1

Introduction

1.1 The Three Goals of the Book

In our society, which is focused on *success* in any domain, *failure* is an extremely negative value. We all still remember the strong emotion produced worldwide by the crash of the Space Shuttle *Challenger*. On 28 January 1986, *Challenger* exploded after 73 seconds of flight, leading to the deaths of its seven crew members. The cause was identified after a careful failure analysis (FA): an O-ring seal in its solid rocket booster failed at lift-off, causing a breach in the joint it sealed and allowing pressurised hot gas from the solid rocket motor to reach the outside and impinge upon the attachment hardware. Eventually, this led to the structural failure of the external tank and to shuttle crash. This is a classical example of failure produced by the low quality of a part used in a system. Other examples of well-known events produced by failures of technical systems include the following:

- On 10 April 1912, RMS *Titanic*, at that time the largest and most luxurious ship ever built, set sail on its maiden voyage from Southampton to New York. On 14 April, at 23 : 40, the *Titanic* struck an iceberg about 400 miles off Newfoundland, Canada. Although the crew had been warned about icebergs several times that evening by other ships navigating through the region, the *Titanic* was travelling at close to its top speed of about 20.5 knots when the iceberg grazed its side. Less than three hours later, the ship plunged to the bottom of the sea, taking more than 1500 people with it. Only a fraction of the passengers were saved. This was a terrible failure of a complex technical system, made possible because the captain had ignored the necessary precautions; hence the failure was produced by a human fault. The high casualty rate was further explained by the insufficient number of life boats, which implies a design fault.
- On 24 April 1980, the US President Jimmy Carter authorised the military operation Eagle Claw (or Evening Light) to rescue 52 hostages from the US Embassy in Tehran, Iran. The hostages had been held since 4 November 1979 by a commando of the Iranian Revolutionary Guard. Eight RH-53D helicopters participated in the operation, which failed due to many technical problems. Two helicopters suffered avionics failures en route and a sand storm damaged the hydraulic systems of another two. Because the mission plan called for a minimum of six helicopters, the rest were not able to continue and the mission was aborted. This is considered a typical case of reliability failure of complex technical systems.

Obviously, we have to fight against failures. Consequently FA has been promoted and has quickly become a necessary tool. FA attempts to identify root causes and to propose corrective actions aimed at avoiding future failure.

Failure Analysis: A Practical Guide for Manufacturers of Electronic Components and Systems, First Edition.
Marius I. Bâzu and Titu-Marius I. Băjenescu.

Given the large range of possible human actions, many specific procedures of FA are needed, starting with medical procedures for curing or preventing diseases (which are failures of the human body) and continuing with various procedures for avoiding the failure of technical systems. In this respect, the word ‘reliability’ has two meanings: first, it is the aim of diminishing or removing failures, and second, it is the property of any system (human or artefact) to function without failures, in some given conditions and for a given duration. In fact, FA is a component of reliability analysis. This idea will be detailed in the following pages.

From the above, one can see that the first goal of this book is to present the basics of FA, which is considered the key action for solving reliability issues. But there is a second purpose, equally important: to promote the idea of reliability, to show the importance of this discipline and the necessity of supporting its goals in achieving a given level of reliability as a key characteristic of any product.

Unfortunately, the first reliability issues were solved by statisticians, which led to a mathematical approach to reliability, predominant in the first 25–30 years of the modern history of the domain. Today other disciplines, such as physics and chemistry, are equally involved. All this issues are detailed in Section 1.2, where a short history of reliability as a discipline is presented.

The mathematical approach was restrictive and created the incorrect impression that the aim of reliability analysis was to impede the work of real specialists, forcing them to undertake redesigns due to cryptic results that nobody could understand. Today this misapprehension has generally been overcome, but its after-effects are still present in the mentality of some specialists. We want to persuade component manufacturers that reliability engineers are their best friends, simulating the behaviour of their product in real-life conditions and then recommending necessary improvements before the product can be sold. Manufacturers and reliability engineers must form a team, with information flowing in both directions.

Even more importantly, this book is aimed at showing to industry managers the reasons for taking reliability issues into account from the design phase onwards, through the whole cycle of development of a product. It has been proved that the only way to promote reliability requirements is top-down, starting with the manager and continuing down to every worker.

The third goal of the book starts from our subjective approach to reliability. We think reliability is a beautiful domain, offering immense satisfaction to any specialist, and involving a large range of knowledge, from physics, chemistry and mathematics to all engineering disciplines. That is why strong interdisciplinary teams are needed to solve reliability issues, which are difficult challenges for the human mind.

We want to show to young readers the beauty of reliability analysis, which can be compared to a simple mathematical demonstration. Another approach is to consider a reliability analysis to be similar to the activity of a detective: we have a ‘dead component’ and, based on the information gathered from those involved, we have to find out why this happened and ‘who did it’. This is possible because failures follow the law of cause and effect [1].

Our focus on the above three goals has imposed the structure of this first chapter. As you can see, we want not only to deliver a high quantity of information, but to convince the specialists who manufacture electronic components and systems how important FA is, and, more generally, to attract the reader to the ‘charming land of reliability’. This first chapter has a huge importance, as our main attractor. Consequently, we have tried to structure it as straightforwardly as possible. We have presumed the subject is a new one for the reader, so we thought it best to begin with a short history of reliability as a discipline, with a special emphasis on FA. A section on terminology will furnish definitions of the most important terms. Finally the state of the art in FA will be described, including a short description of the main challenges for the near future.

This first chapter will thus show the past, present and future of FA, together with the main terminology. With this knowledge acquired, we think the reader will be ready to learn the general plan of the book, which is given in the final part of this chapter.

1.2 Historical Perspective

There is a general consensus that reliability as a discipline was established during World War II (1939–1945), when the high number of failures noticed for military equipment became a concern, requiring an institutional approach. However, attempts to design a fair quality into an artefact or to monitor the way this quality is maintained during usage (i.e. reliability concerns) were first made a long time ago.

