Some Particular Aspects of Manufactured MEMS and their Reliability

(Full text in English)

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Abstract

A scientific and technical revolution has begun that is based upon the ability to systematically organize and manipulate matter on the micrometre length scale. We do not have a great deal of information about the useful life of these sophisticated products even though they are flooding the market. Conventional reliability theories need to be restudied to be applied to micro-engineering. A confident use of these technologies relies on our capacity to better understand their fault mechanisms, and our ability to deduce related fault models

Keywords: MEMS/MOEMS, simulation, reliability, failure, failure mechanisms, lifetime prediction.

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1. Introduction

Micro-electro-mechanical systems (MEMS) are integrated micro-devices or systems combining electrical and mechanical components. MEMS are fabricated using many of the same techniques that are utilised in the ICs domain such as oxidation, diffusion, ion implantation, low pressure chemical vapour deposition (LPCVD), sputtering, etc., and combines these capabilities with highly specialized micromachining processes.

MEMS is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology.

MEMS has been identified as one of the most promising technologies for the 21st century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. These systems can sense, control, and actuate on the micro scale and function individually or in arrays to generate effects on the macro scale.

Although they are built using semi-conductor equipment, MEMS devices, in general, have a completely different set of failure mechanisms (FMs) and reliability concerns than ICs.

The reliability issues concerning on MEMS have steadily developed in recent years.

Knowing the failure modes and FMs (Table 1) of these micro-devices is one of the processes to understand MEMS reliability[1].

Table 1. Examples of MEMS failure mechanisms and accelerating factors (after [18]).

Failure mechanism	*Accelerating factors*	*Additional comments*
Cyclic fatigue	Number of cycles, maximum	Models exist for this failure mechanism in mechanical applied strain, humidity engineering texts and literature, as well as some MEMS structures.
Creep (plastic deformation)	Temperature, applied strain	Well understood materials science field.
Stiction	Humidity, shock, vibration	Difficult to model. Surface conditions are critical.
Shorting and open circuits	Electric field, temperature, humidity	Well understood field, yet the geometries in MEMS and for materials used could make this difficult to model some structures. Again, processing effects can be critical.
Arcing	Electric field, gas pressure, gas composition	Small gaps are prone to this in specific environments. Breakdown voltage relationships should be investigated.

[1] Reliability is the characteristic of a device concerning its ability to achieve specified requirements under well-defined conditions over a given period of time.

Failure mechanism	*Accelerating factors*	*Additional comments*
Dielectric charging	Electric field, temperature, radiation, humidity	Some MEMS structures such as RF MEMS are particularly susceptible to this.
Corrosion	H umidity, voltage, temperature	Polarity is important if accelerating anodic corrosion.
Fracture due to shock and vibration	Acceleration, frequency(resonance), vacuum	Models exist for this failure mechanism in mechanical engineering texts and literature, as well as some MEMS structures. Micro-scale materials properties are needed.

The goal of the reliability process is to understand the effect of design, processing, and post-processing on the device lifetime. That is why issues on MEMS reliability are seeking to discover new methods and technologies to increase the lifetime of MEMS.

Although MEMS technologies and device structures have made significant progress in the past three decades and have found widespread application in many areas, including Micro-Opto-Electro-Mechanical Systems[2] (MOEMS), packaging and assembly techniques suitable for many of these emerging applications have not kept pace.

A variety of MEMS devices have been produced and some are commercially used in industrial defence, information technology, aerospace, automobile applications, and medicine such as digital micro-mirror devices, accelerometers sensors, etc. which were sold annually in millions of units.

These technologies allow numerous novel designs to be developed and will probably have important social, economic, military and environmental applications. Their names and applications are given in Table 2.

