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Three-step concept (TSC) in modeling microelectronics reliability (MR): Boltzmann–Arrhenius–Zhurkov (BAZ) probabilistic physics-of-failure equation sandwiched between two statistical models

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ABSTRACT

When encountering a particular reliability problem at the design, fabrication, testing, or an operation stage of a product's life, and considering the use of predictive modeling to assess the seriousness and the likely consequences of the a detected failure, one has to choose whether a statistical, or a physics-of-failure-based, or a suitable combination of these two major modeling tools should be employed to address the problem of interest and to decide on how to proceed. A three-step concept (TSC) is suggested as a possible way to go in such a situation. The classical statistical Bayes' formula can be used at the first step in this concept as a technical diagnostics tool. Its objective is to identify, on the probabilistic basis, the faulty (malfunctioning) device(s) from the obtained signals ("symptoms of faults"). The recently suggested physics-of-failure-based Boltzmann–Arrhenius–Zhurkov's (BAZ) model and particularly the multi-parametric BAZ model can be employed at the second step to assess the remaining useful life (RUL) of the faulty device(s). If the RUL is still long enough, no action might be needed; if it is not, corrective restoration action becomes necessary. In any event, after the first two steps are carried out, the device is put back into operation (testing), provided that the assessed probability of its continuing failure-free operation is found to be satisfactory. If the operational failure nonetheless occurs, the third, technical diagnostics step should be undertaken to update reliability. Statistical beta-distribution, in which the probability of failure is treated as a random variable, is suggested to be used at this step. While various statistical methods and approaches, including Bayes' formula and beta-distribution, are well known and widely used in numerous applications for many decades, the BAZ model was introduced in the microelectronics reliability (MR) area only several years ago. Its attributes are addressed and discussed therefore in some detail. The suggested concept is illustrated by a numerical example geared to the use of the prognostics-and-health-monitoring (PHM) effort in actual operation, such as, e.g., en-route flight mission.

1. Introduction

The art and science of reliability engineering employs both statistical and probabilistic modeling approaches. Although these approaches are closely related, they pursue different objectives and usually have different times of application in the lifetime of a product. While statistical approaches are a-posteriori ones, probabilistic predictive modeling (PPM) is an a-priori approach, and, as such, is naturally applied first at the design stage of the product's life. Reliability is conceived, whether one admits that or not, at the design stage of a product and should be taken care of, first of all, at this stage. If, owing to the design for reliability (DfR) [1–6] and, particularly, the probabilistic design for reliability (PDfR) [7–9] efforts, one manages to create a "genetically healthy" product, then the powerful technical diagnostics "checkups" [10,11] and subsequent "therapeutic" PHM treatments [12–31] at later stages of the product's life will be dramatically facilitated and will have much better chances to succeed. If such a combined health management activity takes place and is successful, then there is a reason to believe that, by analogy with human's health, a durable and failure-free service life of a product could be achieved, managed and assured.

In the analysis that follows a TSC is suggested as a possible PDfR type PPM methodology. This methodology could be considered,

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Acronyms

BAZ	Boltzmann–Arrhenius–Zhurkov (model)	PM	predictive modeling
DfR	design for reliability	PPM	probabilistic predictive modeling
FOAT	failure oriented accelerated testing	PRA	probabilistic risk analysis
HALT	highly accelerated life testing	PHM	prognostics and health management
QT	qualification testing	RUL	remaining useful lifetime
MTTF	mean time to failure	SoF	symptoms of faults
MR	microelectronics reliability	TSC	three-step concept
PDfR	probabilistic design for reliability		

whenever appropriate and possible, but not necessarily implemented, when there is a need to obtain, on the continuous basis and at different stages of the product's life, the most trustworthy and comprehensive information, affecting the product's reliability. The well known statistical Bayes formula [32–39] is used at the TSC first step as a technical diagnostics tool, with an objective to identify the faulty (malfunctioning) device(s) from the obtained signals ("symptoms of faults"). The recently suggested physics-of-failure-based BAZ and particularly multi-parametric BAZ models [40–44] can be employed at the TSC second step. The objective of this step is to assess the remaining useful life (RUL) of the malfunctioning device(s). Statistical beta-distribution [45–47] is suggested to be employed as the possible third step. This step should be undertaken when there is a need to update reliability, if failure occurs despite the expected low probability of failure.

