FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 30, N° 1, March 2017, pp. 1 - 25
DOI: 10.2298/FUEE1701001B

MICROELECTRONIC RELIABILITY MODELS FOR MORE THAN MOORE NANOTECHNOLOGY PRODUCTS

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Abstract. *Disruptive technologies face a lack of Reliability Engineering Standards and Physics of Failure (PoF) heritage. Devices based on GaN, SiC, Optoelectronics or Deep-Submicron nanotechnologies or 3D packaging techniques for example are suffering a vital absence of screening methods, qualification and reliability standards when anticipated to be used in Hi-Rel application. To prepare the HiRel industry for just-in-time COTS, reliability engineers must define proper and improved models to guarantee infant mortality free, long term robust equipment that is capable of surviving harsh environments without failure. Furthermore, time-to-market constraints require the shortest possible time for qualification. Breakthroughs technologies are generally industrialized for short life consumer application (typically smartphone or new PCs with less than 3 years lifecycle). How shall we qualify these innovative technologies in long term Hi-Rel equipment operation? More Than Moore law is the paradigm of updating what are now obsolete, inadequate screening methods and reliability models and Standards to meet these demands. A State of the Art overview on Quality Assurance, Reliability Standards and Test Methods is presented in order to question how they must be adapted, harmonized and rearranged. Here, we quantify failure rate models formulated for multiple loads and incorporating multiple failure mechanisms to disentangle existing reliability models to fit the 4.0 industry needs?*

Key words: *Reliability, GaN, SiC, DSM, Nanotechnology, More than Moore*.

1. INTRODUCTION

Hi-Rel embedded system applications in Aeronautic, Space, Railways, Nuclear, Telecommunication rely on reliability engineering Standards [1] [2] related to Physics of Failure (PoF) [3]. When systems are constructed on innovative and disruptive technologies, such standards and methods are in general obsolete and inadequate to prepare their industrialization and qualification for just-in-time commercialization. Suggested Probabilistic Design for Reliability (PDfR) [4] and Prognostic Health Monitoring (PHM) [5] concepts open the door to anticipate and assess their reliability and quantification. Reliability prediction as Remaining Useful Life (RUL), failure rate and accelerating factors are mathematic and tools related to PoF describing macroscopic changes in materials and devices

Received May 18, 2016
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having their own microscopic behavior. Indeed statistics helps to predict population comportment but are unable to predict the performance on a single item as part of this population. This is exactly what did Ludwig Boltzmann (1844-1906) [6] when he gave a new perception of the universe on microscopic scale in the kinetic theory: a macroscopic state for some probability distribution of possible microstates.

Section 1 of this paper will review existing standards and clarify some route to implement and generalize existing reliability JEDEC or MIL Standards. These Standard methods develop failure mechanism models and their associated activation energies or acceleration factors that may be used in making system failure rate estimations. For large scale integration processes in the nanoscale range (now lower than the 10 nm) used for microcontrollers or PC's chip, the physic of interaction, the temperature distributions and the critical path for signal processing are extremely variable. The average value of the apparent activation energies of the various failure mechanisms can't be exploited because a) different failure mechanisms have different weighting factors and effects differently each portion of an IC's and b) the apparent activation energy values affect the acceleration factor exponentially rather than linearly.

Section 2 will detail accelerated stress models as exposed in well-established JEDEC documents prior to recall the multiple stress Boltzmann-Arrhenius-Zhurkov (BAZ) reliability model [**7**], [8] which can be considered also as a development of the COX proportional hazards model [9]. We will settle multiple failure mechanisms [10] as mandatory to be pondered for DSM nanotechnology nodes and will show how the HTOL reliability model elaborated by J. Bernstein [11] [12] can support a more robust easy-to-use theory.

Section 3, will show how a multi-dimensional tool named M-STORM (*M*ulti-phy*S*ics mul*T*i-stress*O*rs predictive *R*eliability *M*odel) [13] can be implemented in a concrete situation existing for the Deep-Submicron process devices highlighting the remaining steps to be carried out for a complete tool release.

2. QUALITY STANDARD OVERVIEW

Well-known Quality Standards in various industry domains rely or are close to Military Standards MIL-STD and JEDEC methods. Now entering the 4.0 industry paradigm as the fourth Industrial Revolution (the Age of cyber and robots), quality/reliability models and tools headed by Health Monitoring (HM) leads toward more crucial and vital questions. This section is not intended to be an exhaustive cookbook but on the other hand will highlight how generic approaches and hypotheses are considered to assure products and equipment's quality and how to built-in reliability products dynamically. The name "dynamically" means that hardware's and software's must be designed in order to pre-identify and characterize system degradation when still in-operating condition. To diagnostic the healthiness of a system for anticipating failure requires to open new roads to imagine and to design dedicated hardware and software installed within the system itself and to define procedures and tests which will decide self-corrections at hardware and/or software level (Artificial Intelligence). This requires a high level of intelligence integration within a system or a product and this is the challenge of the 4.0 era.

JEDEC or MIL Standards are generally based on the principle of separating the variables and considering a single stress at a time and a single failure mode and mechanism at a time. A failure mechanism may be characterized by how a degradation process proceeds including the driving force, e.g., oxidation, diffusion, electric field, current density. When the driving force is known, a mechanism may be described by an explicit failure rate model; identifying that model with associated parameters is the main objective.

The existing technologies, extended also to highly critical innovative technologies, oblige design engineers to consider those driving forces to be quantified considering multiple internal stress parameters inducing interfering stress settings (current, voltage, power and temperature) and loads (DC and AC, environment as thermal cycling, radiation, ElectroStatic Discharge -ESD, Electrostatic Over-Stress -EOS, Energetic electromagnetic pulse, etc.).

2.1. European standards

As an example, the European Cooperation for Space Standardization (ECSS) (www.ecss.nl) is an initiative established to develop a coherent system of European Space Standards. The ECSS organization standardization policy develops a documentation architecture with three branches (Project Management, Product Assurance and Engineering) to overcome issues due to the existing standard resulting in higher costs, lower effectiveness and in a less competitive industry.

The framework and basic rules of the system were defined with the involvement of the European space industry. A short overview of the main system documentation is presented here with the intention to show how, when and where the Quality Assurance requirements affect electronic parts supply chain considering long term harsh environment space missions. Most of Space Product Assurance documents are constructed to guarantee final customers' and operators' satisfaction for satellite mission duration greater than 18 years without repair. Most of them rely on well-established technologies and products avoiding to use innovative products. The ECSS-Q-ST-60C [2] standard defines the requirements for selection, control, procurement and usage of Electronic, Electrical, and Electromechanical (EEE) components for space projects considering the characteristics of the space environment condition. When selected, parts must be integrated on system based on best design practices. The "Space Product Assurance - Derating - EEE components" ECSS-Q-ST-30-11C [14] specifies electrical derating requirements applicable to EEE components. Derating is a long standing practice applied to components used on spacecraft's. COTS microcontrollers and core IC chips produced on nanoscale technology are now integrating 1 billion transistors (below the 10 nm node) on a single chip with CASH memory, I/O accesses, CPU, Flash and DDR memory, all biased at low voltage (below 1V) and accessed at increasing clock frequency (few GHz). As derating is under the control of designers and manufacturers nanoscale makers: due to the tremendous increase of system capability, big data management, world-wide telecommunication and Internet of Things, the Space industry must collaborate or impose new design rules if they want to use such innovative technologies.