Table 2. MEMS component categories based on their applications (after [1])

Name	**Definition**
Micro-sensors	*Devices designed to detect physical or environmental changes*
Infrared sensors, pressure sensors, inertial sensors, gas sensors, accelerometers, gyroscopes, chemical sensors, motion, thermal and optical sensors	
Micro-actuators	*Devices designed to activate or stimulate other MEMS component devices*
Electrostatic actuators, thermal stimulus actuators	
RF MEMS	*Devices used to switch, transmit, filter an manipulate radio frequency signals*
Metal contact switches, tunable capacitors, tunable filters, micro-resonators, RF switches	
Optical MEMS	*Devices to direct, reflect, filter or amplify light*
Optical reflectors, micro-mirrors, optical switches, attenuators	
Microfluidic MEMS	*Devices designed to interact with fluid-based systems*
Pumps, valves, channels	
Bio MEMS	*Devices designed to interact with biological samples such as proteins, biological cells, medical reagents, etc.*
DNA chips, microsurgical instruments, intra-vascular devices, laparoscopic procedures, microfluidic chips	
Power MEMS	*Devices to generate and store on-chip power or energy for portable systems*
Microscale turbochargers, power generators, micro-thrusters	
MEMS-based data storage systems	*Small storage systems with large capacity*
Micro-positioning and tracking devices, optical, thermal or atomic force data tracks	

Reliability issues are becoming increasingly important as MEMS shrink in size and become more complex, because failures are discovered as a later phase of fabrication which causes high costs and waste of manufacturing resources. It is very important to reconsider reliability aspects from the traditional reactive way to the proactive way, and to pay more

[2] The most significant MOEMS device products include waveguides, optical switches, cross connects, multiplexers, filters, modulators, detectors, attenuators and equalizers. Their small size, low cost, low power consumption, mechanical durability, high accuracy, high switching density and low cost batch processing of these MEMS-based devices make them a perfect solution to the problems of the control and switching of optical signals in telephone networks.

attention to the failure physics approach[3].

By understanding these possible failure modes, potential reliability problems can be identified and solved. Material design, characterization, and process evaluation therefore play an important role in assuring product reliability. A general scheme of the methodology for the microsystem reliability issues is given in Figure 1.

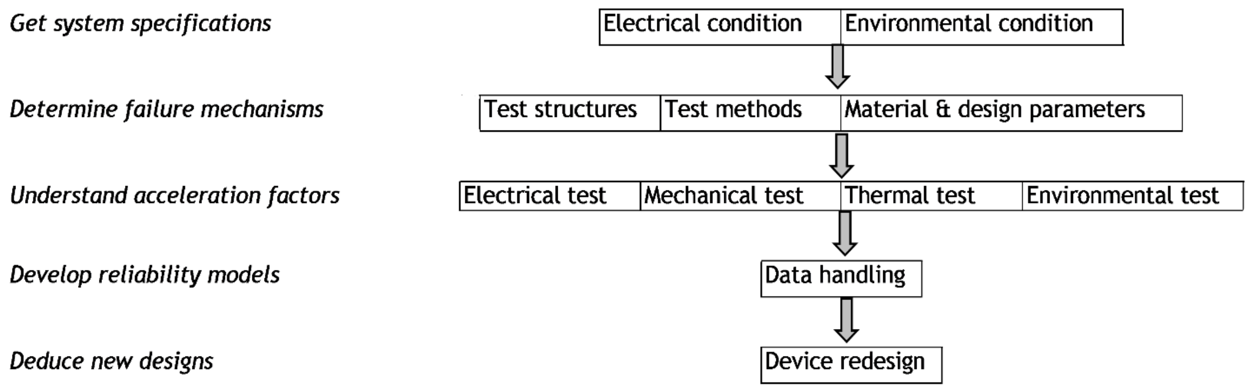

Figure 1. Scheme of microsystem reliability issues analysis methodology (after [1])

2. Applications of MEMS

A MEMS device may find numerous applications across a diversity of industries. For example, the MEMS inkjet printer head nozzle in widespread use today has developed from a nozzle originally used in nuclear separation. Today, high volume MEMS can be found in a diversity of applications across multiple markets.

MEMS has enabled the air bag function to be accomplished by integrating an accelerometer and the electronics into a single silicon chip, resulting in a tiny device that can be housed within the steering wheel column and costs only a few dollars (Figure 2).

