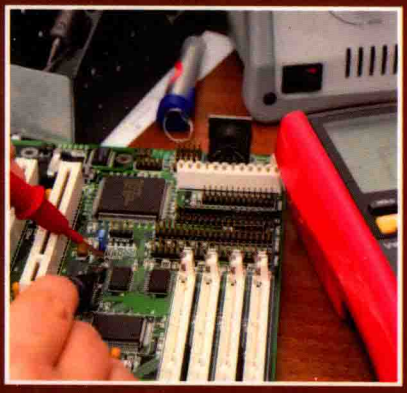
WOODHEAD PUBLISHING SERIES IN ELECTRONIC AND OPTICAL MATERIALS



Reliability Characterisation of Electrical and Electronic Systems

Edited by Jonathan Swingler

WP
WOODHEAD PUBLISHING

Woodhead Publishing Series in Electronic and Optical Materials: Number 74

Reliability Characterisation of Electrical and Electronic Systems

Edited by

Jonathan Swingler

ELSEVIER

AMSTERDAM • BOSTON • CAMBRIDGE • HEIDELBERG
LONDON • NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Woodhead Publishing is an imprint of Elsevier

Woodhead Publishing is an imprint of Elsevier
80 High Street, Sawston, Cambridge, CB22 3HJ, UK
225 Wyman Street, Waltham, MA 02451, USA
Langford Lane, Kidlington, OX5 1GB, UK

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Control Number: 2014954005

ISBN 978-1-78242-221-1 (print)
ISBN 978-1-78242-225-9 (online)

For information on all Woodhead Publishing publications visit our website at http://store.elsevier.com/