Another scale, is for new packaging and connection techniques to be pondered. The ECSS-Q-ST-70-08C, [15] "Space Product Assurance Manual soldering of high-reliability electrical connections" is a Standard defining the technical requirements and quality assurance provisions for the manufacture and verification of manually-soldered, high-reliability electrical connections. For temperatures outside a normal range (−55°C to +85°C) special design, verification and qualification testing is performed to ensure the necessary environmental survival capability. Packaging and assembly reliability models must be improved too when additive manufacturing techniques and new materials for high power dissipation are mobilized. "Commercial electrical, electronic and electromechanical (EEE) components" document named ECSS-Q-ST-60-13C [16] applies only to commercial components which meet technical parameters that are on the system application level demonstrated to be unachievable with existing space components or only achievable with qualitative and quantitative penalties. All of these normative documents as ECSS and ESCC standards are generally based on MIL-STD and JEDEC test methods.

Component failures and system failures determination have been extensively described on handbook and tools but all of them are now mostly obsolete with respect to the emerging technologies proposed on the COTS market. They are unable to predict and quantify the reliability of new products having short product's life cycle and being complex and technically highly sophisticated.

2.2. Standards and handbooks

For EEE parts, the *AT&T reliability manual* [17] is more than just a prediction methodology. Although it contains component failure data, it outlines prediction models based on a decreasing hazard rate model, which is modeled using Weibull data.

FIDES [18] is a new reliability data handbook (available since January 2004). The FIDES Guide is a global methodology for reliability engineering in electronics, developed by a consortium of French industry under the supervision of the French DoD (DGA). The important fact is that FIDES evaluation model proposes a reliability prediction with constant failure rates. The infant mortality and wear out periods are today excluded from the prediction.

The IEC 62380 Electronic Reliability Prediction supports methods based on the latest European Reliability Prediction Standard. It was originally, the RDF 2000 (UTE C 80-810, IEC-62380-TR Ed.1) [19] from CNET handbook previously published as RDF93 and covers most of the same components as MIL-HDBK-217.

MIL-HDBK-217 [1] Reliability Prediction of Electronic Equipment, has been the main stay of reliability predictions for about 40 years, but it has not been updated since 1995.

The *Siemens SN29500* [20] Failure Rates of components and expected values method was developed by Siemens AG for use by Siemens associates as a uniform basis for reliability prediction.

The Reliability Prediction Procedure for Electronic Equipment documents *Telcordia SR-332* [21] recommends methods for predicting device and unit hardware reliability. This procedure is applicable for commercial electronic products whose physical design, manufacture, installation, and reliability assurance practices meet the appropriate Telcordia (or equivalent) generic and product-specific requirements.

In July 2006, RIAC released 217Plus™ [22] as the successor to the DoD-funded, Defense Technical Information Center (DTIC)-sponsored Version 1.5 of the PRISM® software tool. The *RAC (EPRD) Electronic Parts Reliability Data Handbook database* is the same as that previously used to support the MIL-HDBK-217, and is supported by PRISM®. The models provided differ from those within MIL-HDBK-217. The PRISM software is available from the Reliability analysis Center [23]. The models contain failure rate factors that account for operating periods, non-operating periods and cycling. Traditional methods of reliability prediction model development have relied on the statistical analysis of empirical field failure rate data. The RIAC new approach is predicated on component models considering the combination of additive and multiplicative model forms that predict a separate failure rate for each class of failure mechanism. A typical example of a general failure rate model that takes this form is:

$$\lambda_p = \lambda_0 \cdot \pi_0 + \lambda_e \cdot \pi_e + \lambda_c \cdot \pi_c + \lambda_i + \lambda_{sj} \cdot \pi_{sj} \quad (1)$$

where,

λ_p = Predicted failure rate
λ_o = Failure rate from operational stresses
π_o = Product of failure rate multipliers for operational stresses
λ_e = Failure rate from environmental stresses
π_e = Product of failure rate multipliers for environmental stresses
λ_c = Failure rate from power or temperature cycling stresses
π_c = Product of failure rate multipliers for cycling stresses
λ_i = Failure rate from induced stresses, including electrical overstress and ESD
λ_{sj} = Failure rate from solder joints
π_{sj} = Product of failure rate multipliers for solder joint stresses

One can note that part-count prediction assumes a "constant failure rate per part" as a linear combination (+ and x) of π factors and specific λ factors. Failure rate is for a stated period of the life of an item, the ratio of the total number of failures in a sample to the cumulative time of that sample.

A consistent frame work for reliability qualification using the Physics-of-Failure (PoF) concept is provided by the JEDEC JEP148 procedure [24]. The Physics-of-Failure (PoF) concept [25] is an approach to design and development of reliable product to prevent failure based on the knowledge of root-cause failure processes. It is based on understanding

- relationships between requirements and the physical characteristics of the product (and their variation in the production process),
- interactions of product materials with loads (stresses at application conditions) and their influence on product reliability with respect to the use conditions.

2.3. Discussion

Reliability engineering and mathematics have been many times presented, see for example detailed by Suhir, E. in his book "Reliability Applied Probability for Engineers and Scientists", McGraw-Hill, [26]. *Talking about reliability engineering of objects is studying property of complex elements that do not lend themselves to any restauration (repair) and have to be replaced after first failure. The reliability is completely due to their dependability*. This property is measured by the probability that a device or a system will perform a required function under stated conditions of a stated period of time. Suhir explain, this involves three major concepts:

1. Probability: The performance of a group of devices in a system described as a failure rate. Such an overall statistic does not have a meaning for an individual device.
2. Definition of a "Reliability Function": For a device, a failure is relatively easy to be fixed, based on guaranteed performance which can be measured. For a system, this concept is rather elusive and harder to set since based on customer satisfaction.
3. Time: What is "time", in defining reliability? There may be many critical time period, at component, equipment or at system level, but the reliability for each critical time period can be determined in appropriate terms.

Standards listed in section 1.2 are generally related to item as parts and system hardware functions based of constant failure rate considering the element of interest have been manufactured and screened efficiently, operating in a given environment and assuming wearout failure rate well beyond the operating End of Life time (EOL). The next sections developed in this paper will show how these hypotheses must be reexamined for present and future application based on new technologies but also on existing ones as Deep Sub Micron nanotechnologies already used for ASICS, FPGA or Memories.

The book from P. A. Tobias and D.C. Trindade [27] "Applied Reliability" (3rd edition), is an extensive and powerful document exposing mathematics and methods, statistical software helping reliability engineers addressing applied industrial reliability problems. Once developing statistical life distribution models, reliability prediction and quantification on emerging technology is somewhere a matter to look inside a fuzzy crystal. We are unable to obtain reasonable set of data from short endurance stress tests and extrapolate or approximate what should be the effect at normal use condition on their behavior.

What a product is likely to experience at much lower stress knowing its failure rate at a higher stress? The model used to bridge the stress gap are known as acceleration models but assumes to be constructed and grounded on some hypotheses:

- Lot homogeneity and reproducibility: It is assumed components under stress are manufactured from an homogeneous lot and supposing no major change in manufacturing technology,
- Stress effects are representative, homogeneous and reproducible,
- Failure mechanism duplication: independent of level of stress, and reproducible,
- The failure rate of a device is independent of time. This is the usual, but often very inappropriate, assumption in conventional reliability-prediction methods .
- Linear acceleration: *When every time to failure, every distribution percentile is multiplied by the same acceleration factor to obtain, the projected values at another operating stress, we say we have linear acceleration* [27].
- Temperature effect governed by Arrhenius law: "things happen faster at high temperature". Lower temperatures may not necessarily increase reliability [10] [5], since some failure mechanisms are accelerated at lower temperature as seen for example for Hot Carrier Degradation mechanisms. Generally Quality standards and prediction tools are focusing only on high temperature acceleration models.
- Multiplicity: multiple stresses (loads) and multiple failure mechanisms at a time (*cf* discussion in section 3 and 4).
- PoF signature: Activation energy determined from experiments based on catastrophic degradation or related to electrical parameter drift (a predictor).
- Temperature definition: An accurate and agreed concept to be the core of reliability prediction tool based on thermal accelerated testing.