1.2.1 Reliability Prehistory

This story may begin thousands of years ago, during the Fifth Dynasty of the Ancient Egyptian Empire (2563–2423 BCE), when the pharaoh Ptah-hotep stated (in other words, of course, but this was the idea) that good rules are beneficial for those who follow them [2]. This is the first known remark about the quality of a product, specifically about the design quality. Obviously, during the following ages, many other milestones in quality and reliability history occurred:

- In Ancient Babylon, the Code of Hammurabi (1760 BCE) said: 'If the ship constructed for somebody is damaged during the first year, the manufacturer has to re-build it without any supplementary cost.' This could be considered the first specification about the reliability of a product!
- In China, during the Soong dynasty (960–1279 CE), there were six criteria for the quality and reliability of arches: to be light and elastic, to withstand bending and temperature cycles, and so on. Close enough to modern specifications!
- At the same time in Europe, the guilds (associations of artisans in a particular trade) elaborated principles of quality control, based on standards. Royal governments promoted the control of quality for purchased materials; for instance, King John of England (1199–1216) asked for reports on the construction of ships.
- In the 1880s mass production began and F.W. Taylor proposed the so-called 'Scientific Management': assembly lines, division of labour, introduction of work standards and wage incentives. Latter, he wrote two basic books on management: *Shop Management* (1905) and *The Principles of Scientific Management* (1911).
- On 16 May 1924, W.A. Shewhart, engineer at the Western Electric Company, prepared a little memorandum about a page in length, containing the basics of the control chart. He later became the 'father' of statistical quality control (SQC): methods based on continual on-line monitoring of process variation and the concepts of 'common cause' and 'assignable cause' variability.
- In 1930, H.F. Dodge and H.G. Romig, working at Bell Laboratories, introduced the so-called Dodge–Romig tables: acceptance sampling methods based on a probabilistic approach to predicting lot acceptability from sampling results, centred on defect detection and the concept of acceptable quality level (AQL).

All these contributions (and many others) have paved the way for current, modern approaches in quality and have prepared the development of reliability as a discipline (see Sections 1.2.2 and 1.2.3).

Following World War II, in parallel with the rise of reliability as a discipline, the quality field has continued to be developed, mainly in the USA. Two eminent Americans, W. Edwards Deming and Joseph Juran, alongside the Japanese professor Kaouru Ishikawa, were successful in promoting this field in Japan. Another name has to be mentioned, Philip B. Crosby, who initiated the quality-control programme named 'Zero Defects' at Martin Company, Orlando, Florida, in the late 1960s. In 1983, Don Reinertsen proposed the concept of concurrent engineering as an idea to quantify the value of development speed for new products.

Due to the efforts of the above, a new discipline, called quality assurance, was born, aimed at covering all activities from design, development and production to installation, servicing, documentation, verification and validation.

1.2.2 The Birth of Reliability as a Discipline

The following two events are considered the founding steps of reliability as a discipline:

1. During World War II, the team led by the German rocket engineer Wernher Magnus Maximilian Freiherr von Braun (later the father of the American space programme) developed the V-1 rocket (also known as the Buzz-Bomb) and then the V-2 rocket. The repeated failures of the rockets made a safe launch impossible. Von Braun and his team tried to obtain a better device, focusing on improving the weakest part, but the rockets continued to fail. Eric Pieruschka, a German mathematician, proposed a different approach: the reliability of the rocket would be equal to the product of the reliability of its components. That is, the reliability of all components is important to overall reliability. This could be considered the first modern predictive reliability model. Following this approach, the team was able to overcome the problem [3].
2. In 1947, Aeronautical Radio Inc. and Cornell University conducted a reliability study on more than 100 000 electronic tubes, trying to identify the typical causes of failures. This could be considered the first systematic FA. As a consequence of this study, on 7 December 1950, the US Department of Defense (DoD) established the *Ad Hoc Group on Reliability of Electronic Equipment* (AHGREE), which became in 1952 the *Advisory Group on the Reliability of Electronic Equipment* (AGREE) [4]. The objectives proposed by this group are still valid today: (i) more reliable components, (ii) reliability testing methods before production, (iii) quantitative reliability requirements and (iv) improved collection of reliability data from the field (including failure analyses). Later, in 1956, AGREE elaborated the first reliability handbook, titled 'Reliability Factors for Ground Electronic Equipment'. This report is considered the fundamental milestone in the birth of reliability engineering.

1.2.3 Historical Development of Reliability

The reliability discipline has evolved around two main subjects: reliability testing and reliability building. In this discussion, we think the history of *prediction methods* (which are based on FA) is the relevant element, being deeply involved in both subjects: as input data for reliability building and as output data for reliability testing.

Following the issue of the first reliability handbook, the TR-1100 'Reliability Stress Analysis for Electronic Equipment', released by RCA in November 1956, proposed the first models for computing failure rates of electronic components, based on the concept of activation energy and on the Arrhenius relationship.

On 30 October 1959, the Rome Air Development Center (RADC; later the Rome Laboratory, RL) issued a 'Reliability Notebook', followed by some other basic papers contributing to the development of knowledge in the field: 'Reliability Applications and Analysis Guide' by D.R. Earles (September 1960); 'Failure Rates' by D.R. Earles and M.F. Eddins (April 1962); and 'Failure Concepts in Reliability Theory' by Kirkman (December 1963).

From the early 1960s, efforts in the new reliability discipline focused on one of the RADC objectives: developing prediction methods for electronic components and systems. Two main approaches were followed:

1. '*The statistical approach*', using reliability data gathered in the field. The first reliability prediction handbook, MIL-HDBK-217A, was published in December 1965 by the US Navy. This was a huge success, being well received by all designers of electronic systems, due to its flexibility and ease of use. In spite of its wrong basic assumption, an exponential distribution of failures [5], the handbook became the almost unique prediction method for the reliability of electronic systems, and other sources of reliability data gradually disappeared [6].

2. '*The physics-of-failure* (*PoF*) *approach*', based on the knowledge of failure mechanisms (FMs) (investigated by FA) by which the components and systems under study are failing. The first symposium devoted to this topic was the 'Physics of Failure in Electronics' symposium, sponsored by the RADC and the IIT Research Institute (IITRI), in 1962. This symposium later became the 'International Reliability Physics Symposium' (IRPS), the most influential scientific event in failure physics. On 1 May 1968, the MIL-HDBK-175 Microelectronic Device Data Handbook appeared (revised in 24 October 2000), with a section focused on FA ('Reliability and Physics of Failure').

The two approaches seemed to be diverging; system engineers were focused on the 'statistical approach' while component engineers working in FA were focused on the PoF approach. But soon both groups realised that the two approaches were complementary and attempts to unify the two methods have been made.

