Fifty Years of Physics of Failure

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This year marks the fiftieth anniversary since Physics of Failure (PoF) was first formally conceptualized in the first of a series of symposia in 1962 organized by the Rome Air Development Center (RADC)[1] of the US Air Force. The major driving force that established this approach to reliability had its roots in the 1940s and 1950s due to concerns in US military establishments about the reliability of electronic systems. According to *Mclinn* (2011), "By the 1940s reliability and reliability engineering still did not exist." At the start of the World War II, it was discovered that over 50% of the airborne electronics equipment in storage was unable to meet the requirements of the Air Core and Navy (*Mclinn, 2011*). Much of the reliability work during that period had to do with fatigue and fracture of metals. For example, in 1945 a paper titled "Cumulative Damage in Fatigue" was published in the Journal of Applied Mechanics (*Miner, 1945*) in which expended life of metals were empirically modeled. In 1948, another paper titled "Statistical Aspects of Fracture Problems" was published in the Journal of Applied Physics (*Epstein, 1948*) in which the statistical foundation for the assessment of the life of materials was discussed. Then in 1950, the US military initiated an Ad Hoc group on reliability

[1] Now known as the Rome Laboratory.

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of electronic equipment, which stated that for improving part reliability it is essential to develop better parts, establish quantitative reliability requirements for parts, and collect field failure data to determine the root cause of problems (*Ebel, 1998*). Several conferences began in the 1950s to focus on various reliability topics. One conference that warrants special mention is the Holm Conference on Electrical Contacts, which was started in 1955 emphasizing reliability physics. This conference established itself over the years as the primary source of reliability physics information on connectors.

Between 1955 and 1963, Waloddi Weibull produced several publications related to fatigue and creep mechanisms and derived the Weibull distribution on the basis of the weakest link model of failures in materials. For example, in 1959 Weibull produced a report for the US Military titled "Statistical Evaluation of Data from Fatigue and Creep Rupture Tests: Fundamental Concepts and General Methods" (*Weibull, 1959*) in which methods for evaluating fatigue failure data were discussed. In 1961, Weibull published a book on materials and fatigue testing while working as a consultant for the US Air Force Materials Laboratory (*Weibull, 1961*).

Having exposed to the mechanistic-based life models developed to assess fatigue and fracture caused failures, in 1961 RADC introduced a PoF program to address the growing complexity of military equipment and consequently higher number of failures observed using the underlying failure mechanisms. In 1962, researchers from Bell Labs published a paper on "High Stress Aging to Failure of Semiconductor Devices" that justified using of the Kinetic Theory as a basis for assessment of temperature-induced aging of semiconductor devices, and proposed the Arrhenius model to estimate life (*Dodson & Howard, 1961*). Based on these developments, the RADC and Armour Research Foundation of Illinois Institute of Technology (now IIT Research

Institute) organized the first PoF symposium in electronics in 1962. This symposium led the groundwork for future research and development activities related to PoF by RADC and several other organizations. Numerous original papers and ideas introducing and explaining the PoF concepts and methods were presented in these symposia.

In one of the original PoF paper presented in the first PoF symposium, *Vaccaro* (1962) opined that PoF should seek to relate the fundamental physical and chemical behavior of materials (i.e., failure mechanisms) to reliability parameters. This approach is based on the principle that to eliminate the occurrence of failures, it is essential to eliminate their root causes, and to do that one must understand the physics of the underlying failure mechanisms involved. *Davis* (1962) described the need for identifying probable failure mechanisms by which components fail as a function of time, environmental and operating stresses, as well as developing mathematical models to represent these mechanisms in order to meet reliability requirements of components. Various companies and universities conducting research on failure mechanisms were active participants. These included Raytheon, Syracuse University, and Motorola. Although PoF was key to improving design and reliability of components, higher costs in terms of facilities and manpower was identified as the critical impediment for using PoF at that time (*Ryerson, 1962*). The various key elements of PoF approach such as, identification of failure mode, mechanism, and cause were defined for the first time in this symposium (*Zierdt, 1962; Earles & Eddins, 1962*). *Levinson and Pohl* (1962) stated that change in performance of a component or material with time occurs as a result of natural processes that can be described by well-known laws. A thorough analysis of these laws as applied to a device, and its operating environment, can yield a mathematical relation for the failure rate as a function of the stresses to which that the device would be subjected.