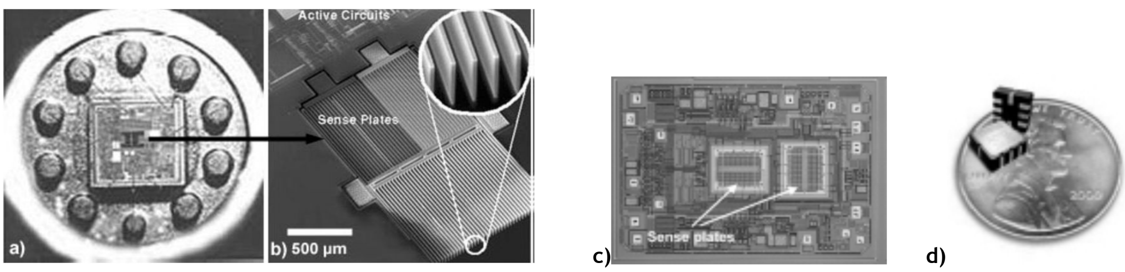

Figure 2. *(a)* the first commercial accelerometer from Analog Devices (1990), its size being less than 1 cm^2 (after [2]); *(b)* capacitive sense plates, 60 μm deep (after [3]); *(c)* modern day MEMS accelerometer; *(d)* the fully packaged device (after [2])

3. MEMS simulation

The evolution of design and simulation tools for MEMS is as varied and as broad as their manufacturing approaches and transduction mechanisms. Cross-cutting many physical domains (including biological, optical, and chemical) design tools and methodologies have focused on the core areas of mechanical and electrical engineering as these fields gave birth to transducers, sensors and more high volume products such as accelerometers, gyroscopes, and pressure sensors that operate electromechanically. Design solutions have matured, but often in diverging directions [4].

Because MEMS/NEMS touch on so many application areas, the ideal simulation tool must follow suite and provide a vast range of coupled multi-domain physical effects. In reality no single tool caters to all the needs of the MEMS community. Hence, MEMS designers carry the burden to find the appropriate tools

[3] This is due to the fact that failure modes are governed by mechanical, electrical, thermal and chemical processes or a combination of them all. Reliability of microsystems is dependent on their structure, material properties, fabrication process, and the life cycle environment.

and strategy for their task. Fortunately, many alternative routes exist to achieve a given goal, but some insight is needed to get the most out of simulators, especially if the target is to use simulation to achieve a design advantage [5].

MEMS simulation tools can be grouped into four broad usage categories:

(i) Circuit and system simulators;
(ii) Domain simulators;
(iii) Simulation drivers (CAD integration and design automation);
(iv) General numerical and symbolic tools.

In contrast, the domain simulation tools address deeper levels of detail, all the way from continuum to atomic resolution. These tools can be categorized according to usage as follows [5]:

- Materials domain simulators,
- Process domain simulators,
- Equipment domain simulators,
- Device domain simulators.
- Environment domain simulators

Discrete MEMS devices are expected to see a continuous incremental increase in performance, and reduction in cost and package size. The greatest challenges for them are related to packaging: decreasing package size while at the same time drastically lowering cost. There are no known solutions to meet the packaging and cost projections out to 2017 [4].

4. 3D integration

In recent years, a new technology referred to as 3D integration has been emerging, in which ICs are stacked vertically with direct electrical interconnects between each IC. The two key process technologies required for 3D integration are the fabrication of through silicon/substrate via (TSVs) and chip-to-wafer or wafer-to-wafer bonding. The bonding provides a mechanical as well as an electrical interconnect between the different chips in the IC stack, while the TSVs provide the electrical interconnects through the chips themselves. Provided that potential yield and reliability issues are addressed, 3D integration offers the benefits of device miniaturization, improved performance, and reduced costs. 3D integration and wafer level packaging (WLP) with through silicon via offer benefits like reduced footprint and improved performance. Also sensor and actuator systems based on micro- and nano-electromechanical systems will greatly benefit from WLP and 3D integration of the transducers and their readout and controller ICs. Ultimately, heterogeneous integration of different device technologies will allow the fabrication of MEMS/IC and NEMS/IC products with new and improved functionalities. For this to become a reality, cost-effective and reliable 3D integration technologies need to be developed.

