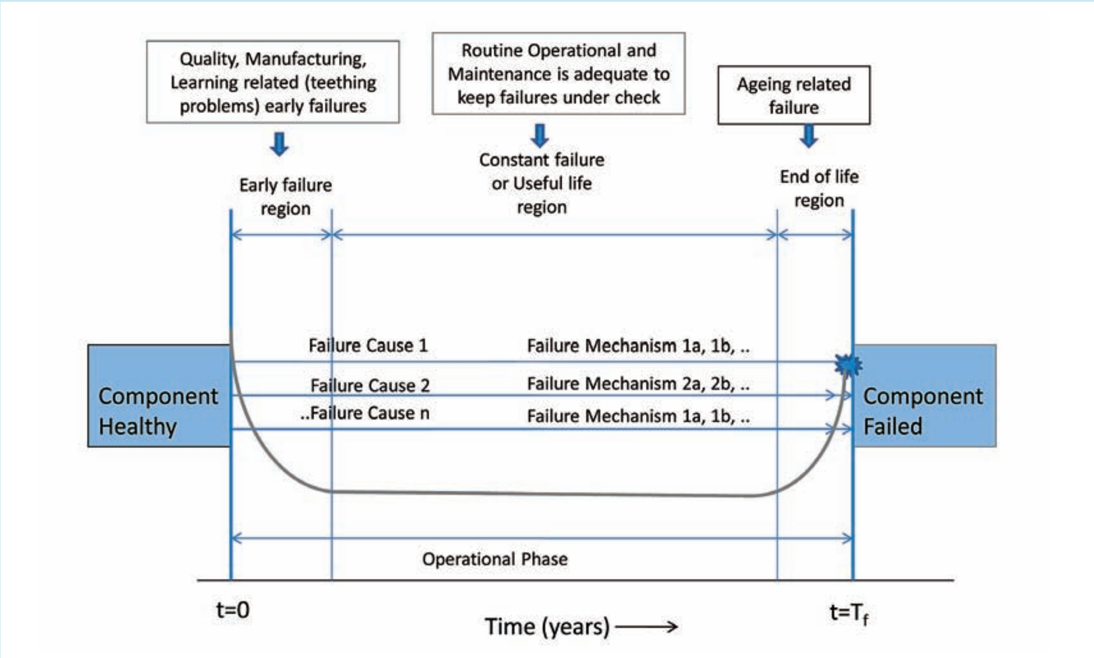

Fig. 1: Depiction of competing failure causes / mechanisms along the component life cycle

The associated component failure mechanisms are evaluated, considering basic phenomenon involved in degradation / failure of components. These models recreate the life of the component with operating stresses and load profiles. The existing physics-of-failure (PoF) for electronics components in general and embedded systems in particular, is becoming the most sought after approach, for reliability professions all over the world. This approach tends to overcome the limitations that are inherent in traditional approaches as it facilitates; a) estimation of life and root causes of failure, employing models that are based on first principles of science and engineering, which address deterministic as well as probabilistic applications, b) incorporation of operational load profiles of the component, c) evaluation of associated failure mechanisms and detailed modelling for identified dominant failure mechanisms, among more than one failure mechanisms, and d) modelling for wear out phenomenon as part of life cycle loads. Fig. 2 depicts the broad features of the procedure followed to implement (PoF) approach for predicting the reliability of electronics components and systems. The following sections deal with the major features of PoF:

4.1 Input Data

The first step is collection of input data which includes material properties, design and constructional features of the component, and operational load profiles, like number of cycles of operations, test and maintenance provisions, current and voltage characteristics, power supply quality, etc. It is also required to establish the failure criteria of the component, based on the operational and engineering requirements of the system.

4.2 Design of Experiment

For effective planning and execution, for characterizing the reliability attributes of the components, it is very important to optimize all

