# Manufacturing, Encapsulation and Reliability of Micro- and Nano-Sensors

Titu-Marius I. BĂJENESCU[1]

[1]Prof. Eng., *Doctor Honoris Causa* of Military Technical Academy of Romania and of Technical University of Republic of Moldova (Chișinău); *Romanian Academy „Tudor Tănăsescu" Prize Laureat*; La Conversion, Switzerland; e-mail: tmbajenesco@bluewin.ch

### Abstract

One of the most common applications of MEMS/NEMS is using them as microsensors and micro-actuators. They have become varied in their applications and can be found almost everywhere in everyday life. The popularity of these microsensors and micro-actuators is mostly due to the great advantages that they possess. In addition to their small size, MEMS sensors and micro-actuators consume very little power and are capable of delivering accurate measurements.

**Keywords:** Microelectromechanical systems, nano-electromechanical systems, manufacturing, packaging, reliability, micro-actuators, microsensors

*Received*: day Month 2019

**To cite this article:**
BĂJENESCU I. T.-M., "Manufacturing, Encapsulation and Reliability of Micro- and Nano-Sensors", in *Electrotehnica, Electronica, Automatica (EEA)*, 2020, vol. 68, no. 1, pp. 21-27, ISSN 1582-5175.

## Introduction

Micro- and nano-electromechanics, optoelectronics, micro- and nano-manufacturing have experienced phenomenal growth in recent years, thanks to the theoretical developments, experimental results, and high-performance computer-aided design (CAD) software. Fundamental conquests and recent applied research in nano- and microelectronics, computer science and nano-technologies have contributed notably to current progress. The synergy between engineering, science and technology is essential to achieving the proposed objectives; and the theories of micro- and nano-electromechanics must be further developed and applied.

## Microelectromechanical systems (MEMS)

Microelectromechanical systems (MEMS) devices are mainly sensors and actuators capable of converting a form of energy into another form. MEMS technologies have been combined with microelectronic and optical systems to form MOEMS micro-optic-electromechanical systems and nano-electromechanical systems (NEMS), integrated together on a single silicon chip.

MEMS technology is advancing, acknowledged and respected by academics, researchers and industry.

However, despite the global recognition they enjoy, the design of MEMS devices is one of the major challenges for the marketing of these devices.

Thanks to the promising technology of MEMS, many MEMS components are manufactured using silicon and its oxides.

To emphasize the importance of reliability, specialists strive to understand the physics and statistics of failure mechanisms as well as possible. Due to the continuous expansion of the MEMS family, the total manufacturing costs, failure rates and performance of these new devices over a time / date range (and therefore, their reliability) are the most significant aspects that can be solved during their manufacturing.

The reliability of MEMS devices is particularly important in applications where the failure rate can be fatal and / or shocking.

A relatively wide spectrum of materials is used to manufacture these devices; materials that show a growing trend - towards a high reliability over a long period of time - are taken as preferred materials, even if the total costs of the device increase.

## Molecular electronics, micro- and nanoelectronics

The difference between molecular electronics, nano and microelectronics is not the size, but the deeply distinct solutions applied to the devices and systems, the physics and phenomena of each device, the manufacturing, and the specific topologies / organizations / architectures.

For example, a field effect transistor with an insulating thickness less than one nm and a channel length below 20 nm cannot be said to be a nano-electronics device, although the thickness of the insulator is sub-nanometric and can use a carbon nanotube with a diameter below one nm) to form a channel.

The three-dimensional molecular topology and atomic aggregated nano-electronics devices synthesized using bottom-up production (quantum approach) have quantum phenomena, and electrochemical-mechanical effects should only be used as only one.

The topology, organization and architecture of three-dimensional molecular integrated circuits are completely different compared to two-dimensional integrated circuits.

## Failure mechanism (FM)

Unlike ICs, MEMS devices contain mechanical devices in motion, and therefore specific techniques and instruments are needed to measure at nano scale mechanical movement in all six degrees of freedom. These tools are used to understand in detail the behaviour of the device (mechanical shock, thermal cycling, number of thermal blanks, etc.) and to provide feedback to the designer in order to improve design reliability and accurately estimate its duration life after the failure mechanism has been identified.