Due to the success of the first symposium in 1962, four PoF symposia were held in subsequent years (until 1966) with many more papers describing concepts related to PoF. For example, *Tamburrino* (1963) provided key points about the requirements of a reliability physics program, e.g., materials, measurement techniques, and failure mechanisms. The need for part vendors to be kept abreast of available knowledge and understanding in failure physics was identified. It was stated that any changes in pre-established part processing or fabrication can potentially be a key factor in inducing new failure mechanisms, and should be closely coordinated with reliability engineers. *Bretts, Kozol and Lampert* (1963) provided accelerated tests results for resistors, which they correlated with physical degradation models to estimate time to failure. PoF was identified as an essential step in planning accelerated tests as well as evaluating them.

In third PoF symposium, *Ingram* (1964) described performance characteristics and failure mechanisms of a device in probabilistic terms. He suggested, "Environmental and stress conditions applicable to the device, and its performance and strength characteristics, are expressed in the form of multidimensional probability distributions. By joint evaluation of these probability distributions, a quantitative estimate of the reliability of the device can be obtained." *Beau* (1964) described methods for managing and assessing the role of the human elements in PoF. He described three classical causes of failure as: reliability limitation inherent in the design; reliability degradation caused by the factory process; and reliability degradation caused by the user. According to him, the factory operator, in form of poor workmanship or operator error, introduced the human element in reliability of devices. *Workman* (1964) described the failure analysis practices followed in Texas Instruments at that time, and the need for incorporating information gained from failure analysis in new reliability test design, process control, and new device design.

Shiomi (1965) introduced a generalized cumulative degradation model for estimation and prediction of component life under successive different stress levels. *Partridge, Hall, and Hanley* (1965) described the need for qualification and engineering evaluations to select vendors who are capable of supplying reliable semiconductor parts. They further stated that qualification tests alone are insufficient to determine the ability of vendors, but production procurement data from screen and burn-in can provide sufficient vendor history. *Church and Roberts* (1965) presented different causes of failure of a component, such as due to accidental damage during manufacture, assembly, testing, storage, or failure in service due to operating conditions or failure of another component.

Thomas (1966) used basic concepts of dimensional analysis to make general examination of mathematical models, e.g., Eyring's equation. He opined that the concepts of signal, noise and dimensionless variable could be used to formulate mathematical models, physical laws, and probability distributions. *Schenck* (1966) presented two forms of progressive failure mechanisms of a commercial silicon diode, and studied them as a function of various stress and measurement variables. Several papers were also presented that proposed nondestructive inspection and screening procedures based on PoF which later formed the basis for prognosis and health management concepts. For example, *Gill and Workman* (1966) presented a reliability screening procedure (consisting of destructive tests and nondestructive inspections) based on identifying failure mechanisms resulting from high-stress tests and failure analysis. *Potter and Sawyer* (1966) presented an optical scanning-based nondestructive technique to study various semiconductor device phenomena and identify causes of anomalous device behavior in order to improve device reliability.

From 1967 onwards, IEEE sponsored the “Reliability Physics Symposium (IRPS)” that continues even today presenting wide ranges of PoF related research. For example, *Ryerson* (1967) presented mathematical models for semiconductor diodes illustrating how failure mechanisms, part strengths, and application stresses interact and affect the failure rate of component parts. *Keen, Loewenstern, and Schnable* (1967) presented mechanisms of failure in ohmic and expanded contacts, including metal-semiconductor contacts and bonds to metallization in semiconductor devices. *Payne* (1967) presented a failure mechanism for barium titanate capacitors studying the PoF. *Frankel and Kinsolving* (1970) discussed the need of reliability testing of components for hostile environments, by first simulating field conditions and then developing accelerating laboratory conditions. *Hollingshead* (1970) introduced a technique for optimizing the selection of parts for system application by reliability and quality levels through systematizing the compilation and processing of necessary data. The comparative influence of performance parameters such as repair cost, storage time, and cost of failure were discussed. *Schwuttke* (1970) showed that peripheral yield loss in silicon wafers can be minimized whenever temperature gradients arising during cooling of a row of wafers are eliminated.