This has been facilitated by the fact that, in 1974, the RADC, which was the promoter of the PoF approach, became responsible for preparing the second version of MIL-HDBK-217, and of the subsequent successive versions (C . . . F), which tried to update the handbook by taking into account new advances in technology. However, instead of improved results, more and more sophisticated models were obtained, considered 'too complex, too costly and unrealistic' by the user community [6]. Another attempt, executed by RCA, under contract to the RADC, which tried to develop PoF-based models, was also unsuccessful. This was because the model users did not have access to information about the design and construction of components and systems.

In the 1980s, various manufacturers of electronic systems tried to develop specific prediction methods for reliability. Examples include the models proposed for automotive electronics by the Society of Automotive Engineers (SAE) Reliability Standards Committee and for the telecommunication industry (Bellcore reliability-prediction standards).

For the last version (F) of MIL-HDBK-217, issued on 10 July 1992, two teams (IIT/Honeywell and CALCE/Westinghouse (Centre for Advanced Life Cycle Engineering)) were commissioned by the (RL) RADC to provide guidelines. Both teams suggested the following conclusions:

- The constant-failure-rate model (based on an exponential distribution) is not valid in real life.
- Electromigration and time-dependent dielectric breakdown could be modelled with a lognormal distribution.
- Arrhenius-type formulation of the failure rate in terms of temperature should not be included in the package failure model.
- Temperature change and humidity must be considered as key acceleration factors.
- Temperature cycling is more detrimental for component reliability than the steady-state temperature at which the device is operating, so long as the temperature is below a critical value.

Similar conclusions were supported by the studies [7, 8]. In fact, these conclusions are preparing a unified approach on prediction method, which has not been issued yet.

During the first 30 years of the reliability discipline, military products acted as the main drivers of reliability developments. However, starting from the 1980s, commercial electronic components became more and more reliable. In June 1994, the so-called 'Acquisition Reform' took place: the US DoD abolished the use of military specifications and standards in favour of performance specifications and commercial standards in DoD acquisitions [9]. Consequently, in October 1996, MIL-Q-9858, Quality Program Requirements, and MIL-I-45208 A, Inspection System Requirement, were cancelled without replacement. Moreover, contractors were henceforth required to propose their own methods for quality assurance, when appropriate. The DoD policy allows the use of military handbooks only for guidance. Many professional organisations (e.g. IEEE Reliability Society) attempted to produce commercial reliability documents to replace the vanishing military standards [10]. A number of international standards were also produced, including IEC TC-56, some NATO documents, British documents and Canadian documents. In addition to the new standardisation activities, the RL is also undertaking a number of research programmes to help implement acquisition reform.

However, some voices, such as Demko [11], consider a logistic and reliability disaster to be possible, because commercial parts, standards and practice may not meet military requirements. For this purpose, in June 1997 the IITRI of Rome (USA) developed SELECT, a tool that allows users to quantify the reliability of commercial off-the-shelf (COTS) equipment in severe environments [12]. Also, beginning from April 1994, a new organisation, the Government and Industry Quality Liaison Panel (GIQLP), made up of government agencies, industry associations and professional societies, was intimately involved in the vast changes being made in the government acquisition process [13].

MIL-HDBK-217 was among the targets of the Acquisition Reform, but it was impossible to replace it, because no other candidates (prediction methods) were available. However, attempts at elaborating a new handbook for predicting the reliability of electronic systems were made. Supplementary to the existing handbook, this document, called the ‘New System Reliability Assessment Method’, has to manage system-level factors [6]. The system has to take into account previous information about the reliability of similar systems (built with similar technologies, for similar applications and performing similar functions), as well as test data about the new system (aimed at producing an initial estimate of the system’s reliability).

On the other hand, a well-known example of commercial standards replacing the old military standards is given by the ISO 9000 family, first issued in 1987, with updates in 2000, 2004 and 2008. Basically, the IS0 9000 standards aimed to provide a framework for assessing the management system in which an organisation operates in relation to the quality of the furnished goods or services. The concept was developed from the US Military Standard for quality, MIL-Q-9858, which was introduced in the 1950s as a means of assuring the quality of products built for the US military services. But there is a fundamental new idea promoted by ISO 9000: the quality management systems of the suppliers are audited by independent organisations, which assess compliance with the standard and issue certificates of registration. The suppliers of defence equipment were assessed against the standards by their customers. In a well-documented and convincing paper about ISO 9000 standards, Patrick O’Connor elucidated the weak points of this approach [14]:

- The philosophy of ‘total quality’ demands close partnership between supplier and purchaser, which is destroyed if the ‘third party’ has to audit the quality management of the supplier.
- It is hard to believe that this ‘third party’ is able to have the appropriate specialist knowledge about the products to be delivered.
- In fact, the ISO 9000 standards aim only to verify that the personnel of the supplier are strictly observing the working procedures and not whether the procedures are able to ensure a specified quality and reliability level. Of course, some organisations have generated real improvements as a result of registration, but it is not obvious that this will happen in all cases. Moreover, the high costs required to implement ISO 9000 may have detrimental effect on a real improvement, by technical corrective actions, in the manufacturing process.
- Two explanations are proposed for wide adoption of these standards, in spite of the solid arguments of many leading teachers of quality managers: (i) the tendency to believe that people perform better when told what to do, rather than when they are given freedom and the necessary skills and motivation to determine the best ways to perform their work and (ii) working only with ‘registered’ suppliers is the easy way for many bureaucrats to select the most appropriate suppliers for their products. The main responsibility is transferred to the ‘third party’.

As one can see, the ISO 9000 approach seeks to ‘standardise’ methods that directly contradict the essential lessons of the modern quality and productivity revolution (e.g. ‘total quality’), as well as those of the new management.

Some other important contributors to the domain of reliability include the following:

- Genichi Taguchi, who proposed robust design, using fractional factorial design and orthogonal arrays in order to minimise loss by obtaining products with minimal variations in their functional characteristics.
- Dorian Shainin, reliability consultant for various companies, including NASA (the Apollo Lunar Module), who supported the idea of discovering and solving problems early in the design phase, before costly manufacturing steps are taken and before customers experience failures in the field.
- Wayne B. Nelson, who developed a series of methodologies on accelerated testing, based on FA.
- Larry H. Crow, independent consultant as well as an instructor and consultant for ReliaSoft Corporation, who made contributions in the areas of reliability growth and repairable system data analysis.
- Gregg K. Hobbs, the inventor of the highly accelerated life test (HALT), a stress-testing methodology, aimed at obtaining information about the reliability of a product.
- Michael Pecht, the founder of CALCE and the Electronic Products and Systems Consortium at the University of Maryland, which made essential contributions to the study of FMs of electronic components.
- Patrick O'Connor, who made contributions to our understanding of the role of failure physics in estimating component reliability; he also proposed convincing arguments against ISO 9000.

