Reliability of MEMS: A perspective on failure mechanisms, improvement solutions and best practices at development level

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Abstract

Reliability of MEMS (MicroElectroMechanical-Systems) devices is a crucial aspect as it can discriminate the successful from partially or totally missed reaching of Microsystem technology based market products. However, the topic of MEMS reliability is significantly articulated, as it comprises numerous physics of failure and diverse failure mechanisms. Thereafter, it requires a pronounced sensitivity related to the actual operation conditions (environmental and functional) of the Microsystem device within the final application. In other words, reliability of MEMS is nowadays regarded as a standalone transversal discipline that must be seriously taken into account already from the early design phase. The purpose of this paper is to provide the reader at first with basic knowledge around the concept of reliability. Thereafter, the most relevant physics of failure and failure mechanisms typical of MEMS are grouped and briefly discussed, with specific attention to their employment in the field of displays. A synthetic review of valuable solutions to improve specific reliability aspects of MEMS devices for diverse applications is then proposed to the reader. Eventually, a brief discussion focused on best practices to address properly reliability during the whole development chain of innovative MEMS based products completes the contribution. It is a belief of the author that the particular blend of topics and aspects reported in the following pages, as well as the attitude of considering reliability as a transversal discipline of science, contribute to provide this contribution with an important benefit if compared to the reviews on reliability of MEMS previously published in literature.

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1. Introduction

MEMS (MicroElectroMechanical-Systems) technology has established itself as an invaluable enabling platform for the manufacturing of a barely numerable variety of micro-devices and micro-systems implementing diverse sensing and actuating functionalities. Starting from the first attempts, back in the 70s, to blend together fabrication steps typical of semiconductor (Silicon) technology (like selective etching and deposition of thin-films) to yield micro-structures with mechanical properties, the interest of research has always been attracted by MEMS. To this
is currently portraying the afore-mentioned emerging applications beneath the lengthy Time To Market (TTM) that characterized early decades after the inception of Microsystems. The rationale lying earned in recent years by MEMS in mass-market applications, it also in displays based on interferometric modulator technology (IMOD). Such a solution employs subpixels that are actual Fabry–Pérot interferometers called etalons [10]. Each etalon reflects light at a specific wavelength giving pure and bright colors. MEMS devices are typically used to switch the subpixels ON and OFF. Additionally, low-cost transparent displays were also proposed in literature, using once again MEMS electrostatic Fabry–Pérot interferometers. Thin plastic films of Polyethylene Naphthalate (PEN) [11,12] deform under electrostatic actuation thus modulating the color of the transmitting light [13]. To complete this brief overview of MEMS-based displays, it is worth mentioning also stereoscopic displays (known as MEMS 3D displays) [14,15], and Retinal Scanning Displays (RSDs) that are meant to scan images directly onto human eye’s retina [16,17]. Nonetheless, despite the solidity earned in recent years by MEMS in mass-market applications, it should be born in mind that the first commercial MEMS-based sensor (i.e. a surface micromachined accelerometer by Analog Devices) showed up just in the first 90s [18], i.e. nearly two decades after the invention of Microsystems. The rationale lying beneath the lengthy Time To Market (TTM) that characterized early exploitations of MEMS technology in the field of sensors, and that is currently portraying the afore-mentioned emerging applications of Microsystems (also in the field of displays) as well, is a sizable mosaic composed of numerous tiles. In order to breakdown the intricacies of such a canvas, Fig. 1 schematically depicts the typical stages a novel MEMS concept has to pass through before reaching proper commercial maturity (i.e. value chain deployment).