Typeset by Spi Global
www.spi-global.com
Printed and bound in the United Kingdom

Reliability Characterisation of Electrical and Electronic Systems

List of contributors

N. Aitken ERA Technology Ltd, Leatherhead, United Kingdom

B.M. Al-Hashimi University of Southampton, Southampton, United Kingdom

R.W.A. Barnard Lambda Consulting, Pretoria, South Africa

T.-M.I. Băjenescu C.F.C., La Conversion, Switzerland

M.I. Bâzu National Institute for R&D in Microtechnologies, Bucharest, Romania

A. Das University of Southampton, Southampton, United Kingdom

E. George Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD, USA

P.D. Goodman ERA Technology Ltd, Leatherhead, United Kingdom

C. Hendricks Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD, USA

J.-S. Huang Emcore Corporation, Alhambra; CA, USA

D. Medhat Mentor Graphics, Cairo, Egypt

G. Merrett University of Southampton, Southampton, United Kingdom

A.S. Oates Taiwan Semiconductor Manufacturing Company Ltd, Hsinchu, Taiwan

M. Osterman Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD, USA

M. Pecht Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD, USA

K.L. Pey Singapore University of Technology and Design (SUTD), Singapore

N. Raghavan Singapore University of Technology and Design (SUTD), Singapore

F. Schenkelberg FMS Reliability, Los Gatos, CA, USA

R.A. Shafik University of Southampton, Southampton, United Kingdom

R. Skipper ERA Technology Ltd, Leatherhead, United Kingdom

J. Swingler Heriot-Watt University, Edinburgh, United Kingdom

S. Yang University of Southampton, Southampton, United Kingdom

Woodhead Publishing Series in Electronic and Optical Materials

1 **Circuit analysis**
J. E. Whitehouse
2 **Signal processing in electronic communications: For engineers and mathematicians**
M. J. Chapman, D. P. Goodall and N. C. Steele
3 **Pattern recognition and image processing**
D. Luo
4 **Digital filters and signal processing in electronic engineering: Theory, applications, architecture, code**
S. M. Bozic and R. J. Chance
5 **Cable engineering for local area networks**
B. J. Elliott
6 **Designing a structured cabling system to ISO 11801: Cross-referenced to European CENELEC and American Standards Second edition**
B. J. Elliott
7 **Microscopy techniques for materials science**
A. Clarke and C. Eberhardt
8 **Materials for energy conversion devices**
Edited by C. C. Sorrell, J. Nowotny and S. Sugihara
9 **Digital image processing: Mathematical and computational methods Second edition**
J. M. Blackledge
10 **Nanolithography and patterning techniques in microelectronics**
Edited by D. Bucknall
11 **Digital signal processing: Mathematical and computational methods, software development and applications Second edition**
J. M. Blackledge
12 **Handbook of advanced dielectric, piezoelectric and ferroelectric materials: Synthesis, properties and applications**
Edited by Z.-G. Ye
13 **Materials for fuel cells**
Edited by M. Gasik
14 **Solid-state hydrogen storage: Materials and chemistry**
Edited by G. Walker
15 **Laser cooling of solids**
S. V. Petrushkin and V. V. Samartsev
16 **Polymer electrolytes: Fundamentals and applications**
Edited by C. A. C. Sequeira and D. A. F. Santos
17 **Advanced piezoelectric materials: Science and technology**
Edited by K. Uchino
18 **Optical switches: Materials and design**
Edited by S. J. Chua and B. Li
19 **Advanced adhesives in electronics: Materials, properties and applications**
Edited by M. O. Alam and C. Bailey
20 **Thin film growth: Physics, materials science and applications**
Edited by Z. Cao

21 **Electromigration in thin films and electronic devices: Materials and reliability**
Edited by C.-U. Kim

22 ***In situ* characterization of thin film growth**
Edited by G. Koster and G. Rijnders

23 **Silicon-germanium (SiGe) nanostructures: Production, properties and applications in electronics**
Edited by Y. Shiraki and N. Usami

24 **High-temperature superconductors**
Edited by X. G. Qiu

25 **Introduction to the physics of nanoelectronics**
S. G. Tan and M. B. A. Jalil

26 **Printed films: Materials science and applications in sensors, electronics and photonics**
Edited by M. Prudenziati and J. Hormadaly

27 **Laser growth and processing of photonic devices**
Edited by N. A. Vainos

28 **Quantum optics with semiconductor nanostructures**
Edited by F. Jahnke

29 **Ultrasonic transducers: Materials and design for sensors, actuators and medical applications**
Edited by K. Nakamura

30 **Waste electrical and electronic equipment (WEEE) handbook**
Edited by V. Goodship and A. Stevels

31 **Applications of ATILA FEM software to smart materials: Case studies in designing devices**
Edited by K. Uchino and J.-C. Debus

32 **MEMS for automotive and aerospace applications**
Edited by M. Kraft and N. M. White

33 **Semiconductor lasers: Fundamentals and applications**
Edited by A. Baranov and E. Tournie

34 **Handbook of terahertz technology for imaging, sensing and communications**
Edited by D. Saeedkia

35 **Handbook of solid-state lasers: Materials, systems and applications**
Edited by B. Denker and E. Shklovsky

36 **Organic light-emitting diodes (OLEDs): Materials, devices and applications**
Edited by A. Buckley

37 **Lasers for medical applications: Diagnostics, therapy and surgery**
Edited by H. Jelínková

38 **Semiconductor gas sensors**
Edited by R. Jaaniso and O. K. Tan

39 **Handbook of organic materials for optical and (opto)electronic devices: Properties and applications**
Edited by O. Ostroverkhova

40 **Metallic films for electronic, optical and magnetic applications: Structure, processing and properties**
Edited by K. Barmak and K. Coffey

41 **Handbook of laser welding technologies**
Edited by S. Katayama

42 **Nanolithography: The art of fabricating nanoelectronic and nanophotonic devices and systems**
Edited by M. Feldman

43 **Laser spectroscopy for sensing: Fundamentals, techniques and applications**
Edited by M. Baudelet

44 **Chalcogenide glasses: Preparation, properties and applications**
Edited by J.-L. Adam and X. Zhang

45 **Handbook of MEMS for wireless and mobile applications**
Edited by D. Uttamchandani