MEMS devices belong to the same family as ICs and may therefore have the same failure mechanism. However, due to their geometry and specific structure, their failure mechanism is due to the complexity of the devices.

We distinguish four MEMS groups:

1. Devices without mechanical parts in motion (microphones, chemical sensors, etc.).

Particle contamination stimulates the failure as it tends to prevent the proper functioning of MEMS. As the devices have micrometric or nanometric dimensions and the contamination is not electrical, it is difficult to detect it. A typical example of contamination is shown in Figure 1.

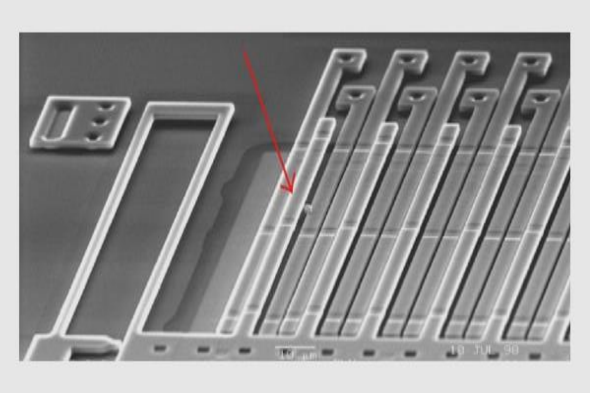

**Figure 1.** Obstruction due to a particle in an inertial sensor (photo by courtesy of Sandia National Laboratories)

As the sensor cannot move, it cannot give rise to an output signal that would be read and amplified by the following circuit [1].

2. Devices with several moving parts and without friction surfaces (accelerometers, gyroscopes, combined devices).

Research has shown that "hinges" and the connection regions of the microgrid are doomed to fatigue (see Figure 2).

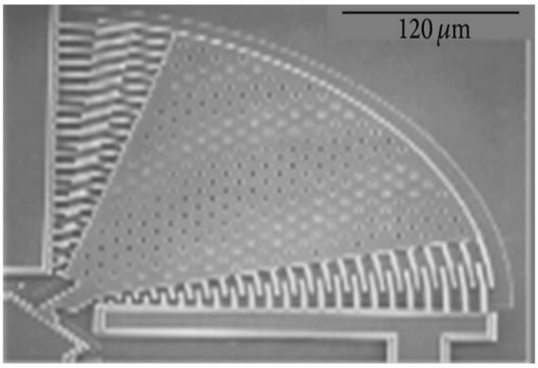

**Figure 2.** MEMS in polysilicon, with "fingers" combined with an anchor notch, powered by static electricity (photo courtesy of Sandia National Laboratories)

3. Devices having moving parts with impact surfaces (thermal actuators, valves, relays, etc.).

They are sensitive to nanoscale "debris" resulting from surface rubbing, fracture of components, cracks, etc.).

4. Devices with moving surfaces that are rubbing against one another (optical shutters, micro-mirrors, etc.).

Moving components create friction and this gives rise to wear material that can cause:

*(1)* damage by particle contamination;

*(2)* particles created by the wear of third bodies that alter the tolerance of movement;

*(3)* adhesion to surfaces in friction or contact.

**Note**: Particle contamination and stiction[1] can cause damage to all types of MEMS.

Therefore, it is recommended that the origin of the fault cause be known before recommending remedies for a particular failure.

Based on the most common generic elements used in MEMS devices, we selected a list of common MEMS degradation/failure mechanisms (see Figure 3).

- Fractures
- overload fracture
- stress fracture

- Creep
- applied stress / solicitation
- intrinsic stress / solicitation
- thermal stress

- Static friction / stiffness
- capillary forces
- Van der Waals molecular forces
- electrostatic forces
- Fixed "bridge"

- Electromigration

---

[1] Stiction is an abbreviation of *st*atic fr*iction*.

- Wear
  - abrasion
  - corrosion
- Degradation of the dielectric
  - leakage
  - loading
  - interruption
- Delamination
- Contamination
- Electrostatic discharge (ESD)

**Figure 3.** Typical/common failure mechanisms of MEMS

### Corrosion

Corrosion has been identified as one of the factors of reliability degradation.