Given the multiphysical behavior of MEMS devices, that always couples mechanical domain to other physical magnitudes (e.g. electrical, chemical, magnetic, etc.) [19], it is evident that none of the development chain stages can be fully straightforward like it happens in other standard (and standardized) technology platforms (e.g. semiconductors). Development of Microsystems arises numerous issues at technology, materials and design level (see Fig. 1). (1) Technology. A MEMS process flow has always to encompass lithography steps typical of standard semiconductors, like selective deposition/removal of conductive/insulating thin-films [20], as well as Microsystems dedicated manufacturing, like patterning of sacrificial layers, deep etching and release of suspended metal or Silicon membranes [21]. This leads to issues concerning materials compatibility, thermal budgets, and so on. (2) Materials. Significant effort must also be directed in the field of material science, as properties are expected to comply diverse specifications at physical level (e.g. mechanical stiffness, electric conductivity, surface roughness, etc.), as well as from the functional point of view, like sensitivity to certain compounds [22]. (3) Design. As a matter of fact, successful design of novel MEMS devices has to conjugate somehow all the mentioned issues, blending together conflicting specifications that emerge across distinct disciplines (mechanics, electrostatics, fluids, electromagnetism, etc.), and joining them with technological and material related aspects [23]. On the other hand, once physical MEMS devices are properly manufactured, other relevant aspects, namely packaging and integration, must be faced (see Fig. 1). In general, MEMS devices cannot be operated as they are, because of mechanical fragility as well as of sensitivity to harmful environmental factors, like mechanical shocks, moisture, dust particles, etc. [2]. Thereafter, a proper package has to be designed and realized in order to protect (i.e. encapsulate) Microsystems on one side, without impairing their functionalities and characteristics, on the other hand [24]. Furthermore, the packaging phase is often expected to ease integration of MEMS components with sub-systems realized in other incompatible technologies, like active electronics and interface circuitry necessary to properly operate Microsystems devices [25]. In summary, the afore-mentioned development phases can be so specific and customized depending on the final application and on the expected specifications, that often the statement “one product, one process” is used to address Microsystems. Coming back to the TTM of MEMS technology, the reasons for its considerable duration might look clearer now. Nevertheless, Fig. 1 depicts another crucial factor that must be carefully evaluated and properly handled in the development chain, as it is capable of making the difference between success and failure of a MEMS concept in the market arena: reliability. If in the early days of Microsystems technology it was considered as a series of issues to be solved [26,27], since several years reliability of MEMS is acknowledged to be a proper discipline, as it concerns every single phase of development, from technology to material properties, as well as from packaging to final operation of MEMS devices [28]. The focus of this paper is reliability of MEMS devices, with reference to the application frame of modern displays. Nonetheless, since MEMS for displays are subjected to failure mechanisms and operation-induced reliability issues that are in common with other applications of Microsystems devices (e.g. accelerometers, resonators, various actuators, and so on), the variety of examples reported in the following pages will be rather comprehensive. The target is to provide the reader at first with a brief but comprehensive overview of the most relevant failure modes affecting Microsystems devices, and then to report a

![Fig. 1. A novel MEMS concept has to pass through numerous stages before reaching the market. Such steps can be grouped in two macro-categories of issues and problems to deal with, namely at technology, material and design level on one side, and at packaging and integration level on the other hand. Reliability is a matter that transversally concerns all the afore-mentioned emerging applications.](http://dx.doi.org/10.1016/j.displa.2014.08.003)
comprehensive review of published research contributions discussing approaches and methods to improve reliability of MEMS devices at various levels, e.g. material, technology, design, etc. The paper is arranged as follows. Section 2 introduces the definition of reliability from a formal point of view and frames important related aspects, like for instance acceleration factors. Section 3 discusses the most common failure modes of MEMS devices arising at design, technology, integration and functional level. Section 4 lists some valuable adopted solutions to improve reliability of MEMS versus specific failure mechanisms, as discussed in literature. Section 5 briefly introduces good practices at development level aiming to high-reliability Microsystem devices. Finally, Section 6 collects a few conclusive considerations.

2. A taste of reliability

Prior to discussion of details, it is profitable to move for a while the level of abstraction away from MEMS, in order to introduce and frame general concepts. Reliability is defined as the probability of a certain product to perform according to its specifications within typical operating conditions for the expected lifetime, and is expressed by the following mathematical formula [29]:

$$R(t) = 1 - F(t)$$

where $R(t)$ is the reliability function also known as survivor function, i.e. the probability to operate without failure to time $t$, while $F(t)$ is the cumulative failure distribution function. Another important parameter is the hazard rate $h(t)$, i.e. instantaneous failure rate, expressed as:

$$h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)}$$

where

$$f(t) = \frac{d}{dt}F(t)$$

When observing a product population it is important to determine the distribution of reliability. The typical $h(t)$ behavior is the so-called bathtub curve, reported in Fig. 2 [29].