Reliability of electronic equipments are designed considering affected by the temperature. Influence of temperature on microelectronics and system reliability published by P. Lall, M. Pecht and E. B. Hakim in 1997 [28], discussed various modelling methodologies for temperature acceleration of microelectronic device failures. MIL-HDBK-217, FIDES and JEDEC standards have advantages to describe such models but are mostly not adapted to breakthrough and new immature technologies.

How to quantify reliability for disruptive technologies? Knowing, a) multiple failure mechanisms are in competition, b) activation energies are parameters determined experimentally, c) based on accelerated tests carried out at extreme temperatures (both at high and low) and d) supposed to be constant but modified by stress conditions, Physics of Failure (PoF) methodology is the alternative suggested approach in the mid 90's by the U.S., CADMP Alliance now known as Electronic Components Alliance [5]. *Problems arise when the failure mechanisms precipitated at accelerated stress levels are not activated in the equipment operating range* as highlighted by Lall, Pecht and Hakim [28].

Since 2010, we first define a generalized multiple stress reliability model and Suhir, E. published a comprehensive model called Boltzmann-Arrhenius-Zhurkov (BAZ) model [7], [8], [29], [30]. The premises of this model was addressed by D. Cox [9] in *Journal of the Royal Statistical Society* 1972. In last decade view, two advanced probabilistic design-for reliability (PDfR) concepts were addressed in application to the prediction of the reliability of aerospace electronics: 1) Boltzmann-Arrhenius-Zhurkov (BAZ) model, which, in combination with the exponential law of reliability, and 2) Extreme Value Distribution (EVD) technique that can be used to predict the number of repetitive loadings that closes the gap between the capacity (stress-free activation energy) of a material (device) and the demand (loading), thereby leading to a failure.

The second concern illustrated by the previous discussion is related to multiple failure mechanism being in competition. The monograph and papers published since 2008 by Pr. J. Bernstein [11], [25], [31] quite precisely define the context and the modified M-HTOL [12] approach. The development of which is part of the following section 2 and 3.

3. Reliability Mathematics and Tools

Many books and papers define basic concepts in reliability and particularly on reliability prediction analysis such as a FMECA (Failure Modes, Effects and Criticality Analysis), RBD (Reliability Block Diagram) or a Fault Tree analysis. In reliability engineering and reliability studies, the general convention is to deal with unreliability and unavailability values rather than reliability and availability (see for example http://www.reliabilityeducation.com/):

- The Reliability $R(t)$ of a part or system is defined as the probability that the part or system remains operating from time t_0 to t_1, set that it was operating at t_0.
- The Availability, $A(t)$ of a part or system is defined as the probability that the component or system is operating at time t_1, given that it was operating at time t_0.
- The Unavailability, $Q(t)$ of a part or system is defined as the probability that the component or system is not operating at time t_1, given that it was operating at t_0.

Hence, $R(t) + F(t) = 1$ or Unreliability $F(t) = 1 - R(t)$ and $A(t) + Q(t) = 1$ (2)

Figure 1 shows the schematic representation of failure distribution functions.

The Instantaneous Failure Rate (IFR), also named the hazard rate $\lambda(t)$, is the ratio of the number of failures during the time period Δt, for the devices that were healthy at the beginning of testing (operation) to the time period Δt.

$$\lambda(t) = \frac{f(t)}{1 - F(t)} \tag{3}$$

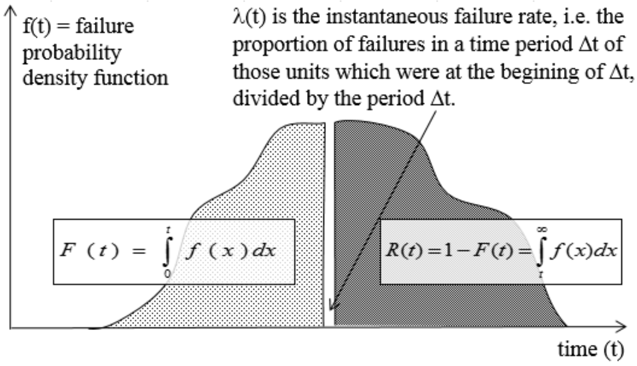

Fig. 1 Instantaneous failure rate, probability density function and reliability distribution functions

The cumulative probability distribution function $F(t)$ for the probability of failure is related to the probability density distribution function $f(t)$ as

$$F(t) = \int_0^t f(x).dx \tag{4}$$

and the reliability function $R(t)$, the probability of non-failure is defined as

$$R(t) = 1 - F(t) \tag{5}$$

Failure rates are often expressed in term of failure units (FITs): 1 FIT = 1 failure in 10^9 device-hours. Probability data obtained when performing accelerated tests (HALT or FOAT) can be modeled by various distribution models, such as exponential law, Weibull law, normal or log-normal distributions, etc.

In most practical applications, life is a function of more than one or two variables (stress types). The next and an important question is how to consider and relate the reliability figures when applying other stresses than temperature, as thermal cycling or radiation?

On JEDEC Standard JEP122G, reliability models as Electromigration [32], Ohmic contact degradation [33] [34], Coffin-Manson [35], Eyring [36], Humidity [37], Time Dependent Dielectric Breakdown TDDB [38], Hot Carrier Injection [39] [40] [41], Hydrogen poisoning [42] [43], Thermo-mechanical stress [44], NBTI [45] are generally expressed by a function of stress parameter or by a function of an electrical predictor multiplying the exponential activation energy factor.

Talking about stress parameters named *Stressors* or electrical *Predictors* may sometimes be confusing because the first one (e.g. *Stressors*), give warning on how is high or low the Free Gibbs energy barrier to cross, and the second concept (e.g. *Predictors*) gives information on how fast the device will cross that barrier. The core of generalizing the existing models must unified this apparent antagonism by using precise definitions and effects. In general this has been unthank by major papers published. Reader will see in the next paragraph how such confusion is considered.

All studies argue and consider the activation energy are deduced experimentally as a constant with respect to temperature (low vs high), stress conditions, and other predictors as for example charge de-trapping for Hot Carrier Degradation or NBTI for PMOS devices under negative gate voltages at elevated temperature. These models are generally applicable for a given technology. Even some end-users and customers are focused to qualify lot production instead of a process. There is a need to simplify the forest of existing models. Is it possible to harmonize the mathematics of the existing paradigm?

First consideration is to define precisely the elements and roles of each parameter separating the thermodynamics (activation energy, Free Gibbs energy), stressor and predictor parameters and their effects in failure mechanisms.

3.1. Reliability standards and Accelerated stress models

Formerly, activation energy is related in one hand to a single pure temperature effect and disregard other stress parameters. It is true in second hand, the activation energy is defined as an effective activation energy mostly modified by several type of other stresses applied and failure mechanisms considered. Steady state temperature stress tests are considered the only stress parameter affecting reliability and are typically time-dependent temperature related.