Another key advantage of 3D integration is the potential for increased functionality. The progress of advanced smart systems relies on the ability to tightly integrate different types of technologies and devices. While Moore's law is all about scaling of traditional ICs and memory chips, functional diversification also called "*More than Moore*" requires the integration of ICs with different types of semiconductor devices like passives, sensors, actuators, bio and fluidic chips [8].

One of the key market drivers for 3D integration of MEMS devices with ICs is portable consumer electronics. Today's cell phones, PDAs and game controllers have functionality based on MEMS devices.

5. FMs and wafer fabrication

In comparison to electronic circuits, these FMs (Table 1) are neither well understood nor easy to accelerate for life testing. It is imperative that the successful design and realization of microsystems or MEMS products must include all levels of packaging and reliability issues from the onset of the project. Besides fabrication related issues, packaging encompasses several other aspects that have also affected the overall manufacturability of MEMS devices. These include:

(i) functional interfacing of the device and their standardization;
(ii) reliability and drift issues;
(iii) hermetic sealing techniques;
(iv) assembly and handling techniques;
(v) modelling issues.

The diversity of MEMS devices and historical reasons have led to scattered developments in the MEMS manufacturing infrastructure. A good manufacturing strategy must include the complete device plan including package as part of the design and process development of the device.

6. MEMS reliability

In today's high-volume semiconductor world, one could easily take reliability for granted, but the study of MEMS reliability and of their physical characteristics is an area that is still in its infancy [9]. However, reliable MEMS exists already and are produced in hundreds of millions MEMS devices and some of them are even intended to use in safety critical applications. The wide variety of materials and physical principles used make it difficult to give general statements about MEMS reliability. However, in several cases reliability is not even studied, confirmed or modelled. Consequently, the lack of long-term reliable devices reduces their level of acceptance considerably. With their extremely low mass and volume, low power consumption and tight integration with electronics, MEMS sensors and actuators are extremely appealing for reducing the size and mass of spacecraft without sacrificing functionality. In view of the harsh and remote environment of space, reliability and qualification is the crucial issues that are holding back MEMS from playing a larger role in space applications.

The fundamental approach to MEMS device reliability employs some of the same basic concepts and methodologies established in high volume automotive and IC manufacturing; including FMEA (failure mode and effects analysis – root cause), DfM (design for manufacturability), DfR (design-for-reliability) and lifetime prediction. A major challenge in MEMS is the shear diversity of potential applications, novel materials and processes, unique sensing and actuation principles, and manufacturing techniques, and hence the focus of this book is on reliability techniques and methodologies as applied to MEMS devices.

Understanding and meeting customer expectations is paramount to building a good relationship. MEMS devices are often uniquely suited to meeting a customer's reliability needs but the challenge is proving it. The digital micro-mirror device (DMD), a digital optical MEMS technology at the heart of DLP® televisions, cinemas, and projectors [10], demonstrates MEMS reliability on a daily basis. DMDs in these applications rarely have even 1 pixel defect through thousands of hours of operation thus demonstrating mirror reliability greater than 99.9999 %.

The reliability issues of MEMS devices are more than a simple combination of electrical reliability, material reliability and mechanical reliability. Fabricating multiple devices on the same chip will have to deal with more failure modes. Complex interactions of cross-domain signals, interference and substances induce new failure modes. For sensor inputs, the chip will have to be exposed to some environmental stimuli, such as heat, humidity, vibration, etc. The input and output voltage may not be within the 5 volts range of standard IC. Some actuators need hundreds of volts to operate. And for microfluidic devices, there might be chemicals and fluids flowing around the chip, with higher potential for corrosion [11].

