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ROLE OF STATISTICAL VIS-A-VIS PHYSICS-OF-FAILURE METHODS IN RELIABILITY ENGINEERING

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Abstract

Traditionally the statistical or more specifically probabilistic methods form the basic framework for assessing the reliability characteristics of the components. However the recent trend for predicting the reliability or life of the component involves application of physics-of-failure methods. This rather new approach is finding wider application as it is based on basic fundamentals of science and thereby provides an improved framework to understand the failure mechanism. Since accelerated testing of component forms part of this approach, the prediction of time-to-failure of the components is more accurate compared to the existing methods which depends only historical data and its evaluation using probabilistic methods. The new approach is all the more relevant when it comes to assessment of reliability of new components as the traditional probabilistic approach is not adequate to predict reliability of new components as it depends on historical data for prediction of reliability.

In view of the above this paper investigates the role of statistical or probabilistic approach and physics-of-failure approach for reliability assessment of engineering components in general and electronics components in particular.

Key words: Random failures, Reliability engineering, Distributions, Failure rate, Failure probability, Root Cause Analysis, Statistics.

1. Introduction

The statistical approach forms the fundamental for reliability or for that matter characterizing the failure rate of the engineering components. The basic assumption is that the failure phenomenon is characterized to a large extent as random event, more particularly in respect of ‘instant’ of failure. Here the failure data collected from a population of similar components operating in the field are collected. Based on the time to failure data estimates and number of failure encountered the failure rates are estimated [1]. It is quite obvious that relatively large level of uncertainties form part of these estimates. The uncertainty could be due to non-availability of sufficient data, adequacy of model that represents the data trends, improper interpretation of data and models, etc. Under these uncertainties, the analysts have only one option, i.e. to use approximate statistical models to characterize failure attributes. Hence, a new approach using physics-of-failure framework is extensively being developed in life / reliability assessment labs world over [2]. The accelerated testing of components using design-of-expert approach and root cause analysis methodology forms the part of physics-of-failure approach. The motivation in support of the application of this approach is a) improved understanding of engineering materials, b) advances in computational methodologies, and c) advances in the development of failure model and data. Even though this approach is very promising there are some limitations, e.g., some failure models are not well understood and lot of research is still required to understand these failure mechanisms and b) even though good amount of work has been done in respect of electronics components not much work has been performed to understand failure mechanism in mechanical and electrical components.

The section 2 brings out the historical perspective in respect of the approach to understand failure and in turn reliability modelling techniques of the component. Section 3 discusses the new framework / approach and the role of physics of failure, root cause analysis, design of experiment methods towards determining the role of statistical approach in new framework. The new approach has been explained to a large extent through discussion on reliability modelling of solid-state devices. Section 4 presents the discussion and conclusions of this paper.

2. Developmental Perspectives

More than 2500 years ego Gautama Buddha had explained the cause of suffering through the Cause and effect relationship. This provided, not exactly scientific, but well founded theory that was accepted in many streams of science to investigate the scientific and engineering processes. The basic tenet of this approach is that for every occurrence that we observe has cause(s). The question is, when every occurrence has a cause preceding it, then why the statistical process treating randomness taking bigger picture than what it should have been or should not have been. Is it that for events or more specifically speaking 'failure' for which no causes could be ascertained are termed as random failure or random phenomenon. Possibly if the situation demands and if resources are provided will it be possible to identify the cause(s) of failure or to be more precise the '*root cause of failure'*. The answer should obviously be 'yes', in particular if we are trying to remove randomness associated with this failure due to the attribute 'Cause'. It may be noted that we are not discussing the 'instant' of failure. It is well recognized fact that predicting exact time or instant of failure requires statistical treatment [3].

For argument's sake let us take into consideration the issues associated with software failures or conversely speaking the software reliability. There are strong opinions that software failures are deterministic in nature and hence treating these failures through probabilistic approach may not be correct. The argument in favour of deterministic approach is that for every software failure there is definite and determinable cause attached to it. But if go back to the cause-effect relationship, so is the case with hardware failure also. Only issue is we do not perform a root cause analysis to investigate the cause of failure. Conversely speaking, even for software failures, it is not always possible to reach a root cause of the failure if the problem is complex, for example the fault was of intermittent (change in input condition for a very small interval of time) nature.

Given the above arguments we can assert that one of the attribute which induces random phenomenon is the root cause of failure. For arguments sake, if it was possible to understand the cause(s) of each failure or outcome then, can we treat the whole modelling using only deterministic approach? Here, we come to a stage where we say that possibly no as we have dealt with only part of the input to randomness, i.e. the cause of the failure and not the instant of failure. Fig.1 depicts the operational phase of a component showing various competing failure causes / mechanisms. As can be seen a typical failure could have one or more than one mechanisms. The randomness associated with type of failure and associated mechanism can be modelled deterministically using physics-of-failure approach while the randomness associated with the 'instant' of failure can be reduced using the accelerated testing performed in controlled atmosphere. The combination of physics-of-failure models and accelerated testing is expected to bring out the mechanism that dominated the failure while at the same time it will also provide the estimates of time to failure and consequently failure rates of the component.