Failure mechanisms are thermally activated or not and can be either catastrophic or parametric (drift of characteristics). A sudden catastrophic failure can be observed due to electrical overstress and is called burnout or due to high electrical field inducing catastrophic breakdown. Breakdown and burnout limits are also temperature dependent. As a consequence it is reasonable to consider a same failure mechanisms being induced by a pure thermal stress to a pure electrical stress: in this case any intermediate condition between these two extremes will be modeled by a pure Arrhenius activation energy modified by a factor depending of stresses applied. This postulate justify the Boltzmann-Arrhenius-Zhurkov model (BAZ) presented in the section 2.2.

The idealized experimental bathtub curve of a material or a device shown in Figure 2 exhibits the combined effect of the statistics-related and reliability-physics-related processes. In the analysis developed by Suhir [46], a probabilistic predictive model (PPM) is developed for the evaluation of the failure rates and the probabilities of non-failure.

Here we draw a synthetized view on how we can clarify some concept for a comprehensive harmonization of existing reliability model of failure mechanism:

- Internal electrical stresses labelled ***Stressor parameters*** are responsible of the wearout failure rate (Weibull β greater than 1). They are only of four types of applied and imposed stress conditions: they are ***voltage***, ***current, dissipated power*** and ***input signal*** or ***ESD/EOS/EMC energies*** and can be either static, dynamic, transient or surge. They are quantified with respect to their level of stress applied compared to their level of burnout instantaneous failure mode. But for sake of standardization and normalization they are limited by the maximum values allowed by the technology.
- When device operates under ***External stress*** (thermal management constraints, packaging and assembly constraints, atmosphere contaminants, radiations environments), such stressor parameters level are modified with respect to their maximum burnout and breakdown limits thus accelerating wearout failures compared to temperature and biasing stress in the absence of external environment.
- Failure modes of interest are electrical or mechanical signatures related to failure mechanisms observed and are ***Predictor parameters***. Such parameters can be measured as absolute drift value of electrical parameter or as relative percentage of drift.

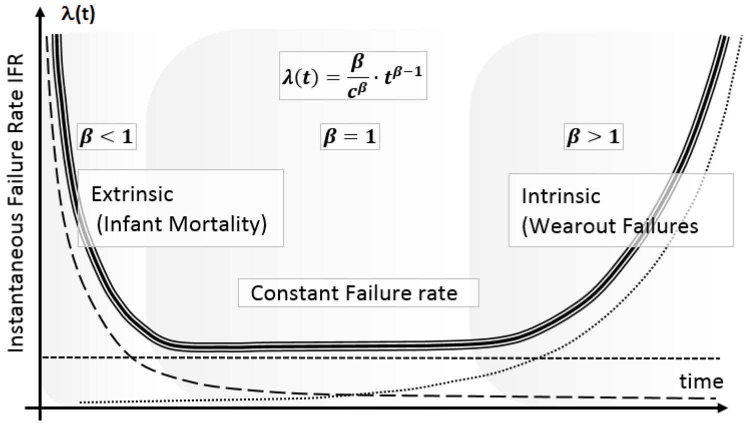

Fig. 2 Bathtub curve. Weibull distribution with two parameters (shape and time).

- ***Constant failure rate*** (Random) are caused by random defects and random events. The Failure rate is modeled by a Weibull shape parameter close to 1 which is equivalent to an exponential distribution law.
- ***Lot-to-lot production variation*** (respectively device-to-device) and performance dispersion from a single manufacturing lot (respectively device) will affect the burnout limits, inducing in return a change of percentage of stress applied on a given lot (device). Statistic dispersion will affect the time to failure on similar way (producing the same statistical effect). Such dispersion at lot and device level will impact the Remaining Useful Life (RUL) for some part of the population.
- ***Infant mortality*** failure population are caused by “defects” and correlates with defect-related yield loss. They are reduced by improved quality manufacturing and by screening.

3.2. BAZ model and Transition State Theory accelerated stresses

Design for reliability (DfR) is a set of approaches, methods and best practices that are supposed to be used at the design stage of the product to minimize the risk that it might not meet the reliability requirements, objectives and expectations.

These considerations have been the basis of the generalized BAZ model mentioned in section 1 constructed from the 1965 Zhurkov’s [47] solid-state physics model, which is a generalization of the 1889 Arrhenius’ [48] chemical kinetics model, which is, in its turn, a generalization of the 1886 Boltzmann’s (“Boltzmann statistics”) [49] model in the kinetic theory of gases.

The paradigm of the Transition State Theory (TST) developed by E. Wigner in 1934 [50] and by M. Evans, M. Polanyi in 1938 [51] is viewed as the equivalent approach we apply to the concept of a unified semiconductor reliability model.

The Arrhenius equation relates reaction rate r of transition from a reactant in state A to a product in state B is depending on temperature and the activation energy as also modeled by Transition state Theory. The probability that the particular energy level *U* is exceeded has been expressed in Boltzmann’s theory of gases:

$$p(U) = \frac{1}{k \cdot T} \cdot exp\left(-\frac{U}{k \cdot T}\right) \tag{6}$$

and a total distribution is found to be:

$$P(E_a) = \int_{E_a}^{\infty} p(U) \cdot dU = exp\left(-\frac{E_a}{k \cdot T}\right) \tag{7}$$

This function defines the probability P that the energy of a defect exceeds the activation energy can be assessed as a function of the ratio of time constant τ_0 to lifetime τ equal to:

$$r = \frac{1}{\tau} = A_0 \cdot exp\left(-\frac{E_a}{k \cdot T}\right) \tag{8}$$

Figures 3.a show a schematic drawing of the principle of the Transition State Theory which represents the amount of Free energy $\Delta G^\ddagger$ required to allow a chemical reaction to occur from an initial state to a final state. If the chemical reaction is accelerated by a catalyst effect the height of energy $\Delta G^\ddagger$ is reduced allowing the transition Initial state → Final State to occur with a transition state energy being a lower value of the energy barrier to cross.

In Transition State Theory with catalyst effect it is possible to get an effective activation energy being negative (shown in Figure 3.b), as observed for example for HCI failure mechanism. It is observed that hot carrier injection induced effects are exaggerated at lower temperatures demonstrating clear negative effective activation energies.

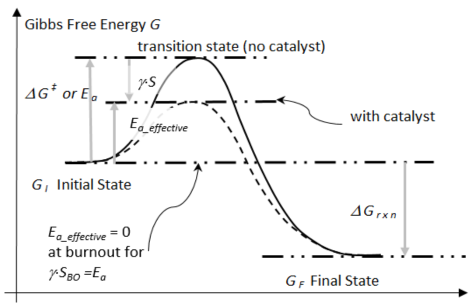

Fig. 3.a Transition State Theory principle diagram

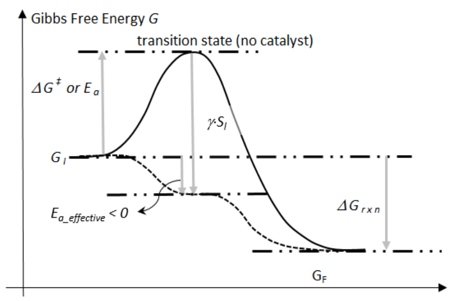

Fig. 3.b with catalyst effect with negative Ea and for HCI failure mechanism.