The IEEE IRPS continued to be organized through the 1970s and 1980s disseminating a plethora of knowledge on PoF. Several failure mechanisms and mathematical models were reported for a wide range of electronic components such as capacitors, semiconductors, resistors, and interconnects. In 1975, J.R. Black (1975) published his famous model for predicting electromigration time to failure, which continuous to be valid even at the present time.

Metallization, metallurgical effects and bonding dominated the key presentations and papers published by IRPS. Some examples of key papers published included the *Agarwala* publication of experimental results for electromigration failures in thin-film conductors, the *Brodeur* (1975) description of high temperature operating life testing as a measure of processes used in fabrication of semiconductor wafers. *Macpherson, Day, Weisenberger and Christou* (1975) introduced the concept of fast temperature cycling as a key agent of failure in transistor metallization. It is worthwhile to note that PoF of non-silicon devices was first introduced in 1975 through six papers in the area of microwave and electro-optic devices. In addition, for the first time in 1975, the applications of accelerated testing were introduced as a method for obtaining PoF data on devices and components.

By 1983, CMOS PoF issues began to dominate the entire microelectronics industry and hence IRPS concentrated to a very large extent on sessions based on semiconductor instabilities, CMOS latch up analysis and MOS failure mechanisms. As current densities increased and device linewidths decreased electromigration became the key issue in the PoF of device structures. J.R. Lloyd (1983) presented the initial analysis of electromigration effects in multilevel geometries. The Time Dependent Breakdown phenomena was first reported in 1985 at IRPS, through the first developed physical model of TDDB by Chen, Holland and Hu (1985)

GaAs Device Reliability became an important part of the conference by 1983, and the paper by Dumas etal (1983) on long term degradation of GaAs Power Mesfets continues to be an important source of data to the present. Also reported was the first concern with single event effects in GaAs MESFETS, by Anderson et al (1983). It is worthy to note that in 1985, the first HEMT Reliability investigation results was reported by Christou et al (1985) at IRPS. High

Electron Transistors were the new devices which have since introduced a wide spectrum of new products such as GPS and mobile communications. The authors reported on the first observation of a diffusion controlled failure mechanism and also a susceptibility to alpha particle degradation.

Crook (1979) presented a model for time dependent dielectric breakdown of semiconductors as a function of operational and environmental conditions, as well as the device physical parameters. *Hieber and Pape* (1984) presented a creep-rupture equation that calculates time to rupture as a function of applied mechanical load and temperature. *Conrad, Mielnik, Musolino* (1988) presented a methodology to monitor and predict early life reliability failure mechanisms. The PoF investigations expanded rapidly and addressed new mechanisms such as the PoF of moisture related mechanisms, packaging and assembly as well as compound semiconductor devices. In 1979, *Vasofsky* published his seminal paper on water vapor sorption, followed by *Anderson, Christou and Sleger* (1979) on ionic-contamination-humidity effects. These were the first publications on the mechanism now known as MGRS (Migrative Resistive Shorts).

The 1990s also resulted in a major change in the assessment of the Pof F of microelectronics due to reduced failure rate requirements as well as the increased use of simulation to estimate reliability. The industry now sees the market pressures as drivers toward improvements in reliability. Reliability trends now parallel technology trends, and concepts of design-in reliability and total quality improvement prevail as reported by Chatterjee, Hunter, Amerasekera et al (1995). The end of the 1990s saw a new reliability challenge being addressed by the P of F community: The mechanisms related to new materials in a new millennium of Moore's law. The first investigations on MEMs reliability appeared, and the first experiments on failure mechanisms of RF MEMs were reported at IRPS by Douglass (1998). This marked a departure for IRPS which previously emphasized P of F of devices and components from established manufacturing lines. The new approach for the reliability engineer is to work upstream, and identify failure mechanisms as early in the development cycle as possible.