1.2.4 Tools for Failure Analysis

Initiated in 1947 for electronic tubes, FA was developed mainly for other microelectronic devices (transistors, integrated circuits (ICs), optoelectronic devices, microsystems and so on), but also for electronic systems. Since 1965, the number of transistors per chip has been doubling every 24 months, as predicted by Moore. Today, ICs are made up of hundreds of millions of transistors grown on a single chip. Key FA tools have been developed continuously, driving the growth of the semiconductor industry by solving difficult test problems.

The search for physical-failure root causes (especially with physical inspection and electrical localisation) is aimed at breaking through any technology barrier in each stage of chip development, package development, manufacturing process and field application, offering the real key to eradicate the error. Testing provides us with information on the electrical performance; FA can discover the detractors for the poor performance [15]. In today's electronic industry FA is squeezed between the need for very rapid analysis to support manufacturing and the exploding complexity of the devices. This requires knowledge of subjects like design, testing, technology, processing, materials science, physics, chemistry and even mathematics [16]!

As can be seen in Figure 1.1, a number of key FA tools and advanced techniques have been developed. These play essential roles in the development of semiconductor technology.

1.3 Terminology

The lack of precision in terminology is a well-known disease of our times. Very often, specialists with the same opinion about a phenomenon are in disagreement because they are implicitly using different definitions for the same term, or because various terms having the same meaning. Of course, standards for the main terms of any technical field have been elaborated, but it is difficult to read a book with an eye to one or many standards. This is why we felt that this book needs a glossary. The glossary is located within the back matter and contains only the basic terms referring to the subject of the book, **failure analysis for electronic components and systems**, divided into two main sections:

- Terms related to electronic components and systems.
- Terms related to FA.

Other more specific terms will be explained within the main body of the text, when necessary.

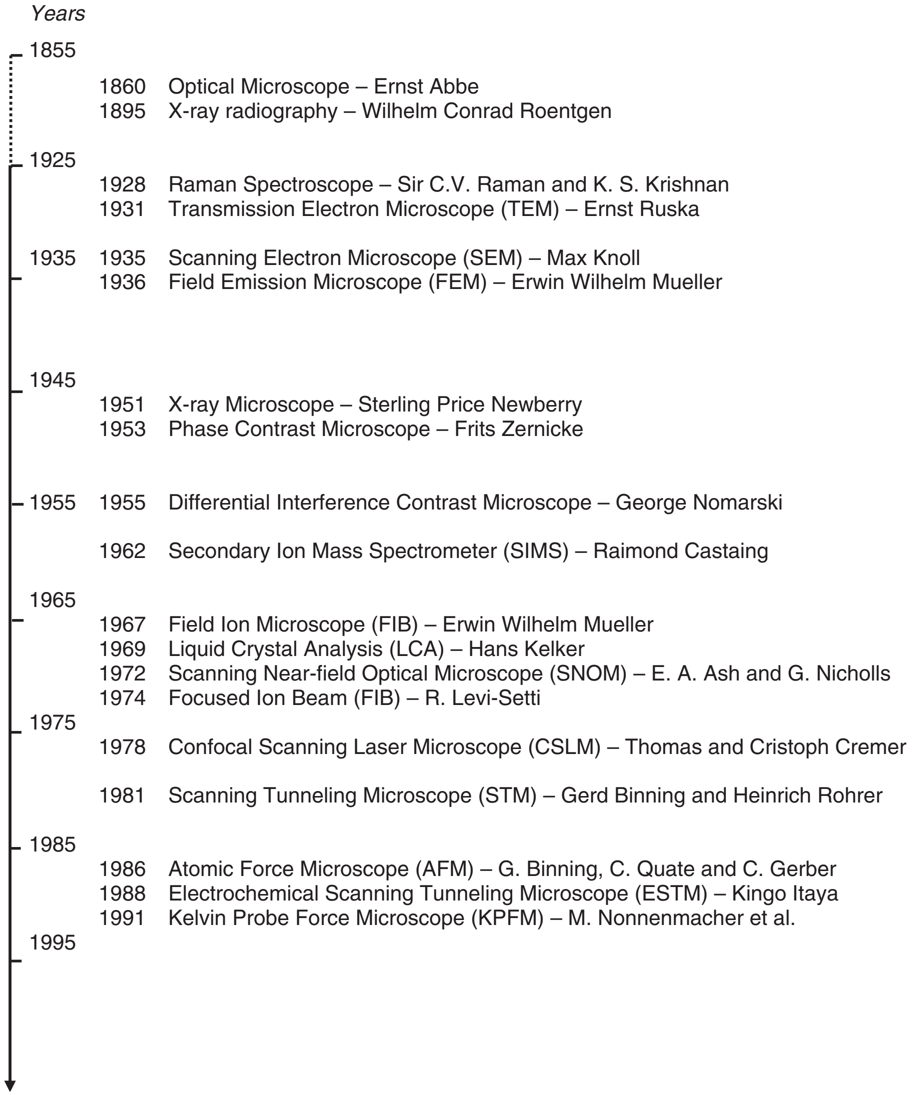

Figure 1.1 History of the main techniques used in failure analysis: year of appearance, name, acronym, name of inventor (After [14])

1.4 State of the Art and Future Trends

The current issues related to FA of electronic components and systems can be structured around three main areas:

- techniques of FA;
- FMs;
- models for the PoF.

In this section, the most important subjects of each area will be discussed.