It can cause a mechanical fracture in the form of scratches or cracks, favoured by the environment. Humidity and temperature favours corrosion in metals, such as aluminium, where *stress corrosion cracks* (SCC) occur at the surface of the material in the area of maximum stress. SCC was identified in silicon coated with a fine oxide layer, leading to the initiation of cracks / cracks under the influence of stress variations.

When cracks occur, they interfere with the deep oxides of the structure and cause the crack to grow, until - ultimately - the fracture occurs.

The phenomenon is represented in Figure 4.

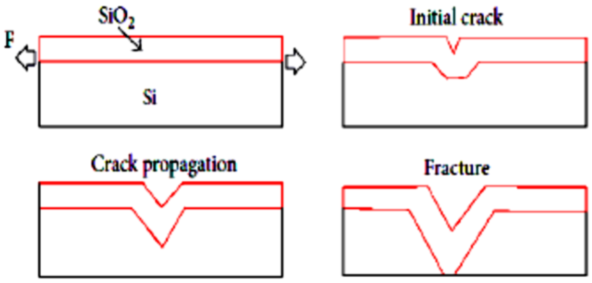

**Figure 4** Formation of SCC in the silicon substrate, subjected to stress (after [2])

### Recent advances

The advances in MEMS technology over the last decades have been the result of communications, medical and automotive innovation, where mass reduction has improved the performance of microsensors and microcontrollers (such as accelerometers for inertial measurements, microfluidic biochips, RF switches, or sensors pressure for automobile winding).

MEMS can be manufactured (see Figure 5) from a wide range of materials (silicon, polymers, metals, ceramics) and use different physical principles (electrostatic, inertial navigation, piezo, optical switches and RF).

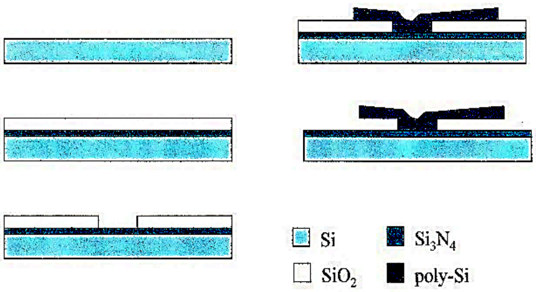

**Figure 5.** Sequence of MEMS / NEMS

The sequence of the MEMS / NEMS manufacturing process uses the same surface structuring and processing methods as those in the classical chip industry. The objective is to build massive parallel, small mechanical devices with high reliability and easy interface with control circuits.

The sensory field resulted from a topic of great interest for a large number of applications in the environment, in the agro-industrial sector for the detection of pathogens and chemicals, and in the medical field for genetic and proteomic detection.

Furthermore, permanent health hazards have raised new issues related to microbial organisms and the spread of infectious diseases requiring their rapid detection and identification.

The design and fabrication of nano-optical plasmonic devices exploit the physical phenomena of plasmons that have the particularity of governing the coupling of light with electrons on the surface of a nanostructured material. Nano-level plasmon control allows for the development of particularly sensitive biological sensors, capable of detecting only a few molecules of DNA.

The Ph.D. thesis [3] deals with the design, manufacture and experimental characterization of plasmon nanostructures used as biosensors.

In order to manufacture Substrates Sensitive to Surface Enhanced Raman Spectroscopy (SERS), which can be used for remote sensing applications, a microfabrication process has been put in place for the easy realization of manufacturable and reproducible devices exploiting various mechanisms of light transmission through grids metal 1D, in order to optimize optical response and device efficacy. In this way, an optimized geometry device was manufactured using electron beam lithography and electrolytic growth, by developing a reliable and easy-to-handle nanoprobe process.

### Nanoelectromechanical systems (NEMS)

Nanodevices are the latest among electronic components, and 'the reliability of nano-devices is still far from perfect,' as noted in an excellent review of nano-reliability [4].

Degradation and FM in micro-technologies (stiffness, friction, wear) have a different physically different at atomic and molecular scale. Of course, the general theory of reliability remains unchanged, but when used at the nano level, a few adjustments must be made.

Also, the use of destructive testing continues [5], but non-destructive testing receives new valences at the nano level.

