Outlook: From Physics of Failure to Physics of Degradation

Driel, W. D. van; Mehr, Maryam Yazdan; Fan, X. J.; Zhang, GuoQi

DOI
10.1007/978-3-030-81576-9_17

Publication date
2022

Document Version
Final published version

Published in
Reliability of Organic Compounds in Microelectronics and Optoelectronics

Citation (APA)
Driel, W. D. V., Mehr, M. Y., Fan, X. J., & Zhang, G. (2022). Outlook: From Physics of Failure to Physics of Degradation. In W. D. van Driel, & M. Y. Mehr (Eds.), *Reliability of Organic Compounds in Microelectronics and Optoelectronics: From Physics-of-Failure to Physics-of-Degradation* (pp. 535-538). Springer. https://doi.org/10.1007/978-3-030-81576-9_17

Chapter 17
Outlook: From Physics of Failure to Physics of Degradation

W. D. van Driel, M. Yazdan Mehr, X. J. Fan, and G. Q. Zhang

The history of reliability as we know it now goes back to the 1950s, when electronics started to play a major role for the first time. Now, seven decades later, with million times more complex electronic systems, the industry is facing a continuous increase of early and wear-out failures with accompanying consequences. Nowadays, products with high failure rates may come under public scrutiny due to negative customer feedback publicly shared on websites, eventually building bad reputation for a company [1, 2]. To cover the increasing demands in product reliability performance, three distinct waves can be noted [3]:

- Wave 1: Stress-based

The first wave was characterized with the establishment of a test-to-failure approach based on standardized stress-based tests. Examples are thermal cycling, moisture testing and operational tests under combined conditions. Each of these tests got standardized in the semiconductors industry by dedicated bodies, like, e.g. JEDEC, IEEE or IEC [4, 5], to enable smooth comparison between suppliers and test houses. Understanding of possible failure modes gradually increased in several industries using semiconductor devices, but the use of prediction models was still limited.

W. D. van Driel (✉)
Signfy, HTC7, Eindhoven, The Netherlands

Delft University of Technology, Delft, The Netherlands
e-mail: willem.van.driel@signify.com

M. Y. Mehr · G. Q. Zhang
Delft University of Technology, Delft, The Netherlands
e-mail: m.yazdanmehr@tudelft.nl

X. J. Fan
Department of Mechanical Engineering, Lamar University, Beaumont, TX, USA

W. D. van Driel, M. Yazdan Mehr (eds.), *Reliability of Organic Compounds in Microelectronics and Optoelectronics*,
https://doi.org/10.1007/978-3-030-81576-9_17

- Wave 2: Knowledge-based

The second wave continued from all the test results obtained over a period of 30–40 years in the first wave. Companies started to understand the physics that caused failure modes in their products. Test schemes changed to test-to-failure instead of test-to-pass. Still standardized tests are used under the condition of similarity: if a previous product that differed slightly from a new one, no new testing was required. This wave is characterized as knowledge-based qualification [6]. Models became commonly used in this wave both analytical and/or numerical (using finite element methods) ones.

- Wave 3: Application-based

In the third wave, application conditions are considered. All industries performed a substantial amount of application studies in which with dedicated sensor are used to measure the actual loading, in terms of temperatures, vibrations and/or external forces. Here measure, in some cases, means monitoring so that the data is logged continuously and send to an online database. Although standards are not yet available, some bodies did publish guidelines [7].

Per today, most industries are in the transfer coming from wave 2 towards wave 3. Wave 3 goes hand in hand with the current development of machine learning, digital twin driven diagnostics or prognostics and health monitoring [8]. These technologies are needed to move to *wave 4: degradation-based*. (Fig. 17.1)

Degradation is apparent in all things and is fundamental to both manufactured and natural objects. It is often described by the second law of thermodynamics, where entropy, a measure of disorder, tends to increase with time in a closed system. Simply said things age. The natural ageing and degradation of materials have been a subject of study by engineers and scientists for many, many years. But with the demands placed on new engineered materials and devices for electronics,

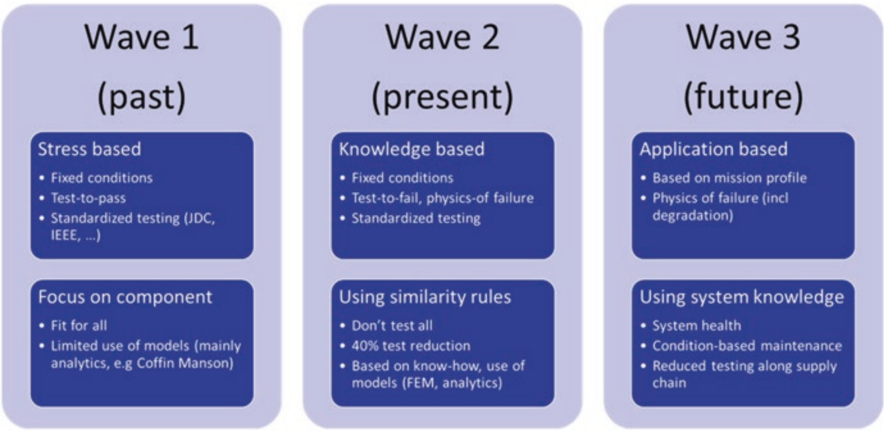

Fig. 17.1 Waves in reliability

computing, aerospace and biomedical applications, the reliability of such over time has become more and more crucial [9, 10].

