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MEMS MANUFACTURING AND RELIABILITY

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Abstract. Today flexibility means to produce reasonably priced customized products of high quality that can be quickly delivered to customers. The article analyses issues related to physic, able to generating defects, affecting the reliability limits for MEMS (Micro-Electro-Mechanical Systems). The MEMS industry is currently at a much more vulnerable position than it appears, regardless of how wonderful its future may look like. A full understanding of the physics and statistics of the defect generation is required to investigate the ultimate reliability limitations for nanodevices. Biggest challenge: cost effective, high volume production.

Key words: *Process errors, MEMS, optical MEMS, failure analysis, MEMS switches, package cracking, failure mechanisms, reliability, creep, lifetime prediction.*

1. Introduction

In the development of advanced MEMS packaging, the following must be noted and understood: The infrastructure of MEMS devices and MEMS packaging is not well established; MEMS packaging expertise is not commonly available; MEMS packaging is unique and custom-built; MEMS general packaging platform technology is not available; hermetic sealing of the MEMS device is necessary; vacuum packaging is even required for some MEMS devices; vertical electrical feed-through with through-silicon vias (TSVs) is still too costly.

Packaging has often been referred as the “Achilles heel of MEMS manufacturing” and a key bottleneck in the process of MEMS commercialization. Other than the few fully commercialized products (i.e. air bag triggers, ink-jet print-heads, pressure sensors and a few medical devices), packaging constitutes the single largest element of cost and a major limitation to the miniaturization potential [1]. No MEMS product is complete unless it is fully packaged. At present, packaging is one of the major technical barriers that has caused long development times and high-costs of MEMS products. Packaging involves bringing together: *(a)* Multitude of design geometries of the various constituent parts; *(b)* Interfacing diverse materials; *(c)* Providing required input/output connections, and *(d)* Optimization of all of these for performance, cost and reliability.

On the other hand, reliability depends on *(1)* the mutual compatibility of the various parts with respect to the desired functionality, and *(2)* the designs and materials from the standpoint of long-term repeatability and performance accuracy.

Reliability testing provides techniques for compensation, and an understanding of the catastrophic failure mechanisms in microsystems [2][3]. Engineers cannot design reliable MEMS without first to understand the many possible mechanisms that can cause the failure of the structure and performance of these devices and systems. And design alone cannot ensure the reliability of the product. 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; and *(v)* modelling issues.

A further challenge is to fabricate more devices than manipulation can facilitate. For this purpose, a parallel integration method is required that can facilitate wafer scale fabrication. This could be in-situ growth, where the nanotube is synthesized from a catalyst particle that already has been placed at the desired position in the microsystem. This has been investigated by developing and fabricating microsystems with integrated catalyst particles and by constructing and optimizing a chemical vapour deposition system for nanotube growth [4]. The fabrication techniques are essentially two dimensional while the third dimension is created by layering. MEMS components by their very nature have different and unique failure mechanisms than their macroscopic counterparts [5].

The manufacturing methods used to fabricate these devices are highly sophisticated and rely heavily on a key processing technique called photolithographic patterning. This methodology has come to dominate the technologies of microfabrication in much the same way as silicon has the materials used to construct semiconductor devices [6].

2. Process errors

The main possible process errors are: (i) Faults in the seal glass (cracks, voids or migration), leading to leakage − intermittent or open circuit − to be identified by stress tests (seal, electrical, high temperature storage, temperature cycling and high voltage tests). (ii) Incomplete hermetic seal (for metallic or ceramic packages), producing characteristic degradation or short circuit due to chemical corrosion or humidity. A seal test is needed to identify the failure risks. (iii) Dielectric particles floating in the package that may produce intermittent or short circuit. The recommended stress sequence for eliminating these failures is: constant acceleration, vibration (monitored), radiography, and shock (monitored) test. (iv) Broken or bent external lead, which leads to open circuit and can be identified by visual inspection followed by lead-fatigue test.

3. About mems

Manufactured by integrated circuit (IC) compatible batch-processing techniques, they are integrating electrical components (sensors, ICs), mechanical components (actuators), optical and fluidic components.

Variants of MEMS: MOEMS (micro optical electro mechanical systems), or BioMEMS (biological MEMS - aimed to manipulate biological matter in order to analyzing and measure its activity).

Electronics-only devices	MEMS
Design methodology focused on fast manufacturing cycles (accelerated testing).	New devices, without a history allowing to design accelerated testing.
Optimized standard processes, high yields.	The processes are not standardized.
The third dimension of the structures may be ignored.	The third dimension (the depth) of the structure cannot be ignored.
Designers rarely know details about the manufacturing processes.	Designers must know details about the manufacturing processes (electronic / mechanical devices).
Package should separate the chip from the environment. Standardized cases.	Package should form a cheap but reliable interface between the active device and an often harsh, demanding environment.
Reliability problems are well-known.	New failure mechanisms (small distances between various functional elements, new phenomena).

A typical microsystem contains, on a single chip, a microsensor, a microactuator (a mechanical component) and the necessary electronics, so one may say that a microsystem has “eyes” (microsensor), “arms” (microactuator) and a “brain” (electronics).