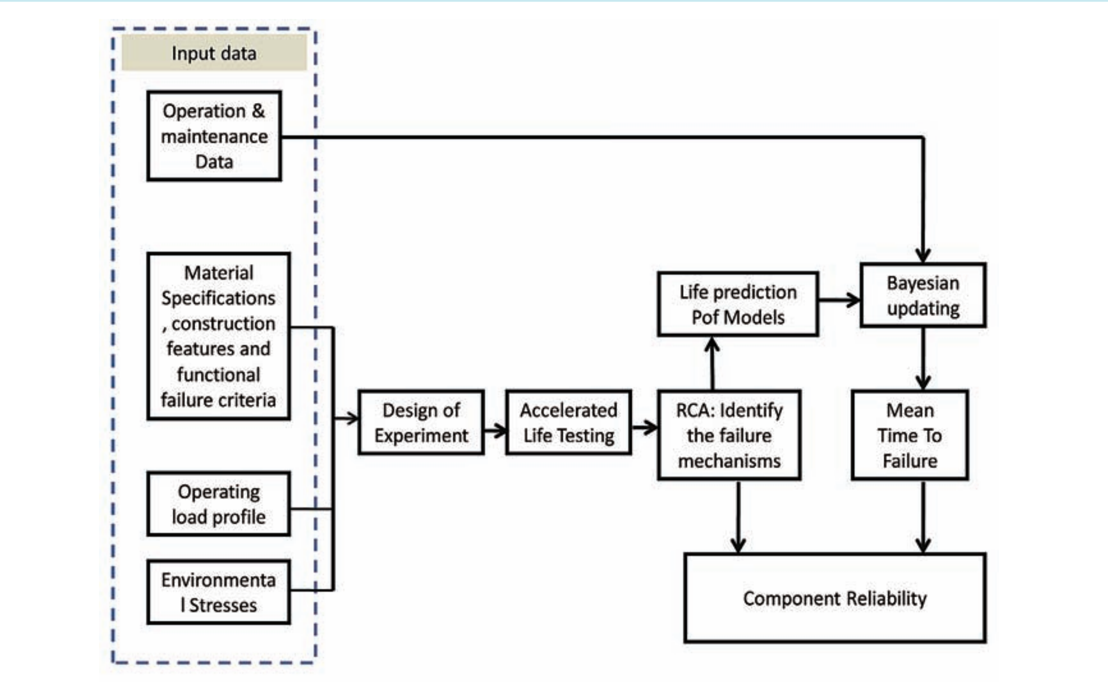

Fig. 2: Depiction of Physics failure approach for electronics component cycle

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the test parameters. Published literature shows that most of the life testing experiments choose arbitrary sets of parameters, like sample size, level of tests, test duration, stress values like temperature, humidity, radiation, etc. The net outcome is the result of the test with relatively large uncertainty bound.

The design of experiment (DoE) approach enables estimation of these parameters based on sound statistical basis [2]. This approach ensures that selection of the test parameters is such that, it helps reveal the hidden failure mechanisms under considerations and at the same time not induce any failure mode that will not be encountered in the actual use condition.

As shown in Fig. 1, the parameters of the life testing experiments, such as number of samples to be tested, the stress levels the components are subjected to (Maximum temperature or humidity level at various stress levels), operational stress levels like current and voltage levels and other features like number of operations to be performed on the component during the test (like actuation of relays or make and break operation for connectors). Once the parameters of the experiments are worked out, the component is subjected to accelerated life testing in life test chambers.

4.3 Accelerated Life Testing

The influence of stress in reducing the life of the component, forms the basic principle of accelerated life testing of components or systems. Fig. 3 depicts how stress vs life relationship is utilized, for predicting the life of the component at the working stress level. Often it is required to design the electronic circuit, to monitor and log the test parameters in on-line mode. For example, if the contact resistance of the control contacts forms the failure criteria for the component, then the circuit is designed to monitor the contact resistance in on-line mode, with an alarm and provision for recording, such that, these criteria can be monitored and recorded. Provision of trip on the chambers power supply and alarm to alert the operator, form part of the preparation of accelerated testing.

As shown in Fig. 3, the component was subjected to two stress levels. The applicable probability distribution is determined using the test data as input to the conventional statistical methods, like probability plotting (for approximations), $\div^{2}$ (Chi-square) method, or any other method that the analyst feels adequate, for interpolation of the life test results to use stress level. The research on life test data modelling and analysis shows, that the modelling of data using Weibull distribution, provides an effective and useful way to interpret the life test data. The estimates of shape parameter β, in Weibull distribution, while on one hand provide information on applicable distribution; the Characteristic life parameter α on the other hand, provides the estimate of characteristic life of the component. The next is Interpolation of this data to estimate the life of the component at use stress level as shown in Fig. 3.

The accelerated test also provides the information on degradation of the components and its constituting part and material. The root cause analysis is performed on the component, to understand the underlying degradation mechanism(s).