The Boltzmann-Arrhenius-Zhurkov (BAZ) model [8] determines the lifetime τ for a material or a device experiencing combined action of an elevated temperature and external stress:

$$\tau = \tau_0 \cdot exp\left(-\frac{E_a - \gamma \cdot S}{k \cdot T}\right) \tag{9}$$

where S is the applied stress (can be any stimulus or a group of stimuli, such a voltage, current, signal input, etc), T is the absolute temperature, γ is a factor of loading characterizing the role of the level of stress (the product $\gamma \cdot S$ is the stress per unit volume and is measured in the same units as the activation energy E_a), and k the Boltzmann's constant (1.3807 10^{-23} J/K or 8.6174 10^{-5} eV/K).

The generalized BAZ model proceeds from the rationale that the process of damages is temperature dependent, but is due primarily to the accumulation of damages resulting from loading above the threshold stress level. Each level of stress is characterized by the corresponding term $\gamma \cdot S$ normalized by the term $k \cdot T$, thereby defining the relationship between the elevated temperature and the energy contained in an elementary volume of the material or the active zone of a device.

In a recent papers E. Suhir et al. presented [52] [53] the substance of the multi-parametric BAZ model considering the lifetime τ in the BAZ model be viewed as the MTTF. The failure rate for a system is given by the BAZ equation can be found as:

$$\lambda = \frac{1}{\tau} = \frac{1}{\tau_0} \cdot exp\left(\frac{E_a - \gamma \cdot S}{k \cdot T}\right) \tag{10}$$

assuming the probability of non-failure at the moment t of time is

$$P = exp(-\lambda \cdot t) \tag{11}$$

This formula is known as exponential formula of reliability. If the probability of failure P is established for the given time t in operation, then the exponential formula of reliability can be used to determine the acceptable failure rate. Such an assumption suggests that the MTTF corresponds to the moment of time when the entropy of this law reaches its maximum value. Using the famous expression due to Gibbs for the entropy which was later used by Shannon to define information [54] from the formula:

$$H(P) = -k \cdot P \cdot \ln P \tag{12}$$

we obtain that the maximum value of the entropy *H(P)* is equal to e^{-1} = 0.3679. With this probability of non-failure, the formula (9) yields:

$$t_{50\%} = \tau_0 \cdot exp\left(-\frac{E_a - \gamma \cdot S}{k \cdot T}\right) \tag{13}$$

Comparing this result with the Arrhenius equation (1), Suhir concludes that the $t_{50\%}$ or MTTF expressed by this equation corresponds to the moment of time when the entropy of the time-depending process $P=P(t)$ is the largest.

Let us elaborate on the substance of the multi-parametric BAZ model using an example of a situation when the product of interest is subjected to the combined action of multiple stressors S_i (electrical stress as for example DC biasing current, voltage, power dissipation or dynamic input signal). Let us assume that the wearout failure rate $\lambda_{WF}(t)$ of an electronic product, which characterizes the degree of propensity of a material or a device to failure, is determined during testing or operation by the relative drift of an electrical predictor parameter ξ_p as the electrical signature of the failure mode of concern [55] and considering equation (10), one could seek the probability of the material or the device non-failure in the form:

$$P = \exp\left[-\gamma_\xi \cdot \frac{\Delta\xi_p}{\xi_{p_0}} \cdot t \cdot \left(\frac{1}{\tau_0}\right) \cdot exp\left(-\frac{E_a - \sum \gamma_i \cdot S_i}{k \cdot T}\right)\right] \tag{14}$$

where ξ_{p0} is the value of the predictor parameter at time = 0 and γ_ξ, γ_i values reflect respectively the sensitivities of the device to the corresponding predictor and stressors. The model can be easily made multi-parametric, i.e. generalized for as many stimuli as necessary [55]. The sensitivity factors must be determined experimentally.

Because of that, the structure of the multi-parametric BAZ expressed by the equation (14) should not be interpreted as a superposition of the effects of different stressors, but rather as a convenient and physically meaningful representation of the FOAT data.

In such condition the suggested approach is to determine the γ factors reflecting the sensitivities of the device to the corresponding stimuli (stressors). This will be detailed when considering the BAZ model derived from the Transition State Theory in the following section related to multiple dimensional reliability model.

One's note the equation (14) can be viewed as a Cox proportional hazards model [9]. Survival models consist of two parts: the underlying hazard function, denoted $\lambda_0(t)$, describing how the risk of event per time unit changes over time at baseline levels of covariates; and the effect parameters, describing how the hazard varies in response to explanatory covariates. The hazard function for the Cox proportional hazard model has the form:

$$\lambda(t|X_i) = \lambda_0(\mathrm{t}) \cdot \exp\left(\beta_1 \cdot X_{i1} + \cdots + \beta_p \cdot X_{ip}\right) = \lambda_0(\mathrm{t}) \cdot \exp(X_i \cdot \beta) \quad (15)$$

This expression gives the hazard rate at time t for subject i with covariate vector (explanatory variables) X_i. Saying this, one limitation of the Cox model is observed on reliability analysis method: for a sound part at time t, the failure probability during time [t, $t+dt$] is related to stress applied during this period of time dt but not taking into account history of stresses applied before t. This may be a limitation when modeling non-constant stress applied during time (e.g. step stress test for example). The Proportional Hazards (PH Cox) model can be generalized (GPH) by assuming that at any moment the ratio of hazard rates is depending not only on values of covariates but also on resources used until this moment.

The application of the PDfR concept and particularly the multi-parametric BAZ model enables one to improve dramatically the state of the art in the field of the microelectronic products reliability prediction and assurance.

4. Multi-dimensional Reliability Models

As seen in section 1 and 2, existing Quality Standards are considering stress tests and related PoF mechanisms without entanglements. Device failure rates are seen to be a sum of each existing failure rate taken individually. Bathtub curve is an idealized view of instantaneous failure rate scenario generally considered in well-known MIL, JEDEC or TELCORDIA Standards.

The multidimensional variable addressed by Boltzmann-Arrhenius-Zhurkov (BAZ) reliability model and the multi mechanism model HTOL (High Temperature Operating Lifetest) proposed by J. Bernstein are discussed now with the intend to generalize how their implementation can be suitable for an easy to use, to quantify and to predict probability of failure of new products and technologies.

4.1. Multiple stressors and predictors

The baseline of the model deals with concept issued from the Transition State Theory and the healthiness of a population of device must grow and change with time and stresses applied. The first concept is that a device or a homogeneous lot of item constituted of population of "identical" device must fail after an observed time due to aging either under operation or under storage conditions. The statistics of this behavior has to do with entropy evolution of such item of population. The transformation from a sound item to a failure is similar to what is described in the Transition State Theory considering similarly a system of products to combine in a new system of product when energy is provided to the system.

Stressor definition and normalization

In a similar way considering a population of devices submitted to heating will only degrade continuously up to malfunction and failure. But when superposing high (or low) temperature and adequate stressors, the time-to-failure of such alike population will reduce. The term "stressors" here is defined as the electrical factors applied to the device of concern. Stressors are all limited by technology boundaries defined by the burnout values of each related electrical parameter (breakdown voltage, current overstress and burnout, power burnout, input signal overstress). These stressors can be normalized with respect to their burnout limits and strains are pondered as percentage of breakdown limits. The main hypotheses, verified by experiments on electronic devices and population of similar devices, are:

i. the physical instantaneous degradation phenomena due to electrical stress above the limits is observed at any temperature and depend of the active zone temperature of the device under test (Sze, S. M [56])
ii. the relative drift of a predictor parameter is a function of time (for example square root for diffusion mechanisms) and relate to a failure mechanism activated by temperature and biasing.
iii. For a biasing set higher and close to the breakdown limit, the two failure mechanisms (e.g. the diffusion and the instantaneous catastrophic ones) are in competition and occurred simultaneously; for sake of simplicity it is assumed they are progressively and linearly combined from a pure diffusion mechanism at nominal biasing to a pure burnout at high bias (voltage or current of power dissipation).