In the first phase, a rather high failure rate is detected (infant mortality) due to defective products. Thereafter, the failure rate remains low and constant in the useful life range, and then increases again and more severely (wear-out) because of products aging. Ideally, infant mortality of an item should be minimized, e.g. via defect reduction measures, and operation in the wear-out region should be avoided. Further formal details and definitions concerning reliability are available in [29,30], and their more in-depth analysis is left to the reader’s curiosity. Conversely, the bathtub curve in Fig. 2 fosters important qualitative considerations that help embrace the broad concept of reliability in the field of Microsystems. In the infant mortality phase high failure rate can be caused both by product defects, as well as by a scarce knowledge of the physics of failure (i.e. failure modes) linked to the product itself, like it might happen when testing novel prototypes. On the other hand, in-depth knowledge of dominant failure modes allows sound prediction of device reliability. In the MEMS world this means holding solid and inter-disciplinary know-how across mechanics, physics, chemistry, material science, electrostatics, electromagnetism, fluid-dynamics, etc., as well as skills in multi-physics modeling, design, fabrication, packaging and testing of micro-devices. Nonetheless, albeit the amount of requested knowledge seems already paramount, it is yet not enough to determine reliability of a certain MEMS product. The discriminating factor upon which all failure modes result to be dependent is the set of operating conditions linked to a certain device. In other words, reliability of any Microsystem device can be studied, enhanced and statistically investigated only after all the specifications concerning its usage (number of cycles, applied voltage/current, etc.) and the environmental conditions in which it will operate (temperature, humidity, vibrations, presence of contaminants, etc.) are determined. These considerations clarify how the discipline or reliability has not exclusively to be based on a sound knowledge of the device and of physics of failure, but also on a good insight into system-level final application, standard operating environment and conditions. Once all these elements are well understood, the MEMS reliability engineer determines the device lifetime following a scheme similar to the one discussed in [29] and reported in Fig. 3.

When failures occur, a solid understanding of their mechanisms and physics has to be gained at first, in order to elaborate acceleration models from which acceleration factors are then extracted. The latter ones are fundamental to perform reliability testing and accelerated testing, closing the loop with study of failure physics and leading, in the end, to the lifetime estimation. Accelerated testing methods [31] make the difference in assessing reliability of MEMS devices, as they enable a component to undergo load and cycling that are supposed to take place in normal operation conditions on a long time basis (e.g. months or years), in a very limited lab testing interval (e.g. hours or a few days at most). Nevertheless, differently from standard semiconductor technologies, the consistency between acceleration factors and normal operation induced aging of MEMS is not straightforward, due to their complex multi-physics behavior [32]. This is the reason why multiple iterations between the acceleration models/factors phases and testing/analysis stages are necessary, as indicated by the circular arrows in Fig. 3. To conclude this introductory section on reliability, the most common MEMS failure mechanisms and the corresponding acceleration factors are listed in Table 1. More details about physics of failures are going to be provided in the next section.

3. Failure modes in MEMS technology

As already stressed before, reliability of MEMS is influenced by a ravelled intricacy of diverse failure modes arising from a variety of

![Fig. 2. The bathtub curve highlights three stages of the devices lifetime, i.e. high initial failure due to infant mortality, constant failure rate in the useful life phase, and increasing failure rate cause by devices aging.](image)

![Fig. 3. Schematic block diagram of a typical development stream followed to determine reliability and lifetime prediction of MEMS.](image)
issues spanning from physics to actual operation of devices. Thereafter, univocal classification of malfunctioning causes and factors is not straightforward to define. On the other hand, it is possible to stress in which phase of a MEMS device lifecycle, including in it also design prior to physical manufacturing, one or more reliability issues can originate and eventually lead to device failure, depending on its functional and operation conditions. Given these considerations, Microsystems' sources of failure are herewith grouped at (1) design, (2) technology, (3) integration and (4) functional level, and discussed more in details in the following subsections.