By the late 1980s and early 1990s, several publications on PoF related research outside of the IEEE *Reliability Physics Symposium* also appeared. For example, *Pecht, Dasgupta, Barker, and Leonard* (1990) advocated use of PoF approach for reliability assessment as opposed to the part count technique. *Dasgupta and Pecht* (1991) presented material failure mechanism and damage models. *Engel* (1993) presented failure models for mechanical wear modes and mechanisms. *Modarres* (1993) distinguished between deterministic and probabilistic treatment of failures, and discussed probabilistic methods for quantifying and propagating uncertainties in physical models and engineering systems. *Cushing, Mortin, Stadterman and Malhotra* (1993) of US Army Materiel Systems Analysis Activity (AMSAA) Physics-of-Failure office, Aberdeen Proving Ground, Maryland compared empirically-based reliability prediction approaches (e.g., MIL-HDBK-217) with the PoF approach. They identified several limitations of using the MIL-HDBK-217, which could be addressed by using the PoF approach.

The 1990s also saw the publication of key radiation damage effects in microelectronics. The industry was now recognizing that cosmic ray effects inducing failure is a key issue in current and future generation of DRAMs. Cosmic rays as a significant source of soft errors in DRAMs and other devices was published as early as 1979. The work presented at IRPS showed clearly, for the first time that high energy neutrons produced by cosmic rays can be a major contributor to system soft error rate effects. In an elegant set of experiments, McKee et al (1996) was able to measure the dependencies on cosmic ray neutron flux. During the 1990s, significant advances in characterization techniques were also important, as we see the convergence of characterization physics with complex mechanism analysis.

The 21st century has seen a new emphasis on technologies beyond CMOS. The demand for faster and lower power continues to grow and has put new pressure of refining the P of F approach. Development of SOI, and SOI related structures, as well as SiGe based bipolar transistors and passive RF elements has generated a new set of reliability problems which can only be solved through the P of F approach. The technological challenges have become formidable, but the new opportunity enabled by these technologies is now the new incentive driving reliability. The 21st century has thus seen the rapid development of statistical models to describle multiple failure such as the work of Fischer et al (2000) in the report on statistical models for bimodal electromigration failures. Other models have been reported by the researchers at the University of Maryland CALCE Center for Electronic Packaging. We now see the reporting of novel transistor findings such as those related to NBTI-induced interface states and hot carrier effects in novel gate dielectrics. The threshold voltage shift in p-FETs caused by negative bias temperature instability has emerged as one of the most serious reliability limitations of modern ULSI technology. This failure mechanism has become significant for newer technologies which operate at lower supply voltages (Stathis, LaRosa and Chou, 2004). Just as important however are the instabilities present with the new GaN HFET technologies due to interface traps as reported by Christou et al (2009).

Although several publications related to the PoF continued to be published through the 1990s and 2000s, a trend towards probabilistic consideration of PoF was also observed from the late

1990s. *Modarres, Kaminskiy, and Krivtsov* (1999) stated that prediction of failures is inherently a probabilistic problem due to uncertainties associated with failure-inducing agents that can result due to changes in environmental, operating, and use conditions; as well as uncertainties in PoF models and their parameters. The earliest effort in probabilistic consideration of PoF was by *Haggag, McMahon, Hess, Cheng, Lee and Lyding* (2000), who presented a probabilistic physics-of-failure (PPoF) approach to reliability assurance of high-performance chips by considering common defect activation energy distribution. *Hall and Strutt* (2003) presented PPoF models for component reliabilities by considering parameter and model uncertainties. *Azarkhail and Modarres* (2007) presented a Bayesian framework for uncertainty management in physics-based reliability models. *Matik and Sruk* (2008) highlighted the need for PoF to be probabilistic in order to consider variations of variables involved in processes contributing to the occurrence of failures. *Chamerlain, Chookah, and Modarres* (2009) presented a PPoF model for reliability assessment of gas cylinders, incorporating uncertainties associated with manufacturing process, material properties, and inspection methodology. *Chatterjee and Modarres* (2011) presented a PPoF approach for estimating steam generator tube rupture frequency considering the PoF and various uncertainties associated with environmental conditions, geometrical and material properties, PoF models, and model parameters.