46 **Subsea optics and imaging**
Edited by J. Watson and O. Zielinski

47 **Carbon nanotubes and graphene for photonic applications**
Edited by S. Yamashita, Y. Saito and J. H. Choi

48 **Optical biomimetics: Materials and applications**
Edited by M. Large

49 **Optical thin films and coatings**
Edited by A. Piegari and F. Flory

50 **Computer design of diffractive optics**
Edited by V. A. Soifer

51 **Smart sensors and MEMS: Intelligent devices and microsystems for industrial applications**
Edited by S. Nihtianov and A. Luque

52 **Fundamentals of femtosecond optics**
S. A. Kozlov and V. V. Samartsev

53 **Nanostructured semiconductor oxides for the next generation of electronics and functional devices: Properties and applications**
S. Zhuiykov

54 **Nitride semiconductor light-emitting diodes (LEDs): Materials, technologies and applications**
Edited by J. J. Huang, H. C. Kuo and S. C. Shen

55 **Sensor technologies for civil infrastructures**
Volume 1: Sensing hardware and data collection methods for performance assessment
Edited by M. Wang, J. Lynch and H. Sohn

56 **Sensor technologies for civil infrastructures**
Volume 2: Applications in structural health monitoring
Edited by M. Wang, J. Lynch and H. Sohn

57 **Graphene: Properties, preparation, characterisation and devices**
Edited by V. Skákalová and A. B. Kaiser

58 **Silicon-on-insulator (SOI) technology**
Edited by O. Kononchuk and B.-Y. Nguyen

59 **59 Biological identification: DNA amplification and sequencing, optical sensing, lab-on-chip and portable systems**
Edited by R. P. Schaudies

60 **High performance silicon imaging: Fundamentals and applications of CMOS and CCD sensors**
Edited by D. Durini

61 **Nanosensors for chemical and biological applications: Sensing with nanotubes, nanowires and nanoparticles**
Edited by K. C. Honeychurch

62 **Composite magnetoelectrics: Materials, structures, and applications**
G. Srinivasan, S. Priya and N. Sun

63 **Quantum information processing with diamond: Principles and applications**
Edited by S. Prawer and I. Aharonovich

64 **Advances in non-volatile memory and storage technology**
Edited by Y. Nishi

65 **Laser surface engineering: Processes and applications**
Edited by J. Lawrence, C. Dowding, D. Waugh and J. Griffiths

66 **Power ultrasonics: Applications of high-intensity ultrasound**
Edited by J. A. Gallego-Juárez and K. F. Graff

67 **Advances in delay-tolerant networks (DTNs): Architectures, routing and challenges**
Edited by J. J. P. C. Rodrigues

68 **Handbook of flexible organic electronics: Materials, manufacturing and applications**
Edited by S. Logothetidis

69 **Machine-to-machine (M2M) communications: Architecture, performance and applications**
Edited by C. Anton-Haro and M. Dohler

70 **Ecological design of smart home networks: Technologies, social impact and sustainability**
Edited by N. Saito and D. Menga

71 **Industrial tomography: Systems and applications**
Edited by M. Wang

72 **Vehicular communications and networks: Architectures, protocols, operation and deployment**
Edited by W. Chen

73 **Modeling, characterization, and production of nanomaterials: Electronics, photonics and energy applications**
Edited by V. Tewary and Y. Zhang

74 **Reliability characterisation of electrical and electronic systems**
Edited by J. Swingler

75 **Handbook of industrial wireless sensor networks: Monitoring, control and automation**
Edited by R. Budampati S. Kolavennu

76 **Epitaxial growth of complex metal oxides: Techniques, properties and applications**
Edited by G. Koster, G. Rijnders and M. Huijben

77 **Semiconductor nanowires: Materials, synthesis, characterization and applications**
Edited by J. Arbiol and Q. Xiong

Foreword

Reliability of systems and their sub-elements – be they optical, optoelectronic, electrical, or electronic – is a crucially important topic in industry for enabling the classification of the faults and failure modes of devices and systems during their operational lifetime and the quantification of their residual useful life. Unfortunately it is a topic absent in the majority of syllabi in universities worldwide. As electrical and electronic devices become more complex, students ought to understand, let alone apply, design-for-reliability and the various testing methods that they might employ in industry.