3.1. Design level

The phases in which a new MEMS device concept is developed are particularly critical for what concerns reliability of the final product, as several concurrent issues can affect the outcome. Starting from design definition itself, violation of one or more Design Rules (DRs) [2,23] imposed by the chosen fabrication flow can lead both to MEMS devices working out of specification or not being operable at all. According to specific technology and lithography constraints, DRs define the minimum features, distances, overlap areas and so on, whose manufacturability is guaranteed. Thereby, violating them means pushing technology in a domain in which yield becomes unpredictable. Another source of performance drift arises from Computer Aided Design (CAD) software tools. As a matter of fact, both 2D and 3D design virtualization represents to a certain extent the simplification (i.e. idealization) of MEMS real features. Physical (often nondeterministic) characteristics like surface roughness of deposited thin-films [2,33], over-etched geometries [34], non-conformal profiles of vertically stacked layers [29], smoothed corners, and so on, can give rise to performance drifts and not negligible reliability issues. Moving to the next step, i.e. multiphysics simulation of the previously defined (2D or 3D) MEMS model, other aspects must be carefully taken into account having in mind reliability. On one side, solid awareness of actual technology and materials parameters (e.g. Young's modulus [35], dielectric constant, resistivity, etc.) as well as of their tolerances with respect to nominal values must be held by the MEMS designer. This leads to the definition of designs that result to be robust against technology spreads and fluctuations. Such aspects will be addressed more into detail later in this paper. On the other hand, several sources of malfunctioning and performance drifts are inherent to the way the simulation and analysis tools are used. Taking as example the popular Finite Element Method (FEM) based tools [36], keeping fixed both the MEMS model geometry and the analysis settings, the accuracy of simulations is often significantly influenced by the mesh density [37]. In particular, coarse meshing typically leads to inaccurate and sometimes mistaken results [29]. On the other hand, mesh refinement ensures more reliable predictions despite there is an upper boundary that must be identified by the designer's common sense, as further increase of computational loads and simulation times might be compensated by negligible enhancement in results accuracy (trade-off). The topic of modeling and simulation of MEMS is rather comprehensive as it encompasses diverse approaches and methods, whose description is out of the paper purposes. Nonetheless, the reader who might be interested in analyzing further aspects can refer to [2,23,38].

3.2. Technology level

As mentioned above, properties of actual materials used for the realization of MEMS structures will differ from nominal values to a certain extent. Apart from unlike cases of major technology failures, it always happens that critical parameters, like the Young's modulus [35], dielectric constant, sheet resistance, surface roughness, and so on, are not exactly as expected. This takes place because properties of thin-films do not depend exclusively on the specific material (e.g. Gold, Aluminum, Silicon Oxide, etc.), but are significantly influenced by the specific technique (sputtering, electrodeposition, evaporation, etc. [20]) and by the conditions of their deposition (temperature, pressure, RF power, presence of contaminants, etc. [39]), as well as by all the other fabrication steps performed afterwards (thermal budged, wet etching, sacrificial layer removal, etc. [40]). Having in mind this scenario, a few additional considerations must be drawn. First of all, assimilate bulk properties of a certain material to those of a thin-film (e.g. bulk and evaporated thin Gold) is not an option, as they might be significantly different. On the other hand, the MEMS scientist, prior to design finalization, should gain in-depth knowledge of the specific fabrication process employed to realize physical devices. Moreover, as mentioned above, he/she should not think in terms of a set of fixed technology parameters, but rather of values admitting a certain range of variation. Thereafter, specific analysis should be conducted in order to identify those design's Degrees of Freedom (DoFs) more sensitive to material parameters fluctuations (e.g. pull-in voltage depending on the Young's modulus), leading to MEMS concepts intrinsically more robust already at design level. Of course, the more controlled and reproducible a certain technology is, the smaller the ranges of uncertainty are (e.g. pre-production processes and industrial facilities). In any case, best practices of MEMS robust design should always be pursued by the scientist/product developer in charge. Before concluding this section, some attention should be focused on a typical non-ideality of thin-films, namely, residual stress. It originates from intrinsic and extrinsic sources, the first ones being more related to the fabrication flow (e.g. material phase change, grain growth, crystal misfit, doping, etc. [29]). Residual stress, often referred to as stress gradient given its typical non-uniformity along film thickness, can be responsible for significant performance drifts as well as for complete failure of MEMS devices [41]. Residual stress gradient induces

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<th>Table 1</th>
<th>List of acceleration factors related to common failure mechanisms in MEMS devices.</th>
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</thead>
<tbody>
<tr>
<td>Failure mechanism</td>
<td>Physical domain</td>
</tr>
<tr>
<td>Fatigue due to cycling</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Creep and plastic deformation</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Fracture due to mechanical shocks and vibrations</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Stiction</td>
<td>Mechanical/electrical</td>
</tr>
<tr>
<td>Short/open circuit</td>
<td>Electrical</td>
</tr>
<tr>
<td>Electrical arcing</td>
<td>Electrical</td>
</tr>
<tr>
<td>Dielectric charging</td>
<td>Electrical</td>
</tr>
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</table>

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bending of MEMS suspended membranes, indeed affecting their planarity [42]. Moreover, depending if residual stress is tensile or compressive [42], it can lead, especially in clamped–clamped membrane geometries [2], to stiffening or buckling [43], respectively, causing in the latter case critical device failure.