Microsystems (MEMS) - relatively new devices, being developed at the end of 1970s, but not commercialized before the 1990s. Basically, there are: biomimetic microsystems (built on principles imitating the basic principles of the living matter) and intelligent microsystems (fulfilling various functions, such as: sensing, processing and/or actuating, and combining two or more operating modes: electrical, mechanical, optical, chemical, biological, magnetical, etc., integrated in a single structure or a hybrid one).

4. Optical mems

Optical MEMS or Micro-Opto-Electro-Mechanical Systems (MOEMS)4 are a marriage of three technologies: (i) Optics (reflective, refractive, diffractive, wave guiding); (ii) Semiconductor devices (optoelectronic III-V devices, Si-CMOS processing and control electronics); (iii) Semiconductor-based micromachining (lithography deposition, epitaxy, etching) [7]. Similar to optical MEMS devices, there is no single standard processing technology for optical MEMS fabrication. Silicon based optical MEMS is dominant materials system and different micromachining processes are being used as the most appropriate fabrication techniques. Also, conventional IC processes (lithography, depositions, implantation, dry etching, etc.) are often used in microstructure formation.

MOEMS are promising for many optical components. Three-dimensional (3D) MEMS optical switches are attracting great interest as large-scale all-optical switching fabrics because of their great potential to lower cost, reduce power consumption, and provide compactness and high optical performance. Several MEMS optical switch fabrics have been reported and received with keen interest [8, 9].

The optical communications market has now clearly embraced wavelength selective switch (WSS) technology for ROADM and ring/mesh interconnect applications [10]. While the drivers for more agile optical networks are now well understood, the initial design-in

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[4] The most significant MOES device products include waveguides, optical switches, cross connects, multiplexers, filters, modulators, detectors, attenuators, and equalizers. The 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.

process for WSS-based modules posed many uncertainties and concerns due to use of long free-space paths, unproven MEMS technology, and significantly increased levels of functional integration. The manufacturing of a complex optical assembly such as a WSS can be very difficult, because of the large number of degrees of freedom in the alignment and the large number of parameters to be optimized (wavelength, channel spacing, insertion loss of up to 10 ports, etc.). To have a commercially viable product, it is essential to minimize the use of skilled labour and maximize the yield of the manufacturing process [11].

Creep and fatigue are more important concerns in metal MEMS than in brittle silicon MEMS, and more so when the melting point of the structural metal is relatively low, like in aluminium devices.

Utilization of optical fibre as the signal transmission medium and in some conditions also as a sensor, allows taking advantage of its properties such as: electromagnetic noise immunity, low signal loss, galvanic insulation, relatively low mass and dimensions [12]. Optical fibres can guarantee safety of the maintenance and test crew, by full isolation from the object; the electromagnetic noise immunity of this sensor is an advantage.

CMOS technology on silicon is the dominating technology for microelectronic systems. Figure 6 shows a technology landscape until the year 2015 to give an overview about the whole area of potential technologies for information processing. Apart from solid-state nanoelectronics other technologies such as optoelectronics, super-conductive and molecular electronics are depicted.

A wrong output signal produced by a defective system is called an error. An error is an effect whose cause is some defect. Errors can be classified into three main groups [13]: permanent, intermittent, and transient errors (the last ones are temporal single malfunctions caused by some temporary environmental conditions which can be an external phenomenon such as radiation or noise originating from other parts of the chip) [17].

Environment / packaging related effects

Humidity effects, out gassing, and residues from die attach and lid attach processes. Packaging and environment are critical elements in life cycle reliability for switches, due to the surface dominated nature of MEMS devices. Humidity may also have a strong effect due to the scaling of capillarity forces at small dimension. Electrostatic Discharge Events could also impair the reliability of micro gap based devices [7].

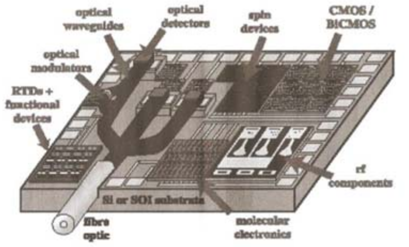

Figure 1. Example of nanocomponents intended to be integrated in a System-on-Chips (SoC).

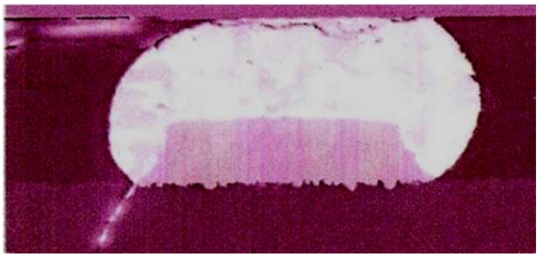

Figure 2. Fatigue cracks at the flip-chip interface.

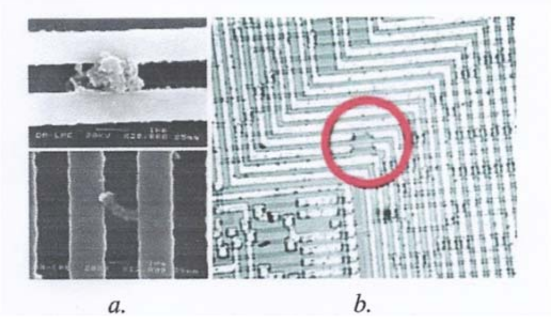

Figure 3. Defect images: *(a)* Bridging defects with low-resistance electrical behaviour on the top and high-resistance electrical behaviour on the bottom microphotograph, and *(b)* Open defect inside the circle [20].