1.4.1 Techniques of Failure Analysis

Today, when FA is performed at *system level*, we have to analyse not only discrete (active and passive) components but a large range of ultra-high-density ICs, with a high design complexity that exceeds 300 million gates, manufactured by a huge variety of technologies (bipolar silicon, CMOS, BiCMOS, GaN, GaAs, InP, GaN, SiC, complex heterojunction structures and microelectromechanical systems, MEMSs), which will be detailed in Chapter 5. This is why the today's analyst faces complex equipment sets (curve tracers, optical microscopes, decapsulation tools, X-ray and acoustic microscopies, electron and/or optical and/or focused ion beam (FIB) tools, thermal detection techniques, the scanning probe atomic force microscope, surface science tools, a great variety of electrical testing hardware and so on) that are necessary to realise a spatial and complex FA. FA is a highly technical activity with increasingly complex, sophisticated and costly specialised equipments. It is very difficult to achieve a balance between customer satisfaction, cost-effectiveness and future challenges. Very often the analyst must use a limited set of tools, as the cost of all the required tools exceeds the budget of current operations. FA techniques are used to confirm and localise physical defects. The final objective is to find the root cause.

Failure modes and effects analysis (FMEA) is the systematic method of studying failure, formally introduced in the late 1940s for military usage by the US armed forces [3]. Later, FMEA was used for aerospace/rocket development to avoid errors in small sample sizes of costly rocket technology. Now FMEA methodology is extensively used in a variety of industries, including semiconductor processing, food service, plastics, software and health care. It is integrated into advanced product quality planning (APQP) to provide primary risk-mitigation tools and timing in the preventing strategy, in both design and process formats. FMEA is also useful at component level, especially for complex components (ICs, MEMS, etc.). In FMEA, failures are prioritised according to how serious their consequences are, how frequently they occur and how easily they can be detected. Current knowledge about risks of failures and preventive actions for use in continuous improvement are also documented. FMEA is used during the design stage in order to avoid future failures and later for process control, before and during ongoing operation of the process. Ideally, FMEA begins during the earliest conceptual stages of design and continues throughout the life of the product or service. The purpose of FMEA is to take action to eliminate or reduce failures, starting with the highest-priority ones.

At *component level*, a broad definition of FA includes: collection of background data, visual examination, chemical analysis, mechanical properties, macroscopic examination, metallographic examination, micro-hardness, scanning electron microscopy (SEM) analysis, microprobe, residual stresses and phases, simulation/tests, summary of findings, preservation of evidence, formulation of one or more hypotheses, development of test methodologies, implementation of tests/collection of data, review of results and revision of hypotheses. Each time, the customer will be notified.

First, the causes of a failure can be classified according to the phase of a product's life cycle in which they arise – design, materials processing, component manufacturing or service environment and operating conditions. Then two main areas of FA enable fast chip-level circuit isolation, circuit editing for quick diagnostic and problem-solving, helping bring forward semiconductor development:

- **Physical inspection**, represented by three important tools: SEM, emission microscopy and transmission electron microscopy (TEM).
- **Electrical localisation**, executed mainly with liquid crystal analysis (LCA), photo electron microscopy (PEM) and FIB.

The package global localisation tool infra-red lock-in thermography (IR-LIT) became widely available in 2005 and is the most popular tool for global localisation for complex packages, such as system-in-package (SiP) and system-on-chip (SoC). Today the tool support for SoC development is X-ray CT, due to a significant resolution and speed improvement. FA has given and gives a continuous contribution to technological innovation in the whole history of semiconductor development.

When ICs are analysed, a number of tools and techniques are used due to device-specific issues: additional interconnection levels, power distribution planes and flip-chip packaging completely eliminate the possibility of employing standard optical or voltage-contrast FA techniques without destructive intervention. The defect localisation utilises techniques based on advanced imaging, and on the interaction of various probes with the electrical behaviour of devices and defects.

The thermal interaction between actively operated electronic components and applied characterisation tools is one of the most important interactions within FA and reliability investigations. It allows different kinds of thermal interaction mechanism to be utilised, which would normally have to be separated–for instance into classes with respect to thermal excitation and/or detection, spatial limitations and underlying physical principle. Although they all have in common the ability to link the thermo-electric device characteristic to a representing output signal, they have to be interpreted in completely different ways. Recently, the complementarity of the methods for localisation and characterisation as well as the according industrial demands and related limitations have been shown [17]; techniques such as IR-LIT and thermal induced voltage alteration (TIVA), case studies and the capability of non-established techniques like scanning thermal microscopy (SThM), thermal reflectance microscopy (TRM) and time domain thermal reflectance (TDTR) are also presented and their impact on reliability investigations is discussed.

Over the last few years, the increased complexity of devices has scaled the difficulty in performing FA. Higher integration has led to smaller geometry and better wire-to-cell ratios, thus increasing the complexity of the design. These changes have reduced the effectiveness of most of the current FA techniques; over the past few years, a variety of techniques and tools, such as electron-beam (E-beam) probers, FIB, enhanced imaging SEM and field emission SEM (FESEM), have been developed to determine the defects at wafer level. All these tools improve FA capabilities, but at substantial cost, running into hundreds of thousands of dollars. Some other examples of new techniques are given below:

- A strategy was derived for FA in random logic devices (such as microprocessors and other VLSI chips) where the electrical scheme is not known. This strategy is based on the use of a test tool composed of an SEM allied to a voltage contrast, an exerciser, an image processing system and a control and data processing system [18].
- Three new FA techniques for ICs have been developed recently using localised photon probing with a scanning optical microscope (SOM) [19]. The first two are light-induced voltage alteration (LIVA) imaging techniques that (i) localise open-circuited and damaged junctions and (ii) image transistor logic states. The third technique uses the SOM to control logic states optically from the IC backside. LIVA images are produced by monitoring the voltage fluctuations of a constant current power supply as a laser beam is scanned over the IC. High selectivity for localising defects has been demonstrated using the LIVA approach. Application of the two LIVA-based techniques to backside FA has been demonstrated using an infrared laser source.
- It is critical to develop improved analysis techniques that are easier to use, less damaging, more sensitive and provide better spatial resolution. One example is ‘passive’ techniques, which are non-invasive, in the sense that the normal operation of the IC provides the information or energy being measured. Recently, dynamic photoelectric laser-stimulation techniques were applied to mixed-mode ICs, where the major difficulty is their considerable intrinsic sensitivity [20]. Indeed, the analogue circuitry is more sensitive than the digital circuitry since a slight change in an electrical parameter can trigger a functionality failure. This property limits the defect localisation because of the complex interpretation of the results: the laser-stimulation mapping. In this case, dynamic laser-stimulation mapping is coupled with photoelectric impact simulations run on a previously analysed structure. The goal is to predict and interpret the laser-sensitivity mapping and to isolate the defective areas in the analogue devices.
- A technique used for decapsulating the device for FA is the ultra-short-pulse laser-ablation-based backside sample-preparation method [21]. This technique is contactless, nonthermal, precise, repetitive and adapted to each type of material present in IC packages. However, it can create thermal

stresses to the device. In order to minimise these stresses, a new method was proposed for controlling the thermal effect of the laser on the component [22].