This last hypothesis is the foundation of the BAZ model, as the stressor is seen like a catalyst effect able to modify the height of the barrier of the pure temperature failure mechanism (Arrhenius thermally activated) and to quantify the effect of biasing on the barrier properties. The predictor parameters is then the sensitive tool we can use to measure this barrier height under various temperature and bias conditions. For unit homogeneity, the stressor is multiplied by a constant factor to be determined by experiments and the term $\gamma \cdot S$ is in eV unit. Indeed the γ coefficients can be easily determined because of hypothesis iii) above and as shown on figure 3, the apparent height of the barrier is reduced to zero and we can verify:

$$\gamma_S \cdot S_{BO} = E_a \tag{16}$$

e.g. when the bias is high enough to reach the instantaneous catastrophic failure.

This major principle is called ***Failure Equivalence*** (FE) principle.

Because *Ea* (pure thermal effect) is assumed to be a constant and considering the burnout limit is temperature dependent potentially distributed (Gaussian distribution), the γ factor should also reflect temperature dependence and have a same Gaussian like distribution. The present paper will not consider this extension and the γ factor is supposed to be a constant on a first basis.

Predictor definition

As mentioned previously, an electrical predictor parameter ξ_p is defined as the electrical signature (failure mode) of a failure mechanism of interest. Such a parameter is normalized with respect to its initial value at time zero. Similarly to the stressor context, we can define an equivalent energy using a prefactor γ_ξ as outlined in equation (14).

Figure 4 is a schematic drawing showing how the FE principle applied and how predictors and stressors takes place in the BAZ model highlighted by the Transition State Theory. All vertical axes are transformed in energy unit.

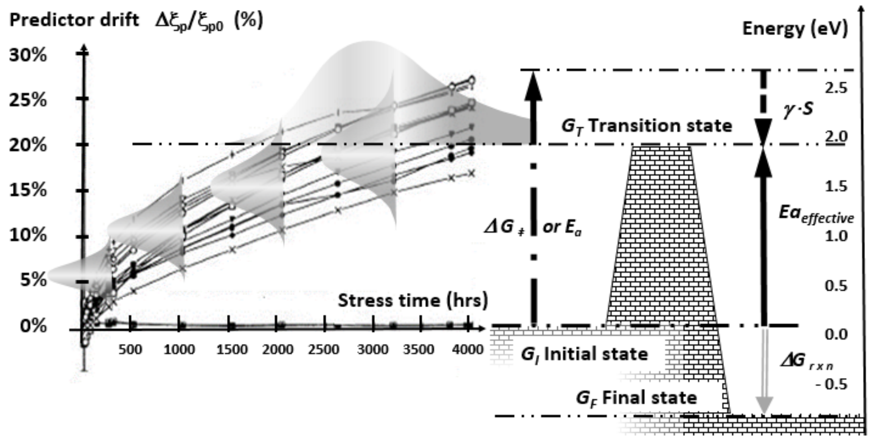

Fig. 4 Predictor ξ_p and stressor *S* for BAZ model and transition state theory

The predictor relative drift shown is an example of actual measurements performed on microwave transistors when submitted to steady state aging testing [57]. The predictor of each single device is normalized with respect to its initial measurement (mean value) and the failure criteria was 20% drift reached. So, the drawing is set in order to consider failed devices for all drift greater than 20%.

4.2. BAZ model simplification and applicability

It is observed from section II, the BAZ model is a generalization of existing well known Arrhenius equation modified by commonly accepted industrial models as Eyring for example. As presented in ref [29], all failure mechanisms models as detailed in JEDEC JEP122 can be rearranged in the following form

$$\tau = \tau_0 \cdot g(S) \cdot exp\left(-\frac{E_a}{k \cdot T}\right) \quad (17)$$

Where the function *g(S)* are a function of stressor parameter always expressed in two ways generalized expressions:

$$g(S) = S^{-m} = exp[-m \cdot ln(S)] \quad (18.a)$$

Or

$$g(S) = exp(-S^p) \quad (18.b)$$

where *m* and *p* = 1 or -1 is a power law factor.

Applying the normalization process for each stressor S_i with respect to its burnout limit parameters or electrical parameter limits, we set:

$$S_i = x_i \cdot S_{i_{BO}} \quad (19.a)$$

$$ln(S_j) = x_j \cdot ln(S_{j_{BO}}) \quad (19.a)$$

From these equations, it is assumed the x_i and x_j are varying from 0 when no electrical stress is applied to 1 when maximum electrical stress induces an instantaneous failure at any given temperature. The value of stressor burnout is considered in a first approximation not temperature dependent. This can be reformulated when the model will be refined to take into account this statement.

Merging equations (17 to19), it is easy to express the general equation of failure rate as:

$$r = r_0 \cdot exp\left(\frac{E_{a_{effective}}}{k \cdot T}\right) \tag{20}$$

With the effective activation energy in the form [13]:

$$E_{a_{effective}} = E_a \cdot \left(1 - \sum_{i,j=1}^{i=p,j=q}\left[x_i \cdot \gamma_i \cdot S_{i_{BO}}{}^{-n_i} + m_j \cdot k \cdot T \cdot x_j \cdot \gamma_j \cdot \ln\left(S_{j_{BO}}\right)\right]\right) \tag{21}$$

Expression 21 is based on the assumption that the stressors are temperature independent and are applied simultaneously, so simply added because of a linear approximation point of view. The stressors are considered independent and they aggregate each other up to a value which compensate exactly the “pure” Arrhenius activation energy leading to an instantaneous burnout (see figure 3.a for clarification): consequently the principle of superposition cannot be invoked in this case, rather it is a principle of aggregation and compensation. The stressors defined above are considered through literature experiments and accumulated data. Of course any other type of stressor can be easily introduced in lieu of or together with the listed stressors providing they are relevant in the considered model. This proposed reliability methodology is agile and consists of measuring the burnout or breakdown true limits (including lot dispersion values mean and standard deviation) or some physical limit as for HCI in order to normalize new stress parameter with respect to its limit and to include it in the equation 13.

4.3. Multiple failure mechanisms (M-TOL)

The key novelty of the Multiple-Temperature Operational Life (M-TOL) testing method proposed by J. Bernstein [58], is its success in separating different failure mechanisms in devices in such a way that actual reliability predictions can be made for any user defined operating conditions. This is opposed to the common approach for assessing device reliability today is the High Temperature Operating Life (HTOL) testing [59], which is based on the assumption that just one dominant failure mechanism is acting on the device [31].

However, it is known that multiple failure mechanisms act on the device simultaneously [25]. The new approach M-TOL method predicts the reliability of electronic components by combining the Failure in Time (FIT) of multiple failure mechanisms [60]. Degradation curves are generated for the components exposed to accelerate testing at several different temperatures and core stress voltage. Data clearly reveals that different failure mechanisms act on the components in different regimes of operation causing different mechanisms to dominate depending on the stress and the particular technology. A linear matrix solution, as presented in [60], allows the failure rate of each separate mechanism to be combined linearly to calculate the actual reliability as measured in FIT of the system based on the physics of degradation at specific operating conditions.