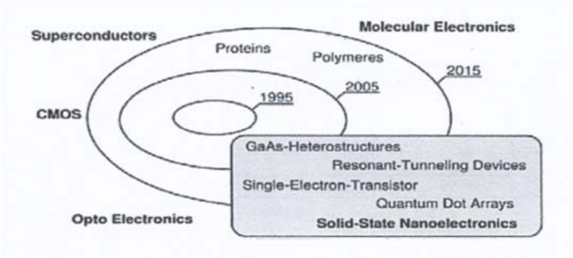

Figure 4. Landscape of different technologies for future information processing [23].

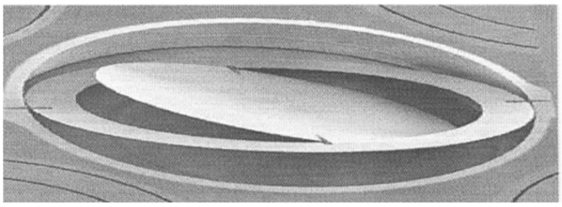

Figure 5. Micromirror (after [6]).

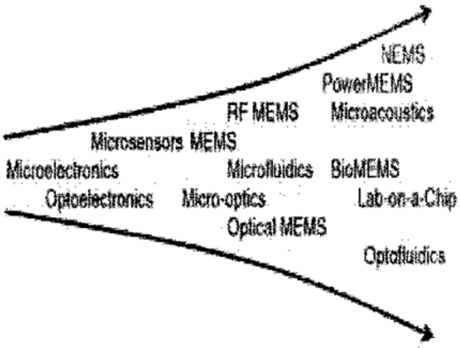

Figure 6. Evolution of microtechnology.

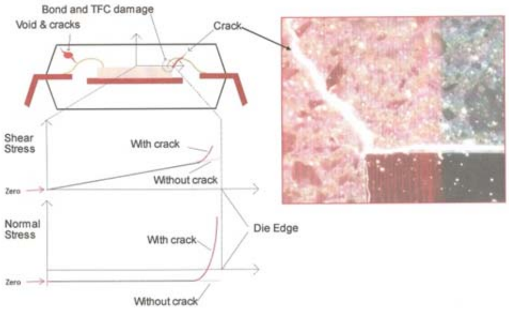

Figure 7. Cracking due to temperature cycle.

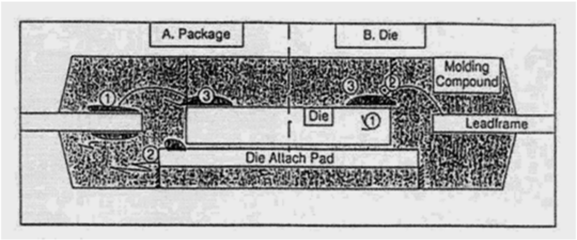

Figure 8. Moisture induced failures.

5. Mems switches

MEMS switches use mechanically moving parts to physically vary the distance between two conductive elements of a signal line in order to make or break an ohmic contact1 (in the case of ohmic switches), or to increase or decrease the enclosed capacitance (in the case of capacitive switches). Since as early as 1971, when the first RF switches were built using commercial technologies, the designs have developed and improved dramatically. The newest switches that are manufactured and tested today, using MEMS technology, operate at radio, even microwave frequencies. Designers are approaching the optimal MEMS switch, yet electro-thermo-mechanical (ETM) effects still limit the design possibilities and adversely affect reliability of the microswitches.

An optimal RF MEMS switch is one with low insertion loss, high isolation, short switching time, and operational life of millions of cycles. The ETM effects are a result of Joule heat generated at the microswitch contact areas. This heat is due to the current passing through the microswitch, characteristics of the contact interfaces, and other parameters characterizing a particular design. It significantly raises temperature of the microswitch, thus affecting the mechanical and electrical properties of the contacts, which may lead to welding, causing a major reliability issue. Reliability issues started to become a serious burden in the early 2000's and actual roadblock toward commercialization. From the beginning, very deep studies have been done in order to understand the different physics of failure occurring during device lifetime. The main reliability problems were found out to be dielectric charging, contact degradation, fatigue and stress control in the movable membranes. The results of the deep investigation in failure mechanisms of RF-MEMS have resulted in the development of materials tolerant to dielectric charging or contact degradation. Despite all these efforts, RF-MEMS are still struggling to reach the mass-market since these failure mechanisms can only be minimized and not avoided even in optimized materials. At this moment, the research community is facing the problem from another perspective: if you cannot solve the problem, remove its cause. This approach takes into account the failure mechanisms and its effects at the very beginning of the device conception. This approach is denoted as "Design for Reliability" [2, 17].

6. Package cracking

Generally, most cracks will start from the die pad area to the bottom where the resin strength is the weakest. Under some conditions, however, cracks may develop in the direction of one side or both sides, or may develop upward; in other cases, package cracking may not occur particularly on thin packages, but the bottoms of these packages may be swollen, and soldering errors may occur.