Microelectromechanical systems are employed in safety critical fields such as automotive, aerospace and medical applications; therefore, their reliability is receiving growing attention. The fact that MEMS structures use not only electrical effects for their operation poses several new reliability issues beyond those well-known problems we can see in IC technology. Since MEMS can have many moving elements, their reliability and lifetime is also a big concern. Stiction, wear, fatigue, thermal degradation and package defects are the most often encountered problems that can significantly affect the lifetime of these structures [12]. However, MEMS behaviour is highly dependent on device design, and those FMs, which have been studied and tested at great length may not apply to all MEMS devices. The ultimate benefit of every work in this field is to find better solutions in future design to maintain longer lifetime and higher reliability in MEMS.

Both wafer fabrication and packaging processes can be contributors to particulate contamination. Not all particles are dangerous to MEMS, however. Electrostatic, capillary, hydrogen-bonding and van der Waals forces contribute to particle adhesion similarly to the way they contribute to stiction forces. However, particle composition, size, roughness, and local environment, also contribute to particle adhesion.

MEMS reliability focuses on mechanical failure modes rather than electrical ones. One major FM is *stiction*, or the tendency of two silicon surfaces to stick to each other. Another concern is *wafer singulation*. Wafer singulation procedures must keep contaminants away from MEMS structures and employ very specialized techniques. *Packaging* is a third concern and is one of the most difficult and expensive to address. Because MEMS devices contain exposed moving parts, they can be made nonfunctional by the presence of liquid, vapour, particles, or other contaminants. Only a few companies have successfully addressed these failure modes and supply reliable commercial MEMS devices in any significant volume.

Stiction is recognized as a major potential FM in surface micro-machined MEMS. Microstructures fabricated by surface micromachining feature large surface areas, small thickness, and gaps, along with dangling chemical bonds on the surfaces. As a result, large adhesion forces form between fabricated structures or between the structures and the substrate when they come in contact [19].

The manufacturing test focuses on deciding whether a device is 'good', i.e. can be shipped to the customer, or 'bad'. The characterization of a device serves the purpose of obtaining a better understanding of its physical behaviour. Although different methods provide detailed information on the behaviour of both fault-free and faulty devices, they are associated with significant cost and are not applicable to volume manufacturing.

In wafer fabrication, stiction becomes an issue during the critical-release phase of the device. For devices released using wet-etches, the surface tension of evaporating droplets can pull two surfaces together, eventually bringing them into contact. Stiction manifests itself as a yield issue to the supplier and a delivery issue to the customer. Manufacturers must develop specialized release processes to solve the problem before they can successfully commercialize a MEMS component. Studying and improving the reliability of the device under test is an important application of the utilized equipment.

Once released, the MEMS device will face shock and vibration during assembly, test, shipment, and operation. MEMS devices are very strong, and their low mass makes them more robust than larger mechanical systems. Still, much of the standard equipment used for die processing and assembly is not optimized to address the shock and vibration environment required by MEMS, as it is of little consequence to ICs. Normal handling can produce hundreds or thousands of Gs of shock anytime the MEMS package comes into contact with another hard surface and can cause surfaces to touch.

In addition, many MEMS devices operate at low resonant frequencies, typically below 1000 Hz. The resonant frequency has a direct relationship to how far a mechanical device will move for a given force. The lower the resonant frequency, the more the device will move. MEMS designers must assume silicon surfaces will touch. Anti-stiction coatings will prevent surfaces from sticking and can be thought of as a passivation method for mechanical devices analogous to the use of oxynitride passivation in the IC world. A robust anti-stiction coating is one of the basic requirements in producing a high-reliability MEMS device.

With the integration of MEMS technology into the microelectronics arena, a number of these standardized reliability tests have been adopted for MEMS reliability testing without the development of appropriate models for the acceleration of MEMS-related FMs. It was found that while mechanical stresses were more effective in inducing MEMS related failures some traditional reliability tests did accelerate MEMS-related failures.

7. Development process of the system reliability

Since MEMS devices are microsystems, the concepts developed by systems reliability engineers apply directly to MEMS. Many of these concepts originated to support the high reliability demands of military electronics. Over the years, commercial products adopted and adapted the concepts to address the increased demand for reliability in the consumer space. Now, the MEMS industry is following the same path by focusing on the methods rather than any specific tests.