- Various methods of preparation to repack dice with a nondestructive access to the backside are shown in [23]. With new processes, and where backside milling is not possible, this work is mandatory for any fault localisation technique. Various mountings – to be chosen depending on the original package (mainly BGA) and on the requirements of the emission techniques – and how these techniques can be used for a new product family (SiP, with multiple dice inside a package) are described. In this specific case the challenge is to extract the failed die without destroying the module.
- As new technologies in the electronic environment develop from 2D IC to 3D complex packages, it becomes necessary to find new techniques to detect and localise the different kinds of failure. A solution to localise defects for SiP devices is to measure the magnetic field that is generated by the current flowing through the device with a magnetic microscope (Magma C20) and compare it with several simulated faults in order to choose the most probable one [24].

1.4.2 Failure Mechanisms

From a technical perspective, failure can be defined as the cessation of function or usefulness. FA is the process of investigating such a failure. Basically, FA analysis the failure modes (FMos) with the aim of identifying the FMs, by using optical, electrical, physical and chemical analysis techniques.

Reliability is built into the device at the design and manufacturing process stages. In most practical cases, the final damage rarely reveals a direct physical FM; often the original cause (or complete scenario of failure) is hidden by secondary post-damage processes. On the other hand, it is impossible to eradicate failures during the manufacturing process and upon field use. Therefore, FA must be performed to provide timely information and prevent the recurrence of similar failures.

The wafer fabrication and assembly process involves numerous steps using various types of material. This, combined with the fact that devices are used in a variety of environments, requires a wide range of knowledge about the design and manufacturing processes. This explains why FA of semiconductor device is becoming increasingly difficult as VLSI technology evolves towards smaller features and semiconductor device structures become more complex. Since it is usually not possible to repair faulty component devices in a VLSI, each device in a chip can become a single point of failure unless some redundancy is introduced. Therefore, VLSIs have to be designed based on the characteristics of the worst devices rather than on those of average devices. Even if a chip is equipped with some redundant device, today’s scale of integration is so high that the yield requirement will still be very severe. The final chip yield is governed by the device yield.

A recent report [25] has demonstrated that, for any item, once the major cause of failure is somehow identified or assumed, the Monte Carlo method may be used to study yield problems. This method was applied to the analysis of leakage current distribution for double-gate MOSFETs; the microscopic FM that limits the final yield was identified. This explains experimental data very well. The insight into the FM gives clear guidelines for yield enhancement and facilitates device design alongside the quantitative yield prediction. It is useful for yield prediction and device design. Transistors should be designed such that I_t (the maximum current generated by a single trap) is very much lower than the tolerable leakage current at the specified cumulative probability. The method does not have any convergence problems, unlike the conventional Monte Carlo approach.

At system level, a general study [6] performed by the Reliability Analysis Centre (RAC) into the predominant causes of failure in electronic systems led to the results shown in Table 1.1. As one can see, only 22% of the failures are directly linked to the reliability of the components. An important number of failures have noncomponent causes, such as defects in design and manufacturing of the system. This could be considered to go against the general belief that the reliability of the components is decisive for the reliability of the system. However, the results from Table 1.1 have to be understood as follows: when appropriately selected components are used, they are responsible

Table 1.1 Distribution of failure causes for electronic systems

Failure cause	Details	Percentage (%)
Parts	Failure of components (e.g. transistors, diodes, ICs, resistors, etc.)	22
Mysterious cause	System failures not reproduced upon further testing; uncertain that there are actual failures	20
Manufacture	Anomalies of the manufacturing process (e.g. wrong manipulation, faulty solder joints, etc.)	15
Induced	Produced by applied stress (e.g. electrical overstress, maintenance-induced failures)	12
Design	Inadequate design (e.g. nonrobust design for environmental stress)	9
Wearout	Wearout-related failure mechanisms of parts and interfaces	9
Software	System failures produced by software fault	9
Management	Wrong management (e.g. wrong interpretation of system requirements, failure to provide required resources)	4

After [6].

for less than a quarter of system failures. If inappropriate components are used, they can determine failures beyond the 22% already mentioned (see Table 1.1): for example, failures from induced causes, design, wear-out and so on. Actually, the total percentage of possible failures linked to the parts is higher that 50%.

1.4.3 *Models for the Physics-of-Failure*

For electronic components, models describing the action of FM versus time and specific stresses arose early in reliability history (as mentioned at Section 1.2.3). This PoF approach has to be used because the statistical processing of reliability data is significant only for a population affected by a single FM; otherwise the extrapolation of data beyond the duration of the reliability tests is no longer valid. Of course, for such models, the reliability engineer has to perform extensive FA in order to identify accurately the populations affected by each FM. In the last few years, these have been called ‘empirical’ models, because the new tendency at component level is to develop ‘physical’ models; that is, models based on the physical or chemical phenomena responsible for degradation or failure of electronic components and materials (details are provided in Chapter 2, Section 2.3 and in Chapter 5).

However, the ‘statistical’ approach is still used, but mainly for electronic systems, offering the only possible solution for assessing the reliability of such a system. This is so because the ‘physical’ approach is difficult, if not impossible, to use at system level. For example, a PoF-like model developed by for small-scale CMOS was virtually unusable by system manufacturers, requiring input data (details about design layout, process variables, defect densities and so on) that are known only by the component manufacturer [6]. So, in spite of their lower accuracy, ‘statistical’ models (e.g. MIL-HDBK-217) are used to evaluate the reliability of electronic systems.

Obviously, the solution is a unified approach, trying to get the best features of each model. It is easy to say this, but more difficult to accomplish. So, such a unified approach is still a dream. The new tool that has to be created from this new approach must offer the possibility of an interactive design (unlike MIL-HDBK-217 models), allowing a trade-off between the physical performances of the device and the reliability implications thereof [6].