When gradually increasing the stress in a film attached to a substrate and given that the interface fracture toughness is high enough to prevent delamination, the film will fail by the formation of a number of cracks propagating from the surface to the interface and subsequent channelling across the film. The crack interaction distance depends on the elastic mismatch coefficient. Thin film cracking (TFC) can be detected electrically by test structures in the corner of the die; it is sensitive to opens and shorts. See Figure 9, where passivation delamination crack propagates into substrate. Figure 9 shows the delamination

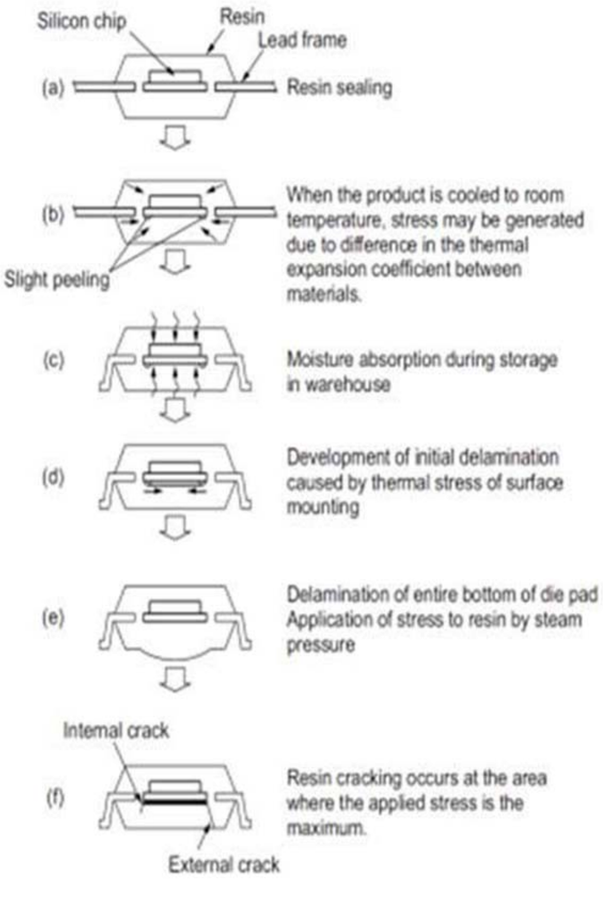

Figure 9. Mechanism of package cracking [14].

at the die edge after 168 hours of steam.

To fully utilize mechanical performance of thin films, optimize MEMS device design, enlarge suitable material range, and enhance reliability of MEMS devices, it is crucial to grasp the relationship between manufacturing technique and mechanical properties. It is significant to control the mechanical parameters of thin films, such as residual stress, Young's modulus, and Poisson's ratio, in surface micromachining process.

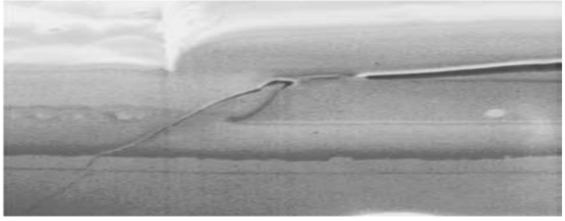

Figure 10. Thin film cracking TFC [33], (Courtey: K. Hayes, Intel).

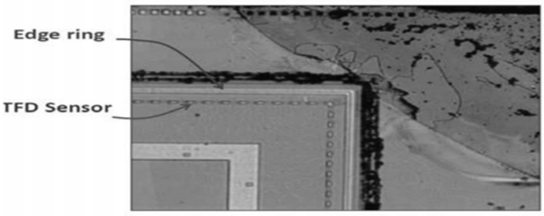

Figure 11. Delamination at die edge after 168 hours of steam [33]. (Courtesy : C. Hong, Intel).

6. Yield and reliability

Yield and reliability are perhaps two of the most important aspects for the development of a new technology. Yield is defined as the probability of failure of an as-processed device, while reliability is defined as functional failure of the device during its operation (for t > 0). A process with low yield (due to various extrinsic defects) is unacceptable to begin with, but even a process with high yield (low initial defects) but relatively large degradation rates (poor reliability) is unacceptably expensive in the long term. For MEMS, reliability of various components is an issue of major interest since they are expected to function without failure for a long period of time (e.g. ten years or more) under extreme operating conditions.

7. Reliability aspects of mems and rf microswitches

MEMS are integrated micro-scale systems combining electrical, mechanical or other (magnetic, fluidic / thermal / etc.) elements typically fabricated using conventional semiconductor batch processing techniques that range in size from several nanometers to microns or even millimeters. These systems are designed to interact with the external environment either in a sensing or actuation mode to generate state information or control it at a different scale. In recent years, MEMS technology has gained wide-spread acceptance in several industrial segments including automotive, industrial, medical and even military applications. Figure 12 illustrates the functional block-diagram of MEMS.