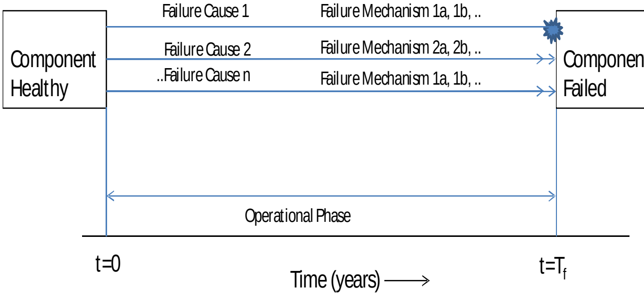

Fig. 1: Depiction of competing failure causes / mechanisms in temporal domain

3. The Framework

Keeping in view the technological developments and the state of the art that is available to understand / interpret an event (more specifically failure event) a framework has been proposed which is expected to facilitates improved treatment analyse the events. The Fig.2 depicts the framework / approach that enables not only prediction of the time to failure more accurately but also identifies the root cause and associated mechanism. The improved understanding of the mechanism enables recurrence of the same fault. In case the faults cannot be avoided altogether, provision can be made to safeguard the affected systems. As can be seen some elements are crucial for conventional (shown in the left side in the box with dotted lines) as well as the scientific based approach (right side in the box). These elements are a) data / historical information, b) probability / statistical models and c) the computational environment. The second approach can be termed as more scientific as the it provides a sound platform to predict failure and its causes. While the advancement in material properties and simulation and testing facility provides better insight into understanding of failure mechanism. This helps in developing improved physics of failure models. For instance, for predicting the life of electronics devices the value of activation energy plays vital role. Similarly the design of experiment approach makes the testing programme more effective in terms of requirements of number of samples, selection of parameter and its limiting values for accelerated tests. The availability of the advanced simulation / computational software are crucial to implementation of physics of failure approach.

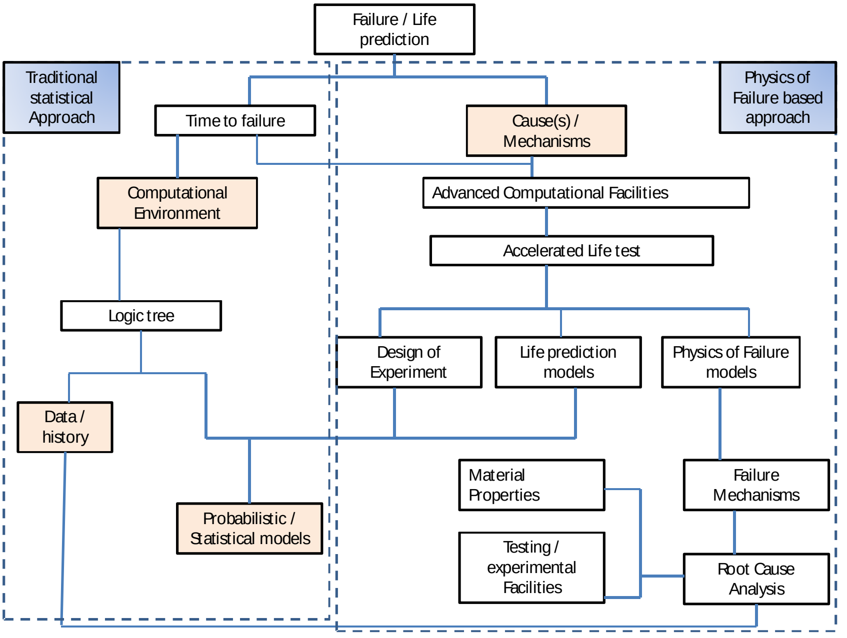

Fig. 2 The framework of the proposed approach

. In the following sections the salient features of the important elements of the proposed approach has been discussed

3.1 Physics of Failure paradigm

Even though statistical approach is still being used for many applications there is a growing interest in physics-of-failure approach as there is feeling that statistical approach alone is not adequate when it is important to understand various failure mechanisms with an objective to eliminate the causes of failure. The application of Physics-of-failure methods is growing as a) there is a better understanding of material properties, b) simulation techniques are proving very effective due to availability of advanced computational environments and models and c) accelerated life test methods and tools make it possible to design experiments for predicting the reliability and life of new components and d) ageing management programme requires assessment of remaining life of the components with reasonable accuracy. The statistical methods even though provides MTTF estimates, but the credibility of estimates obtained employing accelerating methods are more credible as these estimations are based on scientific understand and engineering parameters. Obviously the uncertainty in these estimates is expected to be much lower compared to statistical methods.