Meanwhile, many models were developed for the PoF of FM in semiconductor technology. No details will be furnished in this section, as Chapter 5 is dedicated to the presentation of the typical FMs for various categories of electronic components. As an example of such models, we note here the important contribution of the CALCE Electronic Packaging Research Center, a research team led by

Michael Pecht of Maryland University (USA); a series of tutorial papers on FM linked to packaging issues were published since 1991 by IEEE Transactions on Reliability.

1.4.4 Future Trends

Today, FA is the key method in reliability analysis. It is impossible to conceive of a serious investigation into the reliability of a product or process without FA. The idea that failure acceleration by various stress factors (which is the key to accelerated testing) could be modelled only for the population affected by a single FM greatly promoted FA as the only way to separate populations damaged by specific FMs.

A large range of methods are now used, from (classical) visual inspection to such expensive and sophisticated methods as atomic force microscopy and scanning near-field optical microscopy. Many others are still waiting to be created.

Recently, through device shrinking and complexity growing, it has become more and more difficult to carry out FA of semiconductor devices. A recent prediction [26] of the Semiconductor Industry Association (SIA), made in the International Technology Roadmap for Semiconductor (ITRS), says that silicon technology will continue its historical rate of advancement predicted by the Moore's law. So the challenges for FA in the next few years will be extended to broad new aspects (design for analysis or design for test; physical limit – tools for chip, tools for package; chip–package co-design; and organisational issues like FA cost and FA cycle time). Above all, it is clear that failure diagnosis and failure position analysis have to increase in accuracy. Hitachi High Technologies, Ltd. has developed an extremely fine SEM-type mechanical proving system [27], for example; a high-precision probe and stage mechanism corresponding to the fine devices, a six-probe mechanism expandable to applications including inverter testing and a high-precision unit transistor testing were all investigated, together with an in-vacuum probing, sample-exchanging mechanism and a computer aided design (CAD) navigation system. As this system was applicable to 65 nm devices, it seems likely it will be possible to apply it to any device of such a scale in the future.

The microsystems are relatively new devices, containing, on a single chip, a mixture of components–a sensor, an actuator (a mechanical component) and the electronics–which creates new challenges for their reliability [28]. The package should protect the chip from an often harsh and demanding environment (as for the 'classical' microelectronic devices: transistors, ICs, etc.), but is also an interface between the sensor and that environment. The small dimensions of the mechanical elements of the actuator produce new FMs and the interactions between mechanical, electrical and material reliability must be taken into account. Moreover, the third dimension (the depth) of the structure cannot be ignored, as occurred for microelectronic devices, where all the simulations are basically two-dimensional. This collection of reliability risks has to be taken into account when FA is performed for any type of microsystem. It should be noted that the subject is common in papers today, but we still have limited knowledge about how microsystems fail. The main explanation is a lack of specific tools for studying microsystems. Fabricating multiple devices on the same chip will have to deal with more FMos. Complex interactions of cross-domain signals, interference and substances induce new FMos and FMs.

Another challenge for FA comes from a new domain, called nanotechnology. Here everything is new and the FMs for nanomaterials, which are different from those for the same materials at micro level, have to be studied. Supplementary issues are induced by organic materials, which is a new trend in this field. Also, at nano level, new techniques for FA have to be created [29]. As one can see, nano-reliability (study of the reliability of nano-devices) offers a huge range of subjects for FA. The near future will see an important step forward in this field.

In conclusion, it is both easy and difficult to predict the future evolution of FA. Easy because everyone working in this domain can see the current trend. FA is still in a 'romantic' period, with fabulous pictures and smart figures smashing customers, convinced by such a 'scientific' approach.

Seldom do these users of electronic components understand the essence of the FA procedure, because the logic is frequently missing. But this situation is only a temporary one. Very soon, the procedures for executing FA will be stabilised and standardised, allowing any user of an electronic component to verify the reliability of the purchased product.

But it is also difficult to predict the evolution of FA, because the continuous progress in microelectronics and microtechnology makes it almost impossible to foresee with good accuracy the types of electronic component that will be most successful on the future market. And FA must serve this development, being one step ahead and furnishing manufacturers with the necessary tools for their researches. However, with sufficiently high probability, one may say that nano-devices (or even nanosystems) will become a reality in the next five years, so we must be prepared to delve deeper into the matter, with more and more expensive investigation tools.

1.5 General Plan of the Book

At this point, having delivered a lot of information about the past, the present and the future of FA, we shall explain to the reader the plan of the rest of the book.

FA is a vast subject, being used for almost all manufactured product. Thus procedures for performing FA have been developed in all technical domains. Obviously, in order to be useful, a book about FA must focus on a limited range of subjects; otherwise it will be impossible for the reader to understand many points. In the present volume, we are firmly focused on *electronic components*, which are, in fact, the domain in which FA was initiated. Of course, *electronic systems* will be discussed too, because their reliability is highly dependent on the reliability of electronic components.

So we have defined the subject, which is still a broad one, but will be comprehensible in a single volume, we hope!

The book is divided into four main parts, providing possible answers to four questions:

- **Why** is it so important to use FA (Chapter 2)? Eight possible reasons are presented: (i) forensic investigation, (ii) reliability modelling, (iii) reverse engineering, (iv) controlling critical input variables, (v) design for reliability, (vi) process improvement, (vii) saving money by early control and (viii) a synergetic approach.
- **When** is it appropriate to use FA (Chapter 3)? It is recommended that FA be used during the whole life cycle of any electronic components, starting with design (based on previous knowledge about FMs of similar or quasi-similar components, as part of the concurrent engineering approach; that is, participation from the first phase until the last one of all persons responsible for product achievement), continuing with prototyping, fabrication and (most importantly) post-fabrication, and on into reliability testing and operational life.
- **How** should FA be used (Chapter 4)? This guide contains a large variety of methods of FA (electrical methods, thermal methods, optical methods, electron microscopy, mechanical methods, X-ray methods, spectroscopic methods, acoustic methods, laser methods and so on).
- **What** is the result of using FA (Chapter 5)? Typical FMs for the most important technologies used for manufacturing electronic components are detailed (silicon bipolar and MOS technologies, optoelectronic and photonic technologies, nonsilicon technologies, hybrid technologies and microsystem technologies). The main technologies are discussed, not the main products, because the FMs are more or less dependent on technologies–and, of course, on the main applications of the products!