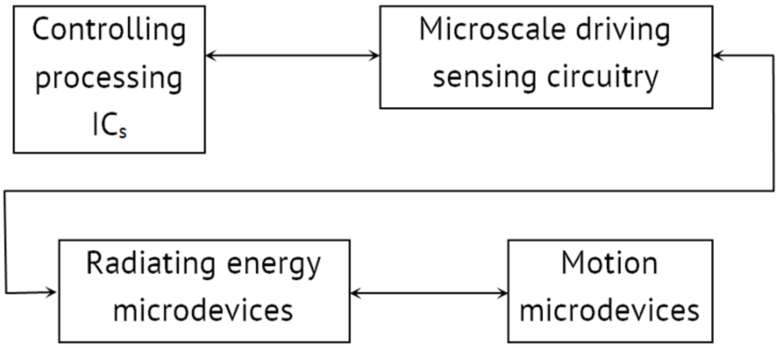

Figure 12. Functional block-diagram of MEMS.

Reliability of MEMS is a very young and fast changing field. Key benefits of MEMS devices include miniature size, light weight, high resonant frequencies, short thermal time constant, and the capability to integrate with microelectronics. Given the wide interdisciplinary behaviour of MEMS and RF MEMS devices, the aspects to be faced as well as the knowledge required to handle their development are multiple, regardless of the specific phase – design, simulation, fabrication, testing – one is dealing with.

8. Failure mechanisms

All failure mechanisms (FMs) have the causes in the design of the device (choice of materials, layout drawing, process/control elaboration, testing/reliability issues, etc.) and in the fabrication process (including here control, testing and reliability as monitored operations).

In general, there are three kinds of failure mechanisms for MEMS devices: process related failure mechanisms, in-use failure mechanisms, and packaging related failure mechanisms. The failure mechanisms (process which leads to failure) that have more importance in RF MEMS are charging of dielectric, creep, plastic and elastic deformation, structural short, capillary forces, fusing, fracture, dielectric breakdown, corrosion, wear, equivalent DC voltage, Lorenz forces, whisker formation, fatigue, electromigration and Van der Waals forces. All these mechanisms are caused mainly by the device thermal budget (during manufacturing and in working stage) and the device working environment (humidity, contamination, etc.) [14, 15]. A list of common degradation/failure mechanisms of MEMS is given in Table 1 [16].

One of the most important and almost unavoidable problems in MEMS is stiction. MEMS structures are so small, that surface forces can dominate all others, and cause microscopic structures to stick together when their surfaces come in to contact. The most important surface forces in MEMS are the capillary force, the molecular van der Waals force, and the electrostatic force.

Table 1.

Examples of MEMS failure mechanisms and accelerating factors

Failure mechanism	***Accelerating factors***	***Additional comments***
Cyclic fatigue	Number of cycles, maximum applied strain, humidity	Models exist for this failure mechanism in mechanical engineering texts and literature, 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 gas composition	Well understood field, yet the geometries in MEMS and materials used could make this difficult to model for some structures. Again, processing effects can be critical.
Arcing	Electric field, gas pressure	Small gaps are prone to this in specific environments. Breakdown voltage relationships should be investigated.

Table 1 continuation

Table 1. Continuation

Dielectric charging	Electric field, temperature, radiation, humidity	Some MEMS structures such as RF MEMS are particularly susceptible to this.
Corrosion	Humidity, voltage, temperature	Polarity is important if accelerating anodic corrosion.
Facture 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 failure mechanisms encountered during testing were the break of bias line, stiction and open circuit. The bias line used to break when the bias voltage was large and the thickness of metal layer very thin.

A bad fabrication process release or contamination may result in a short circuit between bias line and RF lines allowing the current through the circuit. The bias line then evaporates because of its low thickness and the circuit remains open in the end. The stiction is almost predictable since the release voltage decreases before ending in stiction of the switch. The problem has been partly solved designing robust micro-switches with large restoring force.

The switch may end in open circuit if the first metallization is not thick enough. In the ohmic contact area, where the top electrode goes down to the bottom electrode, an impact is left on the bottom side. After numerous impacts, the material is removed and a hole will remain instead. This ends in an increase of contact resistance until no material remains, leading in open circuit.

Each classification of MEMS [17] has failure mechanisms associated with it. Some are specific to that category of devices, while others overlap with other categories of devices.

In paper [18], is showed that substrate charging is another possible failure mechanism limiting the lifetime of capacitive RF MEMS switches. Switches fabricated on different substrates can exhibit a different lifetime. Also, the influence of environmental conditions on the lifetime can depend on the type of substrate. In addition, is showed that switches actuated with an actuation voltage below pull-in voltage can pull-in after some time due to charging of the substrate.

Table 1 gives some examples of MEMS failure mechanisms and accelerating factors [8].

Table 2 gives some application areas for RF MEMS.

Table 2.

Application areas for RF MEMS

Application area	***Frequency range***	***Utility***	***Required cycles***
Defense	5 … 94 GHz	Phase shifter for satellite based radars Missile system radars Long range radars	20 billion 0,1…1 billion 20…100 billion
Automotive	24, 60, 77 GHz	Radars	1…2 billion

Table 2. Continuation

Satellite comm. Systems	12…35 GHz	Switching networks with 4x4 and 8x8 configurations and reconfigurable Butler matrices for antenna applications Switching filter banks Phase shifter for multi-beam	0,1 million 0,1…100 million 10…20 million
Wireless comm.. Systems	0,8 … 6 GHz	Switching filter banks for portable units Switching filter banks for base stations General SP2T to SP4T switches Transmit/receive switches Antenna diversity ST2T switches	0,1…1 million 0,1…10 billion 0,1…10 billion 2…4 billion 10…100 billion
Instrumentation systems	0,01 … 50 GHz	High performances switches, programmable attenuators, phase shifters for industrial test benches	20…40 billion

Reliability issues studied in the dissertation [11] regard mechanical creep and acceleration factors. The mechanical creep occurs in our suspended structures whilst enduring a constant force; it results in deformation of structures and shift of parameters.