Although each of the three major constitutive and subsequent TSC steps – Bayes' formula-based technical diagnostics effort, BAZ-based RUL assessment and beta-distribution-based reliability update – can be and, in effect, have been employed separately in various particular MR related tasks, in the TSC methodology addressed in this paper these parts are consistently combined in such a way that the output of (information from) the previous step is viewed and used as an input for the subsequent step. The suggested TSC is a rather general approach, i.e., is not specific to a particular failure mechanism or loading condition(s). The approach could be applied at an assembly, device (component), sub-system or system level and helps the decision maker to establish the most feasible next step to go at different stages of the product's life.

Various statistical methods and approaches, and particularly Bayes' formula and beta-distribution, are well known and widely used in numerous applications for many years. The BAZ and the multi-parametric BAZ models have been introduced, however, in the MR field as an effective physics-of-failure-based PDfR tool only several years ago. Their attributes are addressed in this analysis therefore in greater detail than those of the Bayes' formula and beta-distribution models. It is noteworthy that while some PDfR models where applied in the past to particular electronics and photonics systems [48–51], it has been only recently suggested [7,8,52] that the PDfR approach be used in MR engineering, as an effective reliability assurance tool, on a wide scale.

Highly focused and highly cost-effective failure-oriented accelerated testing (FOAT) [53], followed by physically meaningful and simple predictive modeling (PM) and extensive sensitivity analyses (SA), are the three major constituents of the PDfR concept. FOAT could be viewed as an extension of the currently widely used and effective highly-accelerated-life-testing (HALT) [52]. As to the PM, BAZ and multi-parametric BAZ models [41,42], they are the most flexible, comprehensive and well substantiated ones in the PDfR effort: many models of the FOAT type (Eyring's equation for the mechanical stress, Peck's equation for relative humidity, Black's equation for current density, etc.) contain Arrhenius equation, a special type of the BAZ model, as their core part. If appropriate and desirable, the BAZ and multi-parametric BAZ models can include many other advanced probabilistic methods, such as, e.g., extreme value distribution, Weibull distribution, and normal or log-normal distributions [11,42].

The addressed TSC could be viewed, with some significant stretching though, as a sort of information integration (fusion) approach. As is known, fusion approach is a technique for merging (fusing, melting) information obtained from heterogeneous sources with different conceptual representations [54–56]. The TSC, however, although contains information from two heterogeneous sources, namely statistical and physics-of-failure based, is not aimed at merging information, but is a sequential three-step methodology, in which each step has a different objective and different time of application.

2. Three step concept (TSC) in modeling microelectronics reliability (MR)

2.1. Three step concept (TSC)

Technical diagnostics should be carried out as the ***first step*** of the TSC, with an objective to identify the faulty (malfunctioning) object(s) from the detected signals, "symptoms of faults (SoF)". This can be done, particularly, using the Bayes' formula. This powerful statistical means is widely used for many years in numerous applications to update beliefs in many areas of engineering and applied science. The attributes and use of Bayes' formula in technical diagnostics of microelectronic devices are addressed, in connection with its role in the TSC, in Appendix A.

At the ***second step*** the physically meaningful BAZ model is suggested to be employed to assess the remaining useful life (RUL) of the malfunctioning device. This model proceeds from the rationale that although the process of damage accumulation is highly temperature dependent, this process is affected primarily by various external loadings (stressors, stimuli) of the relevant nature, such as, e.g., mechanical or thermal stress, voltage, current, light input, and ionizing radiation. The BAZ model is based on the recognition of the experimentally observed situation that the breakage of the chemical bonds in a material under stress is due primarily to an external loading. Temperature still plays an important, but not the decisive, role though, mostly as the degradation (aging) factor.

The ***third step*** of the TSC is aimed at updating reliability from the observed (but not anticipated) failures. It is another statistical means. Four parametric beta-distribution is suggested to be used to update reliability of the faulty object when/if it fails at the end of the anticipated or actual RUL [30,31]. Some attributes of the beta-distribution are described in Appendix B.

The above three steps are addressed below in some detail.

2.2. Step 1: Bayes formula as a suitable technical diagnostics tool

The technical diagnostics effort is the TSC's first step. The objective of technical diagnostics is to recognize, in a continuous fashion