Assessing the reliability of components, integrated circuits, or micro-assemblies is one of the major factors that make research and development of microelectronics conditional.

Also, the growing penetration of nano-technologies in the markets is conditioned by the rapid demonstration of operational reliability built on the current, particularly demanding standards. This situation requires a specific effort with regard to construction and demonstration of reliability, the primary objective being to guarantee the distribution as close as possible to end-of-life failures.

By definition, the problem of reliability is extremely wide, covering at the same time the problems related to physics and chemistry of materials, electric transport phenomena, thermo-mechanical phenomena, optical / electronic coupling interfaces, statistical models, etc.

The theme of the paper [6] is to present the new reliability assessment approaches; these are based on the combined use of physical fault laws, using behavioural simulations and statistical methods that integrate technological variability to extrapolate fault rates and lifetimes under conditions operation (see Table 1).

**Table 1** – Roadmap for the assessment of nano-devices, based on three fundamental steps (after [8])

| Steps | Objectives | Impact | Instruments |
|---|---|---|---|
| Behavioural analysis under constraints | Identifying and locating constraints<br>* Constraint / component interaction | * Design<br>* Technological choices<br>* Manufacturing processes | * Physical analysis<br>* Physical simulation(local effects)<br>* Functional units<br>* Electrical or optical analyses |
| Modelling degradations | * The law of evolution<br>* Predictive indicators<br>* Failures analysis | * Design<br>* Optimization<br>* Duration of accelerated tests<br>* Estimating lifetime | * Physical analysis<br>* Modelling tools<br>* Test structure<br>* Mixed accelerated aging |
| Demonstration of reliability | * Distribution of failures<br>* Lifetime distribution | * Reliability demonstration<br>* Product qualification | * Accelerated optimization tests |

In NEMS metrology, the problem of reconstructing three-dimensional images at the nano level has to be solved. Also, at nano level, the modelling of materials and structures should be made on new bases.

For nano-devices with medical applications, the reliability requirements are extremely severe. In a nutshell, switching from MEMS to NEMS involves solving complex problems with degradation phenomena. If for MEMS these issues are - in principle - known, new problems arise from NEMS because of [7]:

- Changing the physical and chemical properties of nanostructured materials (modelling of these material properties, from nanoscale to macroscopic).
- Transient defects occur due to reduced noise tolerance at much lower currents and working voltages.
- When using molecular techniques for obtaining nano-devices, aging defects occur.
- Manufacturing defects become more significant at the nano level.

In the analysis of nano-level failures, the main problem is the lack of adequate analytical tools.

The major limitations and prospects for future driven by *industry roadmaps* are discussed in [9], where describes the current state of processes, instrumentation and principles of microelectronic failure analysis.

Special emphasis is placed on the need for a fault isolation methodology, essential for the analysis of failures in integrated nano-devices.

However, in recent years, alongside the effort to develop new reliability analysis tools, various contributions have been reported on the reliability of nano-devices. Bae et al. [10] have provided the basis for the physical modelling of MOSFET devices, starting from the nano-level degradation that occurs in gate oxide defects. The authors investigated the distribution of activation energies of hot electrons and derived a mixed distribution based on physical nano-scale principles.

## MEMS / NEMS encapsulation and device reliability

Encapsulation is Achille's heel in the manufacture of MEMS / NEMS and a major obstacle in marketing them. In addition to the few products currently marketed (e.g. airbag triggers, ink jet print-heads, pressure sensors and several other medical devices), because of high problems, encapsulation is the most important cost element and the main limiting the miniaturization potential.

No MEMS / NEMS device is finished until it is completely encapsulated. Currently, encapsulation is one of the technical barriers that generate long development times and high costs for devices. The encapsulation must take into account:

*(i)* a plurality of design geometries of the constituent parts;
*(ii)* the interfacing of different materials;
*(iii)* inbound / outbound connections;
*(iv)* optimizing all of them for high performance, low cost and very good reliability.

On the other hand, reliability depends on:

*(1)* the mutual compatibility of the different parts, taking into account the desired functionality,
*(2)* the designs and materials from the point of view of the long-term repeatability of the different parts and the precision of the performance.

Reliability testing provides compensation techniques and understanding of catastrophic failure mechanisms in microsystems [11].