9. Creep

Creep is known as a failure mechanism in macroscopic mechanical structures, with more impact on flat and thin surfaces. The idea of dissertation [11] is to make an analogy between macro and micro scales and infer if there is a good agreement that can be used to predict lifetime of micro-switches. Creep and fatigue are more important concerns in metal MEMS than in brittle silicon MEMS, and more so when the melting point of the structural metal is relatively low, like in aluminium devices.

Temperature is an important matter regarding the impact of creep. Basically, creep is accelerated with temperature. Every material that has a large thermal expansion coefficient or a low melting point will not be suitable candidates for RF-MEMS. To reach the requirements of electronic circuits that must handle a temperature about 85°C, materials have to be carefully selected. Moreover, even without being under stress, the switch may have an off-state capacitance that varies just because of temperature. Compared to macroscopic mechanical devices, MEMS are less sensitive to fatigue phenomena, but more sensitive to mechanical creep [12]. Creep occurs in MEMS because of the large ratio between surface and thickness, whereas fatigue occurs for thicker structures where the cyclic stresses create fatigue cracks on the surface and then propagate inside the structure. In normal operation, MEMS bend when a constraint is applied on the structure. Locally, atoms move according different mechanisms of creep that depend on constraint, temperature and time [12]. To reach this mode the factories generally do a burn-in so as to control the ageing of their products. And finally, the tertiary mode leads to the rupture of the structure and its mechanisms may be numerous and complicated. The typically curve of deformation of a microstructure under constant constraint and temperature over time is given in figure 13.

Creep phenomenon is associated with some types of mechanism involved at grains, molecular and atomic scales. Depending on temperature and stress, these reactions are preponderants or not. The secondary mode has the longest duration (not truly representative in figure 13). Less the activation energy is and more the structure will be susceptible to temperature, leading to big deformations [19]. In macroscopic structures, creep is divided in two families, one is related to dislocation glide and the other is related to diffusion of defects.

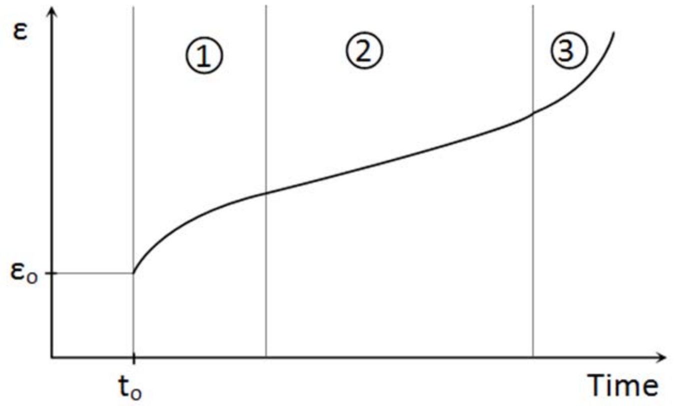

Figure 13. The typical curve of strain versus time to represent creep behaviour at constant constraint and temperature. Creep is divided in three regimes.

Table 3 syntheses MEMS failure modes and underlying causes, with examples. Often MEMS processes are not very mature, so that disregarding process induced spread and the effect it has on reliability will hamper efforts to determine the influence of stress conditions on devices.

Table 3.

Reliability issues in MEMS structures

Failure mode	*Underlying causes / Examples*
Mech. Facture and creep strength	Mechanical stress above yield Fatigue (prolonged cycling) Intrinsic mechanical stress Thermal fatigue
Degradation of dielectrics	Dielectric charging Breakdown Leakage
Stiction	Van der Waals forces Capillary forces
Wear	Adhesion Abrasion Corrosion
Delamination	Loss of adhesion between material interfaces
Environmentally induced	Vibration Shock Humidity effects Radiation Particulates Temperature changes Electrostatic discharge

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

11. Wear

Wear is associated with rubbing and impacting surfaces in MEMS devices. There are mainly four main causes of wear: adhesion, abrasion, corrosion, and surface fatigue.

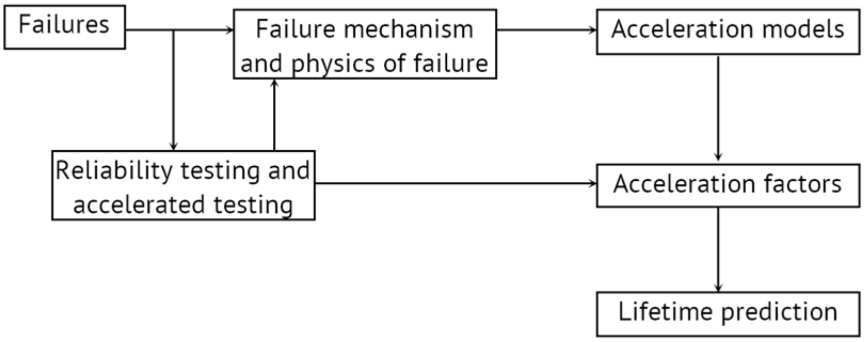

Figure 14. Lifetime prediction diagram (after [32 and 20]).

12. Evaluating the reliability

Potential reliability problems can be identified and solved by understanding the possible failure modes. 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 15.

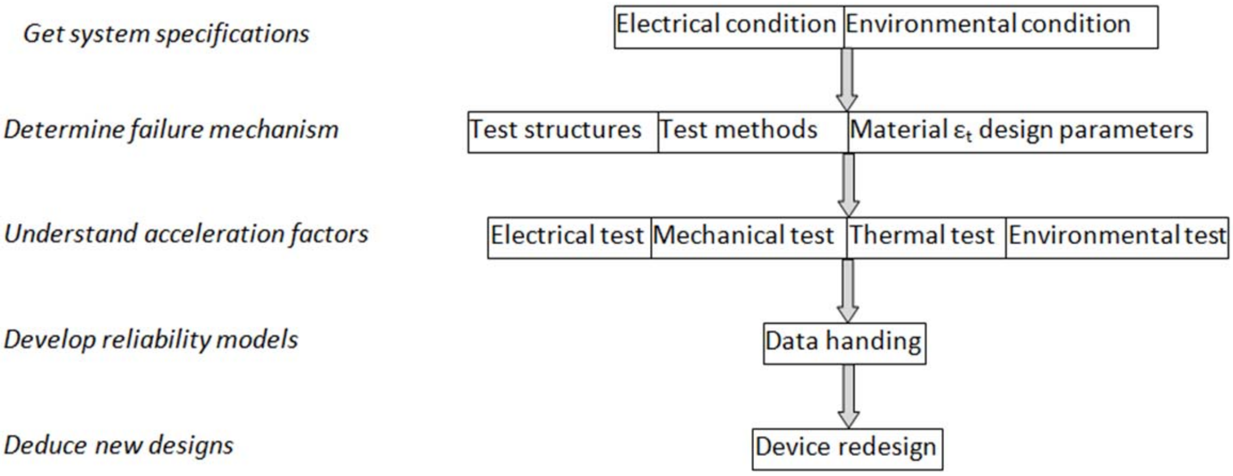

Figure 15. Scheme of microsystem reliability issues analysis methodology (after [21]).

In a reliability sense, components can be treated as fractions of the product and in most cases as links in a chain. The failure rate of a product is equal to the sum of the failure rates of its components. The more components used in a product, the more reliable each one must be. Therefore, for a reliable product, defective, weak or out of specification components must be weeded out. This is done by functional testing, stress testing and by burn-in, i.e. time testing until past the infant mortality period. The adequacy of the testing procedures and the conformance to them, staff training, and the equipment used all affect reliability.

Two procedures were proposed for evaluating MEMS reliability:

- To evaluate the reliability of a Virtual Prototype, i.e. simulating the dependence of the reliability level on device structure and process parameters;
- To shorten the test time by using accelerated testing, this means to test the components at higher values of stress as those encountered in normal functioning, in the aim to shorten the time period necessary to obtain significant results. *Caution:* The failure modes / mechanisms at high stress must be the same as at normal stress!

These two solutions are complementary, because the estimations made on a Virtual Prototype has to be verified by the accelerated testing.

An accelerated test is useful only if, under the accelerated conditions, the item passes through *all* the same states, in the approximately *same* order, as may expected in normal use, but in a much *shorter* period of time.

MEMS: Top five failure mechanisms (production) by device type

Actuators	Sensors	Integrated systems	Passive Elements
Stiction	Electric short/ open	Temperature	Contamination
Wear	Leakage	Contamination	Package stress
Electric short/ open	Package stress	Clogging	Electric short/ open
Package stress	Contamination	Package stress	Crack propagation
Contamination	Crack propagation	Leakage	Deformation

Failure analysis is essential for accelerated life testing: *(a)* An understanding of the anticipated failure mode(s) / mechanism(s); *(b)* Knowledge of the magnitutde of the acceleration of each failure mechanism, as a function of the accelerating stress (ALT models).

13. Failure analysis (FA)

FA plays a very important role in the semiconductor industry in enabling timely product time-to-market and world-class manufacturing standards. Today ICs contain transistors having minimum geometries of 90 nm, but the industry is now rapidly moving into the 65 nm technology node. The actually chips contain hundreds of millions of transistors and operate at frequencies greater than 5 GHz. In general, the investigation of failures is a vital, but complex task.

From a technical perspective, failure can be defined as the cessation of function or usefulness. It follows that FA is the process of investigating such a failure. FA is an investigation of failure modes and mechanisms using optical, electrical, physical, and chemical analysis techniques. A number of tools and techniques enable analysis of circuits where, for example, additional interconnection levels, power distribution planes, or flip chip packaging completely eliminate the possibility of employing standard optical or voltage contrast FA techniques without destructive deprocessing [25, 26]. The defect localization utilizes techniques based on advanced imaging, and on the interaction of various probes with the electrical behaviour of devices and defects. In the recent years, various contributions to the reliability of nanodevices have been reported [27] provided basic physical modelling for MOSFET devices based on the nanolevel degradation that takes place at defect sites in the MOSFET gate oxide. The authors investigated the distribution of hot-electron activation energies, and derived a logistic mixture distribution using physical principles on the nanoscale.

The final chip yield is governed by the device yield. A recent research paper [28] demonstrates that once the major cause of failure is somehow identified or assumed, one could use a Monte Carlo method to study yield problems. Unlike Monte Carlo methods, it produces accurate results even when the probabilities of interest differ from one another by many orders of magnitude. The method proposed in [28] was applied to the analysis of the leakage current distribution of double-gate MOSFETs; the microscopic failure mechanism was identified that limits the final yield. It explains experimental data very well. The insight into the failure mechanism gives clear guidelines for yield enhancement and facilitates device design together with 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, as in the conventional Monte Carlo approach.

The question is: how to make the whole process of root-causing failures better, faster and cheaper? FA has implications on investment, required skills of the analyst, lab organization and time to result; the resulting cost explosion in FA cannot be compensated by any conceivable measures to enhance FA productivity, but this suppose that a rising number of today's FA problems will be solved by modern testing techniques. FA becomes such a substantial cost factor in yield learning that testing must be empowered to do the FA job as well. It is important to integrate FA in semiconductor product and technology development and to introduce it as part of all new projects. This explains while, in the future, analysis productivity will be a key issue for product cost reduction [29]. More reliable electronic systems with high integrated functionality within a shorter period of development time, new methods/models for reliability of components and materials, and lifetime prediction are necessary.

It is also difficult to predict the evolution of FA [30], because the continuous progress in microelectronics and microtechnologies makes almost impossible to foresee with maximum accuracy the types of electronic components that will be the most successful on the market. And the FA must serve this development, being one step ahead and furnishing to the manufacturers the necessary tools for their research.

Recent advances in the design of MEMS have increased the demand for more reliable microscale structures. Although silicon is an effective and widely used structural material at the microscale, it is very brittle. Consequently, reliability is a limiting factor for commercial and defence applications. Since the surface to volume ratio of these structural films is very large, classical models for failure modes in bulk materials cannot always be applied[5].

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[5] For example, whereas bulk silicon is immune to cyclic fatigue failure, thin micron-scale structural films of silicon appear to be highly susceptible. It is clear that at these size scales, surface effects may become dominant in controlling mechanical properties.

The reliability of MEMS is directly related to the occurrence and severity of failures occurring at the manufacturing, operation of the device. It is surprising that little has been done to fully classify these failures. A methodology is also proposed in [31] to assess their severity and high-level design of failures is implemented in the case of a thermal actuator.

As the design of MEMS devices matures and their application extends to critical areas, the issues of reliability and long-term survivability become increasingly important. Packaging of MEMS is an art rather than a science; the diversity of MEMS applications places a significant burden on packaging [1] (standards do not exist in MEMS packaging).

14. Instead of conclusions

MEMS will open a broad new array of cost effective solutions only if they prove to be sufficiently reliable. It is not clear if standardization of MEMS fabrication process à la CMOS will ever happen and is even possible. However currently most of the cost for MEMS component happens during the back end process, thus it is by standardizing interfaces that most savings can be expected.

The similarity between biological and technical evolution forms not only a ‘reference book’ containing successful structural and functional decisions, it also gives a necessary strategic criterion for development in engineering [34].

The development and production of RF MEMS switches aimed specifically at high performance requirements, enabling increased RF hardware integration and significantly improved RF performance characteristics over conventional switching. RF MEMS switches feature ultra-low insertion loss, outstanding isolation, superior linearity and enable full uplink carrier aggregation. The benefits include improved receiver sensitivity leading to fewer dropped calls and better call quality together with optimal carrier aggregation switching for massively improved data rates. Combined with high levels of RF integration, this also results in a lower bill of materials cost for the RF front-end module, and significantly longer battery life.

The correct solution for modelling MEMS devices is to use physical models: full-finite element simulations of the naked die or packaged device. This is a time-consuming task, so the companies are reluctant in using such approach. Very often, independent research groups are involved in such activities. An example is the research group from the Polytechnic University of Milan led by Prof. Alberto Corigliano, which has developed a useful model for the effect of various mechanical and environmental factors on MEMS reliability [21, 22].

MEMS will open a broad new array of cost effective solutions only if they prove to be sufficiently reliable. It is not clear if standardization of MEMS fabrication process à la CMOS will ever happen – and is even possible. However, currently most of the cost for MEMS component happens during back-end process, thus it is by standardizing interfaces that most savings can be expected.

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.

- A good manufacturing strategy for MEMS must include the complete device plan taking into account the reliability as part of the design and process development of the device.
- MEMS fabrication uses many of the same techniques that are used in the IC domain such as oxidation, diffusion, ion implantation, LPCVD, sputtering, etc., and combines these capabilities with highly specialized micromachining processes, which enables the ability to integrate multiple functionalities onto a single microchip.
- One of the disadvantages of surface micromachining is that the mechanical properties of most deposited thin-films are usually unknown and must be measured.
- Packaging is extremely important for the reliability of the device.
- It is not clear if standardization of MEMS fabrication process (CMOS like) will ever happen – and is even possible.
- At manufacturing level, the degree of the difficulty of fabricating MEMS devices is highly underestimated by both the current and emerging MEMS communities.

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