The need to predict, the life of the new components and the remaining life of old components requires more accurate method based more on deterministic models and methods and thereby reduce uncertainties due to random processes.

The basic challenge for the reliability or life assessment projects involving semiconductor devices, like Field Programmable Gate Arrays (FPGAa) and similar class of VLSIs, is that complexity of the chips in terms of number of transistors and interconnects have increased [4]. This resulted in increased current densities of the order of ~ 100 A/cm^2 and consequent thermal effects has potential for inducing failures. The research work performed has demonstrated that the interconnects along with transistors determine the density, reliability and performance.

The salient features of physics-of-failure approach has 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. The following section will bring out i brief the role of deterministic and statistical model in prediction the life / reliability for respective failure mechanism.

3.1.1 Electromigration

Exhaustive research has documented on physics of failure of 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. [5]. The model proposed by Black [6] 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 to understand the physics-of failure of interconnects. The metal atoms get activated by the electron current called 'electron-wind' when force they are subjected to electric field. The positively ionized metal atoms moves against the electron-wind force. The net result is the movement of vacancies and interstitials. The vacancies form voids or micro cracks and interstitials forms hillocks. Further the creation of voids results into 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 increase EM effect. This positive feedback cycle can result into thermal runaway and catastrophic failure. Apart from the semiconductor material, the microstructure of the interconnect dictate / govern the Electromigration process. In this respect the grain boundaries play vital role in forming potential defect sites and thereby conduit for electron flow. Hence, the challenge lies in working out a criteria or model that enable determination 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 of the ion current density is given by the following model as:

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

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 into formation of voids and consequent defects. There is reasonably good understanding of effect of these factors on microchip reliability.

Probability models

From the above discussions it is clear that there are well defined models that have been derived from the first principles of physical science. These models takes away a reasonable part of uncertainty that creeps into the reliability prediction models due to lack of understanding of failure mechanism which otherwise would have required consideration of random phenomenon using statistical approach.

Nevertheless, statistics still forms the part of physics-of-failure approach. This is because prediction of time to failure is still modelled employing probability distribution. Traditionally lognormal failure distribution has [7] been used to estimates failure time due to electro-migration related failure as follows:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\ln(t) - \ln(t_{50})}{\sigma} \right)^2 \right)$$

where t_{50} : median time to failure, σ: standard deviation. The typical observation is that the log normal standard deviation is related to the ratio of the line-width to the grain size [8] and the current density [9] and the value ranges from 0.28 to 1.4 [10]

The Electromigration mechanism has also been modelled using, Black model, Weibull model, etc, however, the lognormal distribution remains one that has found wider acceptability.

3.1.2 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 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 [11]. The presence of mobile hot carrier in oxides induces various physical damage processes that degrades the device performance characteristics and pose critical reliability issues and hence, referred as 'hot carrier degradation'. Even though extensive research is being performed 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 [12].

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

where τ: 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 estimates of device life time, however, the degradation model which is straight forward and simple proposed by Takeda [13] is as follows:

$t \propto I_{sub}^m$ where the value of m lies between 3.2-3.4.

3.1.3 Time-Dependent Dielectric Breakdown

This degradation involves phenomenon of leakage current and finally leads to short circuits due to failure of transistor gets. 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 have been 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 [14].

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

where, έoX 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 are now better understood to understand each of the failure mechanism the role of statistical methods is still relevant to estimate the time to failure. However, better estimates can be obtained by conducting the accelerated life tests/experiments to narrow down the uncertainty band.

3.2 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 in the history forms the basic tenets of root cause analysis approach. This approach assumes that for every event that is being investigated has roots which if addressed, can avoid recurrence of the event. Unlike typical brainstorming activities which are in vogue to investigate the understanding the cause of failure, in root cause analysis systematic attempts are made based on deterministic analysis approach to investigate the basic or root cause of the event or failure [15].

The investigation of component failure is carried out at two levels. One at system level where a systematic analysis is carried out employing 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 the basic cause of the system failure is a component failure, further analysis is required as to why the component failed. This is the point where the role of physics-of failure approach come in to play. In previous section an attempt was made to understand the physics of failure phenomenon of electronics, i.e. semiconductor devices. However, even though basic principles remain the same failure of mechanical components is also investigated using similar approach. It could be finite element modelling or an analytical technique to understand the stresses in a component. Test and simulation methods also employed to understand the root cause of mechanical failures.