4.4 Root cause analysis

The cause-effect analysis based on logical and chronological reasoning of the successive antecedents, associated with any event at any point of time, forms the basic tenet of root cause analysis approach. This approach assumes, that every event that is being investigated has roots, that if properly addressed, can avoid the recurrence of the event. The investigation of component failure is carried out at two levels. One at system level where a systematic analysis is carried out employing

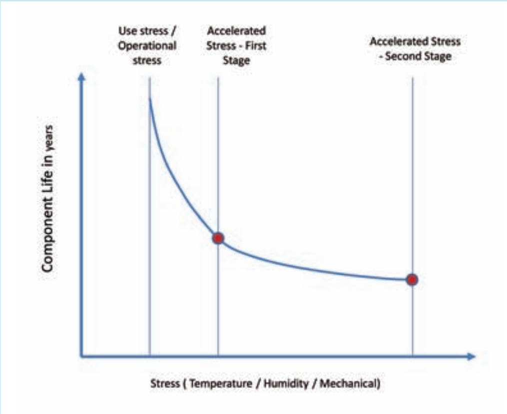

Fig. 3: Reprensentation of Stress Vs Life relationship

various logic models, like logic tree, cause-effect diagram, what-if analysis, binary decision diagram, etc. to arrive at the basic causes of failure. These causes may include, human error, component failure, or procedural failure which is subset of institutional failures, etc. However, when the root cause of failure indicates that the basic cause of the system failure is component failure; further analysis is required as to why the component failed. This is where the role of PoF approach comes into play.

4.5 Pof Models

The salient features of physics-of-failure approach have been discussed in respect of semiconductor based microelectronics devices. There are three basic degradation mechanisms for semiconductor devices, viz., Electromigration, Gate–oxide breakdown and Hot carrier effect, mostly discussed as hot carrier injection [3]. The following section will bring out in brief, the role of deterministic and statistical model, in prediction the life / reliability for respective failure mechanism.

4.5.1 Electromigration

Exhaustive research has documented on physics of failure, involving EM process. Electro-migration involves migration of metal atoms in interconnect, through which large dc current densities pass. The factors responsible for EM include, grain structure, grain texture, interface structure, stresses, film composition, physics of voids nucleation and growth, thermal and current density dependence, etc. [4]. The model proposed by Black [5] shows the dependence of median life on temperature, T and current density, J, as follows;

$$t_{50} = \frac{A}{J} Exp\left(\frac{E_a}{kT}\right)$$

Where A is a material process dependent constant and E_a is activation energy of the diffusion process.

The momentum transfer between electron and metal atom, forms the governing consideration in understanding the physics-of failure of interconnects. The metal atoms get activated by the electron current called 'electron-wind'. The positively ionized metal atoms move against the electron-wind force. The net result is the movement of vacancies and interstitials. The vacancies form voids or micro cracks and interstitials form hillocks. Further the creation of voids results in reduction in cross-sectional area and thereby increases circuit resistance and current density at the affected locations. The synergy of increase in current and temperature increases EM effect. This positive feedback cycle can result into thermal runaway and catastrophic failure. Apart from the semiconductor material, the microstructure of the interconnect also dictates / governs the Electromigration process. In this respect, the grain boundaries play a vital role in forming potential defect sites and thereby conduit for electron flow. Hence, the challenge lies in working out a criterion or model that enables optimization of electron current density, for a given circuit configuration.
The quantum theory in respect of electron transport in a metal shows, that the ion current depends on the effective charge on the ions, the density of the ion available for transport, the ion mobility, and the electric field. Based on the quantum theory, the ion current density is given by the following

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model as:

$$J = (eN)(C_1^{'}\rho_e - 1)\left(\frac{eD}{kT}\right)E$$

Where J : the ion current, N : density of ion available for transport, E : the electric field, ρ_e : the electron resistivity, C_i : proportionality constant, T : temperature and k: Boltzmann's constant. There are other physical affects that might accelerate the net ion currents, like temperature gradient, stress in the conducting strip, material structure in homogeneities, etc. which further result in the formation of voids and consequent defects. There is a reasonably good understanding of effect of these factors, on microchip reliability.