Although the discussion on PoF has been presented chronologically in this article, an important milestone has been the publication of the PoF handbook for microelectronic systems in 2008 (*Salemi and Bernstein, 2008*). The handbook was the first of its kind that presented an approach for microelectronic system reliability assessment and qualification based on PoF. Another important activity currently underway is the development of a Web Accessible Repository of Physics-Based Models (WARP) under the aegis of the Reliability Information

Analysis Center (RIAC)[2]. The objective of the WARP[3] is to collect and analyze the characteristics of the PoF models for electronic, electromechanical and mechanical components in order to provide a centralized web-based repository accessible to researchers and engineers.

As we celebrate the fifty years of the PoF, RADC deserves a special gratitude including its chief and founder Joseph J. Naresky under whose leadership the PoF was first formally conceptualized and the symposium on "Physics of Failure in Electronics" organized in 1962 with considerable efforts by RADC's Joseph Vaccaro. It is remarkable to see that many of the original ideas introduced in these symposia made the most significant impact on the understanding of failures in electronics and offered enduring models to estimate life characteristics. As was observed for the first time in the 1962 symposium, the PoF approach encompasses multiple disciplines such as reliability engineering, physics, metallurgy, and mathematical statistics and probability. The symposia of the 1960s provided PoF approaches for non-destructive test methods and for improving and predicting component reliability with limited resort to mass test data. While PoF analysis is complex, costly to apply, and limited for assessing the entire system; it provides the strongest characterization of reliability of components, structures and systems. The fact, that PoF as an approach for reliable product development has gained wide acceptance today in the commercial sector (e.g., Microsoft) as well as in several countries (e.g., Japan, Singapore, and Taiwan), is a tribute to its strong foundation established fifty years ago.

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Physics of failure and design for reliability can improve product performance throughout the development cycle.Â This DfR methodology served as the basis for the physics of failure (PoF) approach that is common in many industries today. What is Physics of Failure? PoF is a scientific discipline that determines the root causes of failure for electrical, electronic or electromechanical (EEE) items. These items can include: Piece parts.Â However, upcoming autonomous taxis are expected to operate 22 to 24 hours a day over 4 to 6 years. That means that the semiconductors and electronic modules powering these autonomous vehicles will be expected to operate 32,000 to 53,000 hours under conditions that exceed current industry expectations and validations requirements. The year 2012 marked the fiftieth anniversary of the physics of failure concept since it was first introduced in 1962 by the Rome Air Development Center (now known as the Air Force Research Laboratory). A chronological description of the important historical events that led to the birth and subsequent advancement of physics of failure concept over the last fifty years has been presented in this paper. Alongside, a review of physics of failure concepts and methodologies as they evolved in the last fifty years has also been provided. Discover the world's research. 17+ million members. (2) Vol. 175, 1996. Fifty Years of Mathematical Physics Downloaded from www.worldscientific.com by HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY on 03/25/18. For personal use only. The Differential Calculus on Quantum Linear Groups. L. D. Faddeev and P. N. Pyatov. ABSTRACT. The non-commutative differential calculus on the quantum groups SLq(N) is constructed. The quantum external algebra proposed contains the same number of generators as in the classical case. The exterior derivative defined in a constructive way obeys a modified version of the Leibniz rules. The explanation of classical physics: Light is an electromagnetic wave that is produced when an electric charge vibrates. (Strictly speaking, "vibrates" means any change in how the charge moves --- speeding up, slowing down, or changing direction.) Now recall that heat is just the kinetic energy of random motion.Â In fact, there is no limit to how great the frequency can be. Classical physics said that each frequency of vibration should have the same energy. Since there is no limit to how great the frequency can be, there is no limit to the energy of the vibrating electrons at high frequencies. This means that, according to classical physics, there should be no limit to the energy of the light produced by the electrons vibrating at high frequencies. WRONG!!