Engineers cannot design reliable MEMS / NEMS without first understanding:

*(a)* the many possible mechanisms that can cause structural failures,
*(b)* the performance of these devices and systems.

Not to mention that only design alone cannot guarantee the reliability of the product. It is therefore imperative that successful design and microsystems implementation include all levels of encapsulation and aspects reliability, from design to microsystem realization [12].

In addition to the manufacturing aspects already mentioned, encapsulation also covers other aspects that may affect the entire fabricability of MEMS / NEMS devices.

These are:
*(i)* functional device interfacing and its standardization;
*(ii)* reliability and drift issues;
*(iii)* hermetic sealing techniques;
*(iv)* assembly and handling techniques of devices;
(v) aspects of modelling.

That is why, we are pleased to find today active research and development programs on nano-technology applications in electronic encapsulation, with special dedicated sessions at international conferences; or articles published in reputable journals dedicated to research results, demonstrating the progress and class of these applications.

Unlike ICs, encapsulation of a microsystem is totally different from encapsulation of an IC due to the more aggressive environment that has access to the sensitive part of the stripped chip through the sensor window (see Figure 6).

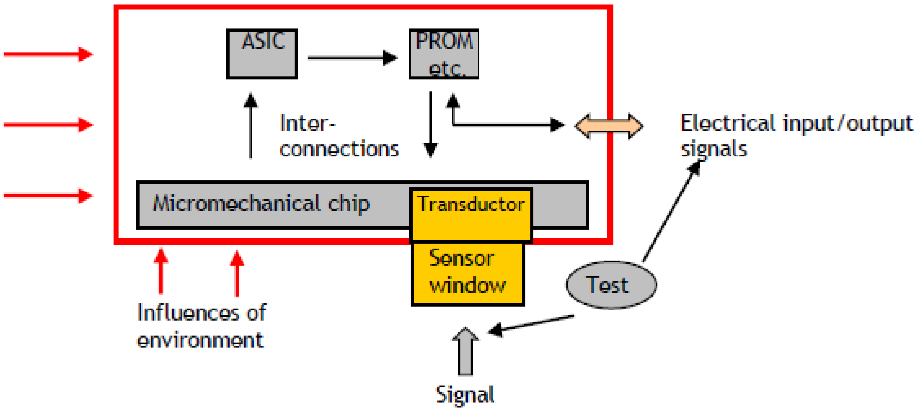

**Figure 6** Typical encapsulation of a sensor microsystem (after [13])

This leads to the application of specific encapsulation and test solutions, which is the current and tomorrow's challenge of MEMS devices [13].

In the past 15 years, the situation of encapsulation has changed dramatically, with the emergence of NEMS sensors, when the scale has shrunk from 1 ... 100 μm to 1 ... 10 nm.

In the coming years, the most important encapsulation activities will focus on *Wafer Level Packaging* (WLP)-*System In Package* (SIP), i.e. integration of different systems into a single capsule (see Figure 7), lead free electrical interconnection, optical interconnection and nano-encapsulation [14-16].

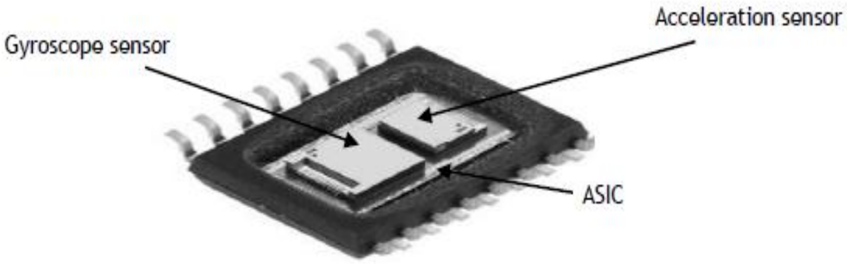

**Figure 7** One example of ”system in package” (SIP)

Encapsulation strategies need to be developed in parallel with core micro- and nano-electronics to make the right decisions on their commercial viability.

Another observation is that, at present, MEMS / NEMS encapsulation research is concentrated in only a few laboratories across the scientific world. Since the reliability of MEMS devices has increased rapidly over the past ten years, these devices are now widely used in dozens of modern automobile brands; accelerometers and gyroscopes are increasingly used in many consumer products.