In that respect, this book fills an important gap in the market. Its unashamedly empirical approach to the topic and the case studies presented in some of its chapters offer the reader a unique opportunity to relate to his/her own experience in the field.

The contributors to the book rightly took a practical view to reliability while presenting physics of failure and accelerated lifetime testing. More importantly, they dissected how knowledge of reliability could be applied not only across various classes of devices—microcircuits, diode, transistors, and embedded systems—but also across many applications ranging from oil and gas, automotive, and photovoltaics. This pedestrian approach is certainly welcome and will help those engineers who require specific information related to their main concerns.

In summary, I am delighted to give this book my personal recommendation and congratulate Dr Swingler and his contributors on providing a book that will be a very useful addition to the body of knowledge already present in the field.

Marc Desmulliez
Heriot-Watt University, Edinburgh, Scotland, United Kingdom

Contents

Introduction

1

J. Swingler
Heriot-Watt University, Edinburgh, United Kingdom

1.1 Introduction

This book has been put together to equip the new graduate and the practicing engineer in the importance of understanding electrical and electronic system reliability from the perspective of those working in the area on particular components and systems. It explores the subtle significance and consequence of building and assessing reliability of a system whether starting with defining it (or not) in the specification stage of a system concept through making particular guaranteed levels at the final implementation stage.

The basics of reliability engineering are not necessarily addressed, even though some chapters may touch on these, and the reader is therefore directed to such texts as *Practical Reliability Engineering* by O'Connor and Kleyner [1] or *Accelerated Quality and Reliability Solutions* by Klyatis and Klyatis [2].

The book repeatedly highlights how reliability engineering has moved from the use of, sometimes arbitrary, standards approach to an empirical scientific approach of understanding operating conditions, failure mechanisms, and the need for testing for a more realistic characterisation.

The book brings together a number of experts and key players in the discipline to concisely present some of the fundamental background of reliability theory, elaborate on the current thinking and developments behind reliability characterisation from components to systems, and give a detailed account of issues across a range of example applications.

1.2 The focus of the book

Firstly, to aid in explaining the focus of the book, a working definition of reliability is presented here. However, a number of more detailed definitions and descriptions, with their particular subtleties, have been presented throughout the book. But here, the working definition of reliability is given as:

An expectation of a system's level of functionality at a particular time.

Functionality is the key. Is the system functioning or partly functioning at a level that matches the specification? How does that functionality change with time?

Reliability Characterisation of Electrical and Electronic Systems. http://dx.doi.org/10.1016/B978-1-78242-221-1.00001-0

1.2.1 Reliability characterisation

The wording of the title of the book combines "reliability" with the noun "characterisation" and that is deliberately done. The word "characterisation," can not only convey the idea of an act of describing essential attributes but also convey the idea of an act of creating or building a character or attribute (e.g., in a literary work). Both ideas are emphasized in this book. The engineer and scientist are aiming to build a specific reliability and assess it to be able to provide evidence that verifies that reliability. These should be two inseparable activities when delivering a system with a reliability character, which is reasonable.

Reliability characterisation could imply that reliability is a feature of a system, which cannot be controlled, and all the developer can do is to characterise its attributes. However, the reliability characterisation of a system should not be seen as something that the engineer conducts passively once there is a product to analyse and describe. As many of the chapters in the book show, reliability is not a given attribute of a final system but should be defined in the specification, continuously built (and enhanced), and characterised throughout all levels of the technology development. That is, from the initial design to the final mass production and beyond, the reliability as with the functionality should be compliant to the specification. Figure 1.1 shows the relationship between the technological readiness levels and reliability building and assessing leading to a "Model of understanding of the system functionality over time," a model of its reliability character.