An experimental results of the M-TOL method tested on both 45 and 28 nm FPGA devices from Xilinx that were processed at TSMC (according to the Xilinx data sheets) is running in the frame of a project granted by research institute of technology named IRT Saint Exupery, Toulouse (France). The FPGAs are tested over a range of voltages, temperature and frequencies, and the test program is conducted by J. Bernstein, Ariel University, Ariel (Israel). Ring frequencies of multiple asynchronous ring oscillators simultaneously during stress in a single FPGA were read and recorded. Hundreds of oscillators and the corresponding frequency counters were burned into a single FPGA to allow monitoring of statistical information in real time. Since the frequency itself monitors the device degradation, there is no recovery effect whatsoever, giving a true measure for the effects of all the failure mechanisms measured in real time.

The common intrinsic failure mechanisms affecting electronic devices are, Hot carrier Injection (HCI), Bias Temperature Instability (BTI), Electromigration (EM) and Time Dependent Dielectric Breakdown (TDDB). TDDB will not be discussed in this paper since it was never observed in our test results. The standard models for failure mechanisms in semiconductor devices are classified by JEDEC Solid State Technology Association and listed in publication JEP-122G. The failure mechanisms can be separated due to the difference of physical nature of each individual mechanism.

The theory of using FPGAs as the evaluation vehicle for our M-TOL verification utilizes the fact that this chip is built with the basic CMOS standard cells that would be found in any digital process using the same technology. The system runs hundreds of internal oscillators at several different frequencies asynchronously, allowing independent measurements across the chip and the separation of current versus voltage induced degradation effects.

When degradation occurred in the FPGA, a decrease in performance and frequency of the RO could be observed and attributed to either increase in resistance or change in threshold voltage for the transistors.

The test conditions were predefined for allowing separation and characterization of the relative contributions of the various failure mechanisms by controlling Voltage, Temperature and Frequency. Extreme core voltages and environmental temperatures, beyond the specifications, were imposed to cause failure acceleration of individual mechanisms to dominate others at each condition, e.g. sub-zero temperatures, at very high operating voltages, to exaggerate HCI.

The acceleration conditions for each failure mechanism allowed us to examine the specific effect of voltage and temperature versus frequency on that particular mechanism at the system level, and thus define its unique physical characteristics even from a finished product. Finally, after completing the tests, some of the experiments with different frequency, voltage and temperature conditions were chosen to construct the M-TOL Matrix.

The results of our experiments give both E_a and γ for the three mechanisms we studied at temperatures ranging from -50 to 150°C. The Eyring model [36] is utilized here to describe the Failure in Time (FIT) for all of the failure mechanisms. The specific TTF of each failure mechanisms follows these formulae:

$$FIT_{HCI} = f \cdot V^{\gamma_{HCI}} \cdot e^{-\frac{Ea_{HCI}}{kT}} \tag{22}$$

$$FIT_{BTI} = e^{\gamma_{BTI} V} \cdot e^{-\frac{Ea_{BTI}}{kT}} \tag{23}$$

$$FIT_{EM} = f \cdot V^{\gamma_{EM}} \cdot e^{-\frac{Ea_{EM}}{kT}} \tag{24}$$

Correct activation energy simultaneously with corresponding voltage factor were determined. The procedure was followed for all three mechanisms for the 45nm as well as the 28nm devices. The E_a and γ for HCI found in 45nm are summarized in Table 1.

Table 1 Summary of *Ea* and γ for FPGA 45 nm.

	E_a (eV)	γ
HCI	-0.37	22.7
BTI	0.52	3.8 V^{-1}
EM	1.24	3.8

As presented by Regis, D. et al. [61], the impact of scaling on the reliability of integrated circuits is the actual concern. It is particularly necessary to focus on three basics of safety analyses for aeronautical systems: failure rates, lifetimes and atmospheric radiations' susceptibility. The Deep Sub-Micron technologies, in terms of robustness and reliability, need to be modeled because the increase in failure rate, reduction in useful life and increased vulnerability to high energy particles are the most critical concerns in terms of safety. When considering the well documented failure mechanisms related to the die only, they can be defined in two families, one for those related to what is call Front End Of Line (FEOL) meaning at transistor level and those occurring in the Back end Of Line (BEOL) mainly metallization. As illustrated on figure 5 (extracted from paper [61]), ICs are affected by different degradation mechanisms during their useful life. These degradation mechanisms can shift the properties of electronic devices and thereby affect the circuit performance.

Due to the exponential nature of acceleration factor (referring to equations 22 to 24) as function of voltage, frequency (equivalent to current) or temperature, it is mandatory to consider at least 3 mechanisms, each of them in competition and accelerated.

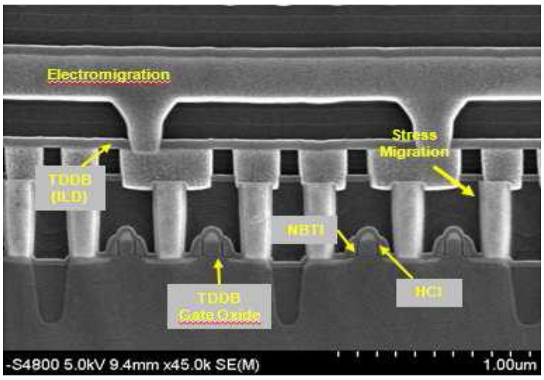

Fig. 5 Wear-out phenomena localization (65 nm IC cross section) (from [61]).

The paper proposed by J. Bernstein [12] is offering a new reliability point of view and is synthetized hereunder. The proposed M-TOL approach is defined with multiple failure mechanism in competition and on the assumption of non-equal failure probability at-use conditions to describe and to determine the correct proportionality. The basic method for solving the system of equations is described in another paper from J. Bernstein [62], and using the suggestion of a Sum-of-failure-rate method as described in JEDEC Standard JEP122G. It is clear that the manufacturers of electronic components recognize the importance of combining failure mechanisms in a sum-of-failure-rates method. 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 under the applied condition. Every potential failure mechanism should be identified and its unique AF should then be calculated for each mechanism at given temperature and voltage so the FIT rate can be approximated for each mechanism separately. Then, the final FIT is the sum of the failure rates per mechanism, as described by:

$$FIT_{total} = FIT_1 + FIT_2 + \cdots + FIT_i \tag{25}$$

where each mechanism leads to an expected failure unit per mechanism, *FITi*.

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, the 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

Whereas each intrinsic mechanism is known to have different statistical distributions, the combination of distributions becomes, at the ensemble level, approximately constant rate as demonstrated by R.F. Drenick [63]. In its theorem, Drenick suggests and justifies the summation of failure rate approach also as explained in the JEDEC handbook.

The mechanism matrix is described in Table 2. Each row of the matrix describes various operating conditions under which the system is tested. Each experiment, *i*, is operated with its unique voltage, frequency and temperature. The ''results'' column, *FITi* is the average time when the failure occurs under the experimental condition, which is associated with a pre-determined failure point. The example studied uses 10% performance degradation as the failure point, however any reasonable value will work as long as it is consistent with the application. The result FIT_i is a failure rate (λ) and measured as $10^9/MTTF$.

Table 2 M-TOL matrix used to solve models with measured times to fail [12]

	HCI	BTI	EM	Results
V_1, f_1, T_1	$X{\cdot}A_1$	$Y{\cdot}B_1$	$Z{\cdot}C_1$	FIT_1
V_2, f_2, T_2	$X{\cdot}A_2$	$Y{\cdot}B_2$	$Z{\cdot}C_2$	FIT_2
V_3, f_3, T_3	$X{\cdot}A_3$	$Y{\cdot}B_3$	$Z{\cdot}C_3$	FIT_3

We assume that each mechanism (A–C) affects the system linearly with its own acceleration factor (*AF*) for a given frequency. The Acceleration factor formulas are in Table 3. Each equation is calculated with the experimental condition of each result on the right hand side.