Statistics say that hundreds of millions of MEMS are sold each year, and their failure rates are only a few ppm.

### Nanofabrication

Among the promising processes of nano-manufacturing are nano-imprint lithography (NIL).

The method offers low costs and high yields, using different materials at just 6 nm.

Thermal NIL is a typical method for NIL; the printing process is based on the use of thermo-plastic polymers and comprises several steps of **a....e**, as can be seen in Figure 8.

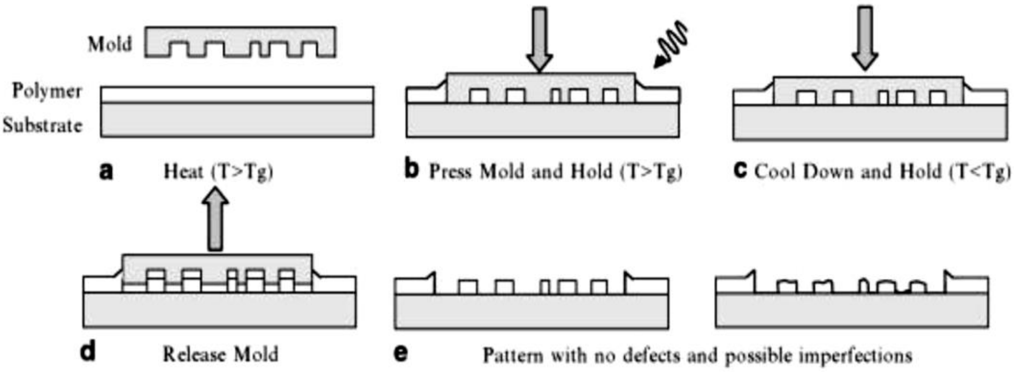

**Figure 8** Typical steps of thermal NIL (after [17])

Important advances have been made in the past decades, ranging from experimental manipulations of a single atom or molecule, to the synthesis and possible applications of carbon nanotubes and nano-wires.

As emerges from the extremely rich literature, nano-device structures provide testbeds for investigating the new physics in a new regime - especially at the quantum level - such as the tunnel effect of a single electron or quantum confinement *Quantum Neighbouring Effect*.

On the other hand, as the size of the device shrinks, traditional top-down micro-processing goes into the nanometric field, and the further diminishing of dimensions will become a defiance, both scientifically and economic. This will motivate researchers across the world to find alternative ways for future growing applications in the field of informatics [19].

All the important objectives of nanoscience depend on the reliability of the fabrication of nano-structures.

The challenges of nano-manufacturing are numerous, starting with the broad spectrum of applications, materials and geometries that have been proposed for nanostructures.

Applications include nano-electronics, nano-photonics, nano-mechanics, nano-antennas, nano-sensors - to mention only a few of the most important.

A difficult number of materials, elements, blends and alloys have been proposed as the subject of nano-structure and nano-manufacturing.

Add to this field, the geometries of nano-structures (disks, holes, pyramids, rods, etc.) and the range of interaction nano-particles that need to be isolated or coupled. Not to mention that random or periodic order of magnitude can be a critical consideration, which can extend in a dimension, in two or three dimensions. You will easily find that this is a daunting task [20-22].

### Conclusions

From a technical and technological point of view, humanity is at the brink of a new era of development - that research scientists, scientists and engineers have been working on over the last decades.

The most important defiance is the reliability of these new devices in order to sell them massively. It has not been for a long time after designing but has to be considered before designing and - permanently - during designing.

In future, the success and fruition of results - starting with the level of devices and ending with circuit and system levels - will depend on the effects of temperature and/or voltage stress on performance, but also on the methods used by designers to build more reliable circuits micro- and nano-technologies.

### References

[1] J. A. Walraven, “Failure Mechanisms in MEMS,” in Proceedings *International Test Conference* (ITC '03), pp. 828–833.

[2] “Metals handbook” (desk edition) chapter 32 (failure analysis), in *American Society for Metals*, vol. 32, pp. 24–26, ASM International, Novelty, Ohio, USA, 1997.