There are many cases to show that the failure that were considered random in nature, after root cause analysis it turned out to be the failures for which a definite cause could be assigned and hence the attributes of randomness in respect of the failure cause no more remained probabilistic. Therefore after the root cause analysis the failure could be categorized as deterministic. For argument's sake one incident can be discussed at this point. The incident related to failure of an 'O' ring which was initially termed as random failure turned out to be due to a particular manufacturing fault. The manufacturing fault was of such a nature that blow hole in the defective 'O' ring induced due to formation of void in the 'O' ring due to material density / homogeneity related issue. It was also understood from the root cause analysis that apart from defective 'O' ring there were other deviations also contributed to the failure. The relative friction between the 'O' ring and the housing due to lack of lubrication also aggravated the situation which accelerated the failure mechanism. However, extensive root cause analysis was required to be performed which required extensive resources in terms of man-power, computational, time, etc to solve the problem.

3.3 Design of Experiment

For effective planning and execution for characterizing the reliability attributes of the components it is very important to optimize all the test parameters. The literature search 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 results of the test with relatively large uncertainty bound.

The design of experiment (DoE) approach enables estimation of these parameters based on sound statistical basis[16]. 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 inducing any failure mode that will not encountered in the actual use condition. The details related to the models and various test plans is not within the scope of this paper hence the same could be found in any publication on DOE.

3.4 Advances in 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 trends changes due to changes in operational or maintenance practices like major modification in the system, major change in overall maintenance practices, or repair / replacement, etc. There models available which facilitate single change point, like poison process mode. It 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 predict accurately 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.

Syamsundar et. al. [17]) proposed a segmented point process model for multiple change point in which it has been demonstrated that the accuracy of prediction is significantly higher. This research work further goes on to incorporate the environmental parameters by developing proportional intensity segmented point process model for maintained system[18]. The additional information available in respect of any data sets, like increase in vibration level, improvement in maintenance practices, use of different lots of spares, etc which normally has correlation to the net performance of the components are included in these models as covariates in the model. Incorporation of this approach forms the major work in the proposed model. The objective is to represent the data trend as accurately as possible to reduce uncertainty in the final predictions.

4. Discussions and Conclusions

The traditional approach for reliability assessment of component is based on statistical methods. In this approach to a large extent, historical data forms the input for predicting the life of the components and system. This approach even though worked well all along, has limitations. The first one is that the results of the analysis are based on past experience therefore new modes of failure which could be encountered in the future do not form part of the prediction model. Obviously, the results of prediction will have associated uncertainties. Second, this approach is not suitable when a new component is being developed. The third limitation is that in this approach a good amount of data is taken from generic source for 'similar components' in the database. Further, as it is accepted widely that even though probabilistic approach which is based on statistical methods forms the mainstay in assessing the component / system reliability provides results with relatively large uncertainty bands. The net effect is the reliability community in general and the risk assessment community in particular have their reservations when it comes to taking decision based on reliability / risk- based approach alone [19]. For instance let us take the example of the traditional approach to reliability assessment of electronic components. Apart from other similar approaches MIL-217 [20] methods are widely used for predicting the reliability of electronic components. This method involves use of a base failure rate value for a component which is modified using various applicable value for π-factors, like quality, environment, size (like, number of gates on semiconductor devices, no. of pins, etc), type of mounting, etc. The experience has been that the results of this analysis are very optimistic as it does not take into account various intimate aspects which are specific to the component in question. For example the typical operation & maintenance practices may affect the component reliability. Second, it deals with component failure without considering different competing mechanisms that causes degradation in the component.

If we take the case of mechanical / electrical components, the failure rate assessment process involves statistical methods where the failure rates are estimated using generic data or even if the data is available the statistical models are approximate to the data trend analysis and final reliability assessment. Accordingly the final results have relatively larger uncertainty bands. The applicability of the data in many cases can be argued [21]. Even if failure rates are obtained using this method, there is no way to understand the cause(s) of the failure.

This paper presents the progress that has been made in assessing the reliability or life characteristic of the component though physics-of-failure approach. This paper attempts to demonstrate that the role of statistical approach has reduced compared to what it was in traditional methods. The positive aspect of the new trend in reliability / life prediction approach is that estimates are based on the sound scientific basis and accordingly the uncertainty as been reduced particularly in respect of assessing the cause or mechanism of failure. This is because the randomness that was associated with the type of failure has been addressed by deeper understating of mechanism of failure. The second uncertainty, which is prediction of instant of failure has also been addressed using this approach. The accelerated testing performed under controlled atmosphere enables not only in revealing the failure modes but also reduces uncertainty in predicting the 'time-to-failure' of the components.

Even though there are significant progress has been made in development of scientific models that predict life time of the component, further efforts are required to develop new models or fine tune the available models like in the case of hot carrier degradation model and time dependent dielectric breakdown model. However, looking at the trend it can be argued that the physics-of-failure based approach will be used on regular basis for predicting reliability and life of components in the years to come.

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