Degradation is apparent in naturally occurring materials and structures as well as human-engineered materials and devices. In everyday experience, it is the ever-present phenomena of spontaneous loss of some quality, functionality and order. Work must be done from outside the system of interest to maintain that functionality or that order. The second law of thermodynamics formally captures this idea with the concept of entropy or disorder, which states [10]:

> *During real processes, the entropy of an isolated system always increases. In the state of equilibrium, the entropy attains its maximum value.*

This loss of order or degradation has many terms or phrases to label the phenomena, such as ageing, deterioration, devolution and wear-out. It is this degradation in electronics that this book has explored.

The mechanisms of degradation for a variety of materials and structures cover a wide range of discipline categories such as thermal, mechanical, chemical, biological and so on. All associated degradation mechanisms require the knowledge and understanding of natural processes and thus are grouped together as the physics of degradation. As mentioned above, the fundamental underlying principle is entropy and the second law of thermodynamics.

Regardless how carefully crafted, devices are made of materials that generally exist in metastable states. A state is referred to as being metastable if it is only apparently stable and susceptible to change/degradation. The driving force for materials degradation is a lower Gibbs Potential. When we apply a generalized stress ξ to a material, it tends to increase (not lower) the Gibbs Potential. Therefore, a stressed material is even more unstable and even more susceptible to degradation. Since electronic devices are fabricated from materials (and materials degrade with time), then these devices will degrade with time. Engineers are confronted with the very difficult situation—they must manage the degradation rate in order to prevent failure.

Here, health monitoring [8] and/or digital twin technologies [11, 12] may support the engineers to understand, master and forecast the physics of degradation. The concept of digital twin is relatively new. It was conceptualized during the early years of the twenty-first century and has gained traction mainly during the last decade. The primary reason behind it is the further digitalization of the electronic industry, which has been accelerated by the newly emerging IT technologies. Digital twin enables system optimization, monitoring, diagnostics and prognostics using integration of artificial intelligence, machine learning and big data analytics. It can be used for predicting failures and estimating lifetime of electronic components, which then allows for scheduling preventive maintenance. Launching a preventive maintenance program like this allows company to save time and costs and avoid customer dissatisfaction as well as unwanted lawsuits. This will be embraced in the fourth wave of reliability, physics of degradation, which will also reduce the amount (and cost) of product release testing.

Acknowledgements This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 876659. The JU receives support from the European Union's Horizon 2020 research and innovation programme and Germany, Austria, Slovakia, Sweden, Finland, Belgium, Italy, Spain, Netherlands, Slovenia, Greece, France and Turkey.

References

1. T. de Groot, T. Vos, R.J.M.J. Vogels, W.D. van Driel, Quality and reliability in solid state lighting, In: W.D. Van Driel, X.J. Fan (editors), Solid State Lighting Reliability: Components to System. 01/2013; ISBN 978-1-4614-3067-4 Springer New York
2. Warrantee Week, Warranty claims & accruals in financial statements, September 16, 2011., http://www.warrantyweek.com/
3. R. Rongen, On the relevance of physics of fail and mission profiles for microelectronics in automotive applications, presentation at the seminar Trends and challenges in Reliability: from components to systems, Eindhoven, May 2019
4. EIA/JEDEC Standard EIA/JESD47, Stress-Test-Driven Qualification of Integrated Circuits, Electronic Industries Association, July 1995
5. JEDEC Standard JESD34, Failure-Mechanism-Driven Reliability Qualification of Silicon Devices, Electronic Industries Association, March 1993
6. International SEMATECH Publication #00053958A-XFR, Knowledge-Based Reliability Qualification Testing of Silicon Devices, 2000
7. International SEMATECH Publication #99083810A-XFR, Use Condition Based Reliability Evaluation of New Semiconductor Technologies, 1999
8. M.S. Ibrahim, J. Fan, W.K.C. Yung, A. Prisacaru, W. van Driel, X. Fan, G. Zhang, Machine learning and digital twin driven diagnostics and prognostics of light-emitting diodes. Laser Photonics Rev, 2000254 (2020). https://doi.org/10.1002/lpor.202000254
9. J. Swingler, *The Physics of Degradation in Engineered Materials and Devices: Fundamentals and Principles* (Momentum Press, New York, 2014). https://doi.org/10.5643/9781606504680
10. J.W. McPherson, Physics of degradation, in *Reliability physics and engineering: Time-to-failure modeling*, (Springer International Publishing, ISBN: 978-3-319-93683-3, 2019). https://doi.org/10.1007/978-3-319-93683-3_2
11. F. Tao, M. Zhang, Y. Liu, A. Nee, Digital twin driven prognostics and health management for complex equipment. CIRP Ann. **67**(1), 169–172 (2018)
12. A.M. Madni, C.C. Madni, S.D. Lucero, Leveraging digital twin technology in model-based systems engineering. Systems **7**(1), 7 (2019)