[3] M. Massari, *Design of nanodevices for sensing applications*, Ph. D. Thesis, Università degli Studi di Padova, 2012.

[4] S.-L. Jeng, A., “Review of Reliability Research on Nanotechnology”, *IEEE Transactions on Reliability*, Vol. 56, No. 3, 2007, pp. 401-410.

[5] J. C. Reiner, P. Gasser, and U. Sennhauser, “Novel FIB-Based Sample Preparation Technique for TEM Analysis of Ultra-Thin Gate oxide Breakdown,” *Microelectronics Reliability*, Vol. 42, No. 9-10, Sept.-Oct. 2002

[6] I. Bechou, et al., “Nouvelles approches d'évaluation de la fiabilité: Perspectives pour les nano-technologies, *Journées scientifiques du CNFRS "Nanosciences et radioélectricité"*, Paris, les 20 et 21 mars 2007. http://ursi-france.institut-telecom.fr/pages/pages_evenements/journees_scient/docs_ journees_2007/L_Bechou_JS07.pdf

[7] T.-M. Băjenescu, M. Bâzu, *Mecanisme de defectare ale componentelor electronice*, Matrix Rom, București, 2012.

[8] Bâzu, M, V. Ilian and L. Gălățeanu, "Typical Failure Mechanisms of Microsystem Technology", *12th International Conference on Quality and Dependability* (CCF 2010), Sinaia, Sept. 21-24, 2010.

[9] D. P. Vallett, "Failure Analysis Requirements for Nanoelectronics," *IEEE Trans. Nanotechnology*, Vol. 1, 2002, pp. 117–121.

[10] S. J. Bae, et al., "Statistical Models for Hot Electron Degradation in Nano-scaled MOSFET Devices," *IEEE Trans. Reliability*, Vol. 56, September 2007, pp. 392-400.

[11] S. H. Voldman, *ESD Failure Mechanisms and Models*, Chapter 8, Chichester and New York: J. Wiley & Sons, 2009.

[12] T.-M. I. Băjenescu, "Microsisteme electromecanice (MEMS) și fiabilitate," *Asigurarea calității*, vol. XVII, nr. 67(2011), pp. 24-29.

[13] T.-M. I. Băjenescu, "Grand Challenges and Relevant Failure Mechanisms of Nanoelectronic Devices," *EEA*, Vol. 62(2014), nr. 2, pp. 39-44.

[14] Jakob Janting, *Reliability of Polymer Adhesive and Coating Materials for Microsystem Packaging*, Ph.D Thesis, Aalborg University, Denmark, 2008.

[15] Rao Tummala, *Introduction to System-on-Package*, McGraw-Hill, 2007,

[16] Mats Robertsson, Proc. of *IMAPS Nordic Annual Conference*, Helsingor, Denmark, 2004, pp. 2-24.

[17] Bharat Bhushan, Springer Handbook of Nanotechnology, Springer, 2004.

[18] J. E. Morris (Ed.), *Nanopackaging*, Springer, 2008.

[19] M. Henini, *Handook of Self Assembled nanostructures for Novel Devices in Photonics and Electronics*, Elsevier, 2008.

[20] [19] S. E. Lyshevski (ed.), *Nano and Molecular Electronics Handbook*, CRC Press, 2007.

[21] G. Wiederrecht (ed.), *Handbook of Nano-fabrication*, Academic Press, 2007.

[22] *Micro and Nanotechnologies, European Space Components Information Exchange System*, https://escies.org/webdocument/showArticle?id=1003

[23] A. Arab, Qianmei Feng, "Reliability research on micro- and nano-electromechanical systems: a review," *International Journal of Advanced Manufacturing Technology,* 74 (9-12), pp.1679-1690,·October 2014

## Author' Biography

**Titu 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 Romanian Army Research Institute, including tours on radio and telecom 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 equipments for Romanian 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 emeritus university professor and has written many papers and contributions 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*.

In 2013, he obtained, together with Prof. Dr. Marius Bâzu (head of reliability laboratory of Romanian Research Institute for Micro- and Nano-technologies – IMT*) the Romanian Academy "Tudor Tănăsescu" prize* for the book *Failure Analysis*, published by John Wiley & Sons.