Table 3 The equations for the acceleration factors matrix [12]

Hot carrier injection	$A_i \equiv AF_{HCI} = \frac{f}{f_0} \cdot \left(\frac{V}{V_0}\right)^N \cdot e^{-\frac{Ea_{HCI}}{k}\left(\frac{1}{T_0}-\frac{1}{T_{ac}}\right)}$
Negative bias temperature instability	$B_i \equiv AF_{NBTI} = e^{\gamma_{BTI}\cdot(V_G - V_{G,0})} \cdot e^{-\frac{Ea_{BTI}}{k}\left(\frac{1}{T_0}-\frac{1}{T_{ac}}\right)}$
Electromigration	$C_i \equiv AF_{EM} = \frac{f}{f_0} \cdot \left(\frac{V}{V_0}\right)^M \cdot e^{-\frac{Ea_{EM}}{k}\left(\frac{1}{T_0}-\frac{1}{T_{ac}}\right)}$

Then the matrix is solved to find a set of constants, P_i, shown here as *X–Z*, across the whole matrix that matches the experimental results with calculated acceleration factors. This linear matrix is solved by multiplying the inverse matrix, AF^{-1}, with lambda at each condition, as shown in Table 4. The solution give the coefficients (X–Z), which make up the relative contribution of each failure mechanism on the system.

Table 4 Matrix solution [12].

$$\overbrace{\begin{bmatrix} \boldsymbol{A_1} & \boldsymbol{B_1} & \boldsymbol{C_1} \\ \boldsymbol{A_2} & \boldsymbol{B_2} & \boldsymbol{C_2} \\ \boldsymbol{A_3} & \boldsymbol{B_3} & \boldsymbol{C_3} \end{bmatrix}}^{AF} \cdot \overbrace{\begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{Y} \\ \boldsymbol{Z} \end{bmatrix}}^{P_i} = \overbrace{\begin{bmatrix} \boldsymbol{\lambda_1} \\ \boldsymbol{\lambda_2} \\ \boldsymbol{\lambda_3} \end{bmatrix}}^{\lambda}$$

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

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. This matrix has been used then to construct the full reliability profile whereby FIT is calculated versus Temperature for several conditions for FPGA 45 nm process, as shown in Figure 6.

The 45 nm technology shows frequency related effects at both low temperatures (below 5°C) due to HCI and at high temperatures. It is observed the high voltage bias (@ 1.2 V) enhance the effect of frequency which reduce the overall HCI contribution at low frequency. The dominant failure mechanism at medium ambient temperature (range from 10°C to 150°C) is related to NBTI while EM failure mechanism is rather observed at high temperature.

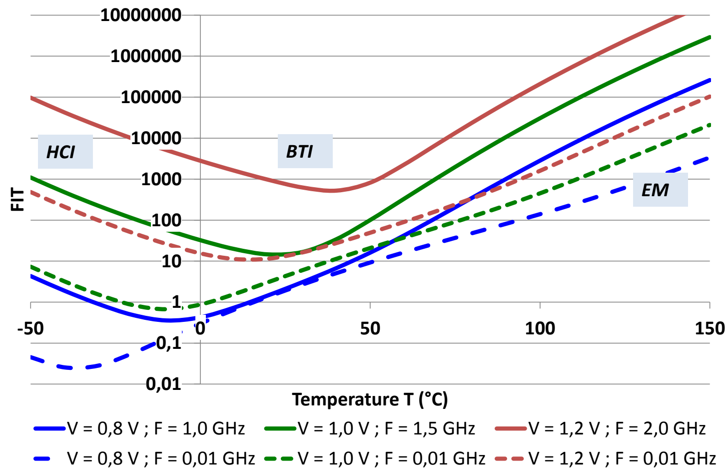

Fig. 6 Reliability curves for 45nm technology showing FIT versus Temperature for Voltages above and below nominal (1.2V) and frequencies from 10 MHz (dashed line) to 2GHz (solid line).

How to disentangle reliability models for More than Moore microelectronics based on nanotechnologies?

An innovative and practical way is to use the various physics of failure equations together with accelerated testing for reliability prediction of devices exhibiting multiple failure mechanisms. We presented an integrated accelerating and measuring platform to be implemented inside FPGA chips, making the M-TOL testing methodology more accurate, allowing these tests at the chip and at the system level, rather than only at the transistor level. The calibration of physics models with highly accelerated testing of complete commercial devices allows to perform physical reliability prediction. The M-TOL Matrix can provide information about the proportional effect of each failure mechanism in competition and offering an easy and simply tool to extrapolate the expected reliability of the device under various conditions.

This practical platform can be implemented on almost any FPGA device and technology to enable making FIT calculations and reliability predictions. The results of this approach provide the basis for improvements in performance and reliability given any design or application. This method can be extended to other processes and new technologies, and can include more failure mechanisms, thus producing a more complete view of the system's reliability.

The BAZ model together with the M-TOL methodology has been combined in a general multi-dimensional tool named M-STORM (*M*ulti-phy*S*ics mul*T*i-stress*O*rs predictive *R*eliability *M*odel) [13] which can be implemented in a concrete situation existing for the Deep-Submicron process devices but also for any other microelectronic disruptive technology.

5. Conclusion

To this day, the users of our most sophisticated electronic systems that include opto-electronic, photonic, MEMS device, GaN power devices, ASIC and Deep-Sub-Micron technologies etc. are expected to rely on a simple reliability value (FIT) published by the supplier. The FIT is determined today in the product qualification process by use of 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 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 HALT testing and on handbooks such as FIDES, TELCORDIA or MIL-HDBK-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 communication 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.

We presented, in this paper, a simple way to predictive reliability assessment using the common language of Failure In Time or Failure unIT (FIT). We evaluated the goal of finding MTBF and evaluate the wisdom of various approaches to reliability prediction. Our goal is to predict reliability based on the system environment including space, military and commercial. It is our intent to show that the era of confidence in reliability prediction has arrived and that we can make reasonable reliability predictions from qualification testing at the system level. Our research will demonstrate the utilization of physics of failure models in conjunction with qualification testing using our Multiple – Temperature Operating Life (M-TOL) matrix solution to make cost-effective reliability predictions that are meaningful and based on the system operating conditions. The BAZ model together with the M-TOL methodology has been combined in a general multi-dimensional tool named M-STORM (*M*ulti-phy*S*ics mul*T*i-stress*O*rs predictive *R*eliability *M*odel) applicable to microelectronic disruptive technologies.

Acknowledgement: *The paper is a part of the research done at IRT Saint Exupery, Toulouse, France. The study was conducted in the frame of Electronic Robustness contract Project IRT-008 sponsored by the following funding partners: Agence Nationale de la Recherche, Airbus Operations SAS, Airbus Group Innovation, Continental Automotive France, Thales Alenia Space France, Thales Avionics, Laboratoire d'Analyse et d'Architecture des Systèmes — Centre National de la Recherche Scientifique (LAAS-CNRS), Safran Labinal Power Systems, Bordeaux University, Institut National Polytechnique Bordeaux (IMS — UMR 5218), and Hirex engineering.*
I would like to particularly thank Professor Joseph B. Bernstein, from Ariel University, Ariel (Israël) for the major comments and deep discussions we had during the manuscript preparation.

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