4.5.2 Hot Carrier Degradation

When either 'electron' or a 'hole' under certain conditions gains kinetic energy (more than 3.3 eV for SiO_2 dielectric) in semiconductor devices, such that it overcomes a potential barrier, it is referred to as 'hot carrier'. Hot carrier injection phenomenon is associated with MOSFET devices where the hot carrier is injected from the silicon substrate to the gate dielectric [6]. The presence of mobile hot carrier in oxides induces various physical damage processes, that degrade the device performance characteristics and pose critical reliability issues and are hence, referred to as 'hot carrier degradation'. Even though extensive research is being carried out to understand this degradation mechanism, the physics behind this degradation mechanism is not as well understood as Electromigration. Based on the 'lucky' electron approach (supply of opportune electron to be available as hot carrier) the device life time can be computed from the following model [7].

$$\tau^{-1} = \frac{B}{T_c}\int_0^{T_c} I_D\left(\frac{I_{Sub}}{I_D}\right)^m dt,$$

Where t is the device life time, T_c: full cycle time, I_{sub}: Substrate current, I_D; drain current; $m=\phi_b/\phi_i$ (ϕ_b= Si-SiO_2 energy barrier and ϕ_i = electron energy for ionization impact); B= constant.

There are many empirical models for estimation of device life time, however, the degradation model which is straightforward and simple proposed by Takeda [8] is as follows:

$$t \propto I_{sub}^m$$

Where the value of m lies between 3.2 and 3.4.

4.5.3 Time-Dependent Dielectric Breakdown

This degradation involves phenomenon of leakage current and finally leads to short circuits due to failure of transistor gates. The degradation mechanism involves creation of charge traps within the gate di-electrics, diminishing the potential barrier. The understanding of trap generation mechanism is the key, to evaluating oxide degradation. There are many models given in literature to estimate the 'time to breakdown' (T_{BD}) of oxide layer, however, the one which is commonly employed is 'anode hole injection' (AHI) model [9].

$$T_{BD} = \tau_0(T)\exp\left(\frac{G(T)}{\varepsilon X}\right)$$

Where, ε'oX is electric field across the dielectric in MV/cm τ_o(T) and G(T) are temperature dependent constants and T; absolute temperature.

As discussed earlier, even though the physics behind the failure of semiconductor devices is now better understood, in each of the failure mechanisms, the role of statistical methods is still relevant in estimating the time to failure. However, better estimates can be obtained, by conducting the accelerated life tests / experiments, to narrow down the uncertainty band.

4.5.4 Statistical data Modelling

The modelling of data is crucial to the quality and

accuracy of the results of the analysis. The traditional approach involves either assuming a distribution for the set of data based on common practices or assessing the applicable distribution by conventional techniques like probability plotting or using the methods like Chi-square tests, etc. Taking a decision based on parameter evaluation like, employing the Weibull distribution selecting a particular distribution based on β-value (shape parameter) also forms a popular method for data trending. However, it is known that a single distribution alone may not be adequate represent to the entire set of data. The reason is that the data trend changes due to changes in operational or maintenance practices like, major modification in the system, major change in overall maintenance practices, or repair / replacement. There are models available which facilitate single change point, like poison process model etc. It is possible to accommodate single and more than one change points using models like hazard model. However, the prediction capability of these models is determined by their capability to accurately predict the change point location. Other limitations of these change point models is that, it is not possible to incorporate the effect of change in environment in the analysis and thereby the accuracy of prediction can always be argued. Segmented point process model for multiple change point has been developed and shown that accuracy of prediction can be improved significantly [10].

5. Conclusions

This article discusses the experience and observations on reliability and life prediction of components. Even though traditional approaches, like MIL-217 approach and Accelerated Testing form the mainstay of reliability prediction, it is a well recognized fact that these methods provide only one component of reliability i.e. failure rate estimates. Apart from this, it is also recognized that these approaches tend to provide, at times, optimistic estimates of life and reliability. One of the possible explanations is that, these approaches do not consider component load profile, which is an additional feature against which the life or reliability predicted should be carried out. The above observations corroborate with the insights available on reliability modelling of conventional components of electronic channels of nuclear plants and industrial systems. Hence, there is a need to focus R&D efforts on development of PoF based simulation approach, for reliability & life prediction of electronic components.

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New Publication

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Recent years have seen a growing interest in the field of thermodynamic properties of solids, due to the development of advanced experimental and modeling tools. Predicting structural phase transitions and thermodynamic properties, find important applications in condensed matter and materials science research as well as in interdisciplinary research, involving geophysics and earth sciences. The present book, with contributions from leading researchers around the world, is aimed at meeting the needs of academic and industrial researchers, graduate students and non-specialists working in these fields. The book covers various experimental and theoretical techniques relevant to the subject. The wide range of topics include:

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