3.3. Integration level

Progressing in the analysis of MEMS failure sources, several reliability issues arise at packaging and sub-system/system integration level, ranging also in this case from device performance drifts, to fatal failure in the most severe cases. The first aspect to be kept in mind is rather conceptual and positioned on a high level of abstraction. Thereafter it is not straightforward to translate directly into a set of practical hints and design constraints, but it has to be more profitably intended as a methodological approach. System complexity of a MEMS product is fairly high, as it comprises the Microsystem device encapsulated in a package, and interfaced to active control electronics [44,45]. As a matter of fact, when system complexity increases, failure predictability of each sub-component decreases. This happens because interactions and cross-constraints among different parts of the system are more and more intricate as their number steps up. Thereafter, the winning strategy in the development of MEMS concepts has to be oriented to the maximum extent toward design integration [46,47]. In other words, each product component (e.g. MEMS device, package, electronics, etc.) should not be considered as a standalone part, but rather as a tile of the mosaic that must be in harmony with all the other elements in order to compose the desired image. The most beneficial instance to transcribe these concepts in practical considerations is represented by packaging. As already stressed, the package is necessary to protect MEMS devices from harmful factors (shocks, moisture, dust particles, etc.) as well as to ease their integration within hybrid systems. On the other hand, encapsulation of Microsystems is not an effortless operation, since it can unchain various functional and reliability issues. An exhaustive review of packaging solutions for MEMS is discussed in [48,49]. In order to simplify the comprehension, such concerns can be grouped in two classes, namely, problems linked to reliability of the package itself, and aspects related to interaction between MEMS device and package. In the first category, all issues related for instance to mechanical strength of package materials, defects in die attach, etc. [29] are included. On the other side, MEMS/package interactions depict a more complex scenario. First of all, the concurrent facts that MEMS very often are meant to interact with the surrounding environment (sensor and actuators), and that the package protects them from external harmful factors, clearly frame a conflict. Thereafter, in order not to impair normal operability of Microsystem devices, the package has to be developed ad-hoc. A typical example is represented by MEMS pressure sensors, where the package has to be provided with deformable membrane in order to enable the Microsystem device to sense external pressure [50,51]. Apart from limitations of MEMS sensing functionality, presence of package and its application to the device influence the characteristics of Microsystems in several ways, leading from minor performance drifts to serious reliability issues [52]. For instance, different Coefficient of Thermal Expansion (CTE) between package and MEMS substrate materials can induce bending of the whole structure [53], modifying the expected characteristics of the Microsystem device, or leading, in the most serious cases, to its complete inoperability. Furthermore, presence of package also affects electrical characteristics of MEMS, as signals redistribution from device to the external world (through the cap) leads to additional resistive and/or reactive parasitics [54,55]. A comprehensive review of other cases and examples is provided in [52].

3.4. Functional level

Several sources of malfunctioning and reliability issues originate from normal operation of MEMS devices. Thereafter, such factors are closely connected both to physics of materials and to the specifications requested to the device, rather than exclusively to external and environmental factors. As proposed in [29], main reliability issues at functional level are divided into Thermomechanical Failures (TMF), Electrical Failures (ELF) and Environmental Failures (ENF) and are briefly described in the following:

(1) Contact wear (TMF). When certain surfaces come repeatedly into contact under conditions of large stresses (e.g. temperature and current densities), time dependent damage resulting in wear of such areas takes place [56]. It is a typical failure mode of MEMS relays (e.g. RF-MEMS) and leads, among various issue, to the increase of the contact resistance.

(2) Fatigue (TMF). The term fatigue indicates a multitude of phenomena driven by different mechanisms in brittle and ductile materials that result in a progressive load bearing decrease, eventually bringing to catastrophic failures [57]. Effects of fatigue typically emerge in cyclic loading conditions of MEMS device, giving rise to increasing drifts in their performance.

(3) Hardening (TMF). This characteristic of ductile materials (e.g. metals and alloys) takes place when stress above the yield limit [29] is reached. When particularly severe, hardening can lead to plastic deformations significant enough to cause catastrophic failure of the MEMS device.

(4) Delamination (TMF). It takes place between deposited layers and may occur both because of processing defects or interfacial high stress levels [58], like large stress gradient, mechanical shocks, and