The earliest step is to define the reliability and life expectancy in the "reliability specification." Designs should be informed from past experience or any prior relevant data, but as Figure 1.1 illustrates, empirical studies of failure mechanisms need to be conducted to get proper understanding of the system's reliability. This is emphasized in this book. In Figure 1.1, this is separated into the influences of application stresses (stresses associated with its function) and operational stresses (stresses associated with its environment). In the development cycle, operational stresses can often be investigated later, but it must be considered that synergistic effects can occur by combining stress types. Accelerated life testing (ALT) and highly accelerated life testing are used to check and make sure that the product will behave as expected. These are repeatedly

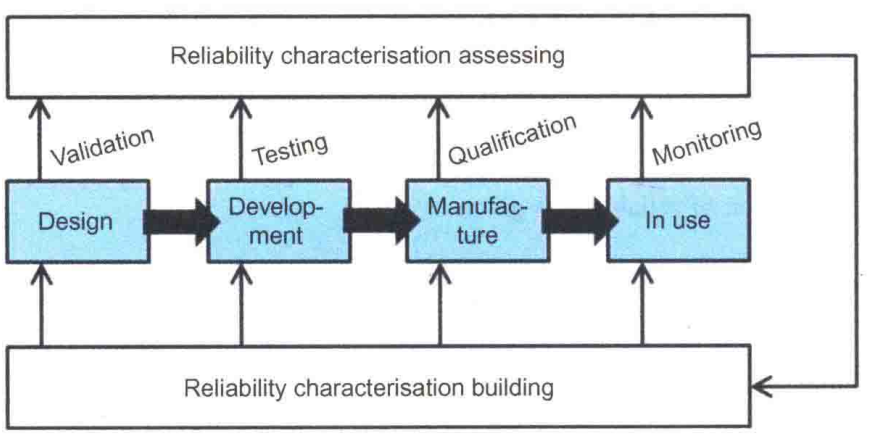


Figure 1.1 Reliability characterisation and technology readiness levels.

addressed throughout the book. What is becoming increasingly of interest is condition monitoring of the system in operation to identify their health. This adds vital real-life data to the understanding of its behaviour. All these enables a "Model of understanding of system functionality over time," which in turn can give a prediction of the reliability, preferably the minimum, mean, and maximum expected lifetime.

1.2.2 Electrical and electronic systems

Both electrical and electronic systems are named in the title to identify and broaden the scope of systems addressed. How the difference between an electrical system and an electronic system is defined may depend on the engineer's background, but a useful definition incorporates at least two concepts: the capability and the scale. Electrical systems tend to have no decision processing capability and tend to be of "higher" voltage scale (say 5 V and up), whereas an electronic system tends to have decision processing capability (handles input signals and delivers an output signal) and tends to be of "lower" voltage scale.

The focus of the book starts from these electrical/electronic systems and works out to their reliability character and how to build and assess it for those specific components/systems. This is the distinct difference with other texts. A simple search on published books in the area of reliability of electrical and electronic systems produces a valuable list of publication. Just to name a few, these are the following:

(1) *Design for Reliability* (Electronics Handbook Series) by Crowe and Feinberg [3].
(2) *Reliability Technology: Principles and Practice of Failure Prevention in Electronic Systems* by Pascoe [4].
(3) *Reliability of Safety-Critical Systems: Theory and Applications* by Rausand [5].

These texts give a wealth of information concerning reliability of electrical and electronic systems. Where the current book is concerned, it is distinguished by giving a survey of components/systems and special application areas of experts working in these particular areas.

1.2.3 The readers and the contributing authors

The book is aimed at the new graduate or the practicing engineer who are perhaps for the first time thinking about the reliability characterisation of a product. The reader is assumed to have some knowledge of reliability issues but wishes to dip into the expertise of others. The contributing authors are practicing scientists and engineers working in industry and academia. They are truly international coming from four continents.

1.3 Reliability science and engineering fundamentals (Chapters 2–4)

Three chapters present current thinking in the context of moving the science forward. The first of these chapters is eye-catching because we are all prone, if we are not careful, to fall into flawed thinking and practice particularly due to time pressures. The