Chapter 6 provides 12 complex case studies, covering the main technologies and using various methods of FA. This is a synthesis of the previous chapters, containing some practical lessons about using FA.

Finally, Chapter 7 provides some conclusions, which will be of value to manufacturers and users of electronic components.

The website of the book offers Q&A sessions about each chapter, as an effective learning tool.

The book as a whole aims to serve as a reference work for those involved in the design, fabrication and testing of electronic components, but also for those who are using these components in complex systems and want to discover the roots of the reliability flaws for their products.

References

1. Kirkman, R.A. (1963) Failure concepts in reliability theory. *IEEE Trans. Reliab.*, **51**, 1–10.
2. Motoiu, R. (1994) *Quality Engineering*, Chiminform Data, Bucharest.
3. DeVale, J. (1998) Traditional Reliability, Carnegie Mellon University Internal Reports, Spring 1998, http://www.ece.cmu.edu/˜koopman/des_s99/traditional_reliability/index.html. (Accessed 2010).
4. Băjenescu, T.I. and Bâzu, M. (1999) *Reliability of Electronic Components. A Practical Guide to Electronic Systems Manufacturing*, Springer, Berlin and New York.
5. Nash, F.R. (1993) *Estimating Device Reliability: Assessment of Credibility*, Chapter 6, Kluwer, Boston, MA.
6. Denson, W. (1998) The history of reliability prediction. *IEEE Trans. Reliab.*, **47** (3), 321–328.
7. Kopanski, J., Blackbum, D.L., Harman, G.G. and Berning, D.W. (1991) Assessment of reliability concerns for wide temperature operation of semiconductor device circuits. Transactions of the 1st International High Temperature Electronics Conference, Albuquerque, 1991, pp. 137–142.
8. Pecht, M., Lall, P. and Hakim, E. (1992) Temperature dependence on integrated circuit failure mechanisms, in *Advances in Thermal Modeling III*, Chapter 2 (eds A. Bar-Cohen and A.D. Kraus), IEEE and ASME Press, New York, pp. 61–152.
9. Yates W. and Johnson, R. (1997) Total quality management in U. S. DoD electronics acquisition. Proceedings of the Annual Reliability and Maintainability Symposium, Philadelphia, January 13–16, 1997, pp. 571–577.
10. Ermer, D. (1996) Proposed new DoD standards for product acceptance. Proceedings of the Annual Reliability and Maintainability Symposium, Las Vegas, January 22–25, 1996, pp. 24–29.
11. Demko, E. (1996) Commercial-off the shelf (COTS): challenge to military equipment reliability. Proceedings of the Annual Reliability and Maintainability Symposium, Las Vegas, Nevada, January 22–25, pp. 7–12.
12. Nicholls, D. (1996) Selection of equipment to leverage commercial technology (SELECT). Proceedings of the Annual Reliability and Maintainability Symposium, Las Vegas, Nevada, January 22–25, 1996, pp. 84–90.
13. Schneider, C. The GIQLP-product integrity's link to acquisition reform. Proceedings of the Annual Reliability and Maintainability Symposium, January 13–16, 1997, pp. 26–28.
14. O'Connor, P.D.T. (2000) Reliability past, present and future. *IEEE Trans. Reliab.*, **49** (4), 335–341.
15. Xue, M., Görlich, S. and Quek, J. Semiconductor Failure Analysis for 60 Years and Beyond http://www.semiconsingapore.org/ProgrammesandEvents/cms/groups/public/documents/web_content/ctr_022432.pdf. (Accessed 2010).
16. Henderson, C.L. Advanced to Failure and Yield Analysis. Overview of a two days course organized by Semitracks Inc., www.semitracks.com/courses/fa-course.htm. (Accessed 2010).
17. Altes, A. *et al*. (2008) Advanced thermal failure analysis and reliability investigations–industrial demands and related limitations. *Microelectron. Reliab.*, **48** (8–9), 1273–1278.
18. Bergher, L. *et al*. (1986) Towards automatic failure analysis of complex ICs through E-Beam testing. Proceedings of International Test Conference, Testing's Impact on Design and Technology, Cat. No. 86CH2339-0, Washington, DC, 1986.
19. Cole, E.I. Jr. *et al*. (1994) Novel failure analysis techniques using photon probing with a scanning optical microscope. Proceedings of Annual IEEE Reliability Physics Symposium, pp. 388–398.
20. Sienkiewicz, M. *et al*. (2008) Failure Analysis Enhancement by evaluating the Photoelectric Laser Stimulation impact on mixed-mode ICs. *Microelectron. Reliab.*, **48** (8–9), 1529–1532.
21. Beaudoin, F. *et al*. (2000) New non-destructive laser ablation based backside sample preparation method. *Microelectron. Reliab.*, **40** (8–10), 1425–1429.
22. Aubert, A., Dantas de Morais, L. and Rebrassé, J-P. (2008) Laser decapsulation of plastic packages for failure analysis: process control and artefact investigations. 19th European Symposium on Reliability of Electron Devices, Failure Physics and Analysis (ESREF 2008); Microelectronics Reliability, Vol. 48, Issues 8-9, August-September 2008, pp. 1144–1148.
23. Barberan, S. and Auvray, E. (2005) Die repackaging for failure analysis. *Microelectron. Reliab.*, **45** (9–11), 1576–1580.

24. Infante, F. (2007) Failure analysis for system in package devices using magnetic microscopy. PhD thesis, CNES. http://www.tesionline.com/intl/pdfpublicview.jsp?url=../__PDF/22186/22186p.pdf. (Accessed 2010).
25. Amakawa, S., Nakazato, K. and Mizuta, H. (2002) A new approach to failure analysis and yield enhancement of very large integrated systems. Proceedings of 32th European Solid-State Device Research Conference, Firenze, Italy, September 2002, pp. 147–150.
26. International Technology Roadmap for Semiconductor (ITRS), http://www.itrs.net/reports.html. (Accessed 2010).
27. Munetoshi, F. (2006) Invisible failure analysis system by nano probing system. *Hitachi Hioron*, **88** (3), 287–290.
28. Bâzu, M. (2007) Quantitative accelerated life testing of MEMS accelerometers. *Sensors*, **7**, 2846–2859.
29. Jeng, S.-L., Lu, J.-C. and Wang, K. (2007) A review of reliability research on nanotechnology. *IEEE Trans. Reliab.*, **56** (3), 401–410.