MEMS devices require new types of reliability testing. At Analog Devices (Cambridge, MA), are used a series of mechanical tests to confirm resistance to mechanical shock, stiction, and other MEMS-specific failure modes. For example, drop testing is one of the best tools to confirm good mechanical design and stiction performance. Devices are typically dropped from heights of 1 ft to 3 ft onto hard surfaces in a variety of orientations [11].

Following the same path taken in IC technology, wafer level reliability (WLR) has received increasing interest in recent years. Polysilicon is the major material used to construct both the electric and mechanical parts of MEMS devices. It is an ideal material, not only because it is the most abundant solid element in the Earth's lithosphere, but also because of its high strength [13]. Researchers have found that at least presently, material strength is not a key limiting factor in MEMS performance and reliability [14], i.e. fracture, wear and tear of the material are not the dominant causes of MEMS failures. The material can endure sustained high stress so that it can be used in joints, beams and springs. However, failures induced by wear can be found in parts that involve sliding motion and operate in stress [15] [16]. Little evidence was found in support of corrosion wear. Surface fatigue, deformation and impact wear typically require forces in excess of those for abrasive wear. Again, such forces were not applied. Fretting wear occurs where machine elements experience fluctuating loads, leading to micro-cracks and fatigue failure. They have not been observed [16].

The reliability of MEMS has increased rapidly in the past 10 years, with highly reliable micro-machined devices being used by the dozens in modern automobiles, and with MEMS accelerometers and gyroscopes becoming commonplace in many consumer handheld devices. MEMS devices are sold by the hundreds of millions per year [6], with failure rates below *ppm*.

Successfully bringing MEMS-based products to market hinges on engineering the component to have sufficient reliability for the intended application, yet the reliability and qualification methodology for MEMS based products is not widely understood. Companies that have a deep understanding of MEMS reliability because of specific high volume manufacturing experience generally view the details of a reliability program as a competitive advantage and are reluctant to share it.

8. Lifetime prediction

The fundamental approach to MEMS device reliability employs some of the same basic concepts and methodologies established in high volume automotive and IC manufacturing; including FMEA (failure mode and effects analysis – root cause), DfM (design for manufacturability), DfR (design-for-reliability) and lifetime prediction. A major challenge in MEMS is the shear diversity of potential applications, novel materials and processes, unique sensing and actuation principles, and manufacturing techniques, and hence the focus of this book is on reliability techniques and methodologies as applied to MEMS devices.

The lifetime prediction portion of the reliability program is seen in Figure 3.

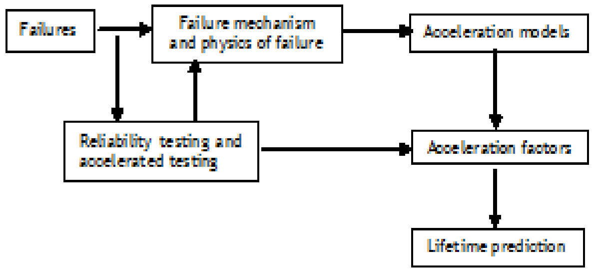

Figure 3. Lifetime prediction diagram (after [7]).

Reliability testing is required to accelerate the lifetime of the MEMS part using acceleration factors, for proper lifetime prediction.

9. Acceleration factors

Reliability testing at accelerated conditions is critical to generating lifetime data in a much shorter period time. Release of a reliable product to market is dependent on this concept. Stresses – such as elevated temperature, temperature cycling, applied voltage or relative humidity – experienced in the use environment are accelerated or increased to a level to accelerate the time to failure of an individual FM. The key is to create the same FM as occurs in use conditions. Development of an acceleration model is performed through knowledge of the PoF; an acceleration factor is calculated as compared to the use conditions. The field of MEMS does not have during history of known models and easily obtained acceleration factors when compared to the more seasoned semiconductor industry. There are examples in semiconductor PoF where many models exist for the same FM; in the case of established models, literature reviews are recommended to assure that the proper model is used[4].

Not included here are extreme use environments such as space. Standards for space missions and other extreme environment MEMS applications exist, yet qualification testing for space is typically mission-specific.

Lifetime predictions require [7]:

[4] To properly use acceleration models and compare to use conditions, operating environment, storage environment (non-operating) and the lifetime of the product must be known.

- Knowledge of environmental (operating and non-operating), lifetime of end product, and manufacturing use conditions such as subsequent processing steps (packaging, printed circuit boards).
- End product packaging and application.
- Customer's acceptable failure rate over the lifetime of the product.
- Stress conditions necessary to identify FMs.
- Acceleration testing and models for lifetime prediction.
- Statistical manipulation of failure distributions in reliability testing.

10. Conclusions

The reliability issues concerning on MEMS have steadily developed in recent years. One of the processes to understand MEMS reliability is to know the failure modes of these micro-devices. MEMS/MOEMS devices are becoming more commonplace every day. Consumers will demand high reliability along with performance and pricing pressure. So far, the industry as a whole has responded appropriately. There are numerous examples of MEMS/MOEMS devices with excellent reliability resulting from well-designed products and well-structured reliability approaches. There is nothing that makes developing MEMS/MOEMS any more challenging than mature technologies other than there are more unknowns to discover. If the MEMS /MOEMS industry continues to use the reliability development methods that have been successfully applied to mature technologies, the journey will continue to be an exciting and rewarding adventure for all involved. There is a continuing need to extend knowledge of the physics of failure in MEMS. Its techniques and microsystem-based devices have the potential to dramatically to affect of all of our lives and the way we live. Extending knowledge of the physics of failure will enable how to improve their reliability and for developing reliability accelerated test methods. It is recognized that there is knowledge for specific devices that resides with companies; however, this knowledge has traditionally been kept secret because it results in commercial advantage.

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12. Biography

Titu Marius I. BĂJENESCU was born in Câmpina (Romania) on April 2, 1933. He received his engineering training at the Polytechnic Institute Bucharest.

He served for the first five years in the Army Research Institute, including tours on radio and telecommunications maintenance, and in the reliability, safety and maintainability office of the Ministry of Defence (main base ground facilities). R&D *Experience*: design and manufacture of experimental equipment for army research institute and for air defence system.

He joined Brown Boveri (today: Asea Brown Boveri) Baden (Switzerland) in 1969, as research and development engineer. R&D *Experience*: design and manufacture of new industrial equipment for telecommunications. In 1974, he joined Hasler Limited (today: Ascom) Berne as Reliability Manager (recruitment by competitive examination). *Experience*: Set up QRA and R&M teams. Developed policies, procedures and training. Managed QRA and R&M programmes. As QRA Manager monitoring and reporting on production quality and in-service reliability.

As Switzerland official, contributed to development of new ITU and IEC standards.

In 1981, he joined "Messtechnik und Optoelektronik" (Neuchâtel, Switzerland, and Haar, West Germany), a subsidiary of Messerschmitt-Bölkow-Blohm (MBB) Munich, as Quality and Reliability Manager (recruitment by competitive examination). *Experience*: Product Assurance Manager of "intelligent cables". Managed applied research on reliability (electronic components, system analysis methods, test methods, etc.).

Since 1985, he has worked as an independent consultant and international expert on engineering management, telecommunications, reliability, quality and safety.

Mr. Băjenescu is the author of many technical books - published in English, French, German and Romanian.

He is university professor and has written many papers and articles on modern telecommunications, and on quality and reliability engineering and management. He lectures as invited professor, visiting lecturer or speaker at European universities and other venues on these subjects.

Since 1991, he won many Awards and Distinctions, presented by the Romanian Academy, Romanian Society for Quality, Romanian Engineers Association, etc. for his contribution to reliability science and technology. Recently, he received the honorific titles of *Doctor Honoris Causa* from the Romanian Military Academy and from Technical University of the Republic of Moldavia (Chișinău). In 2013, he obtained, together with prof. Marius Bâzu (head of reliability laboratory of Romanian Research Institute for Micro- and Nano-technologies – IMT) the Romanian Academy prize "Tudor Tănăsescu" for the book *Failure Analysis*, published by John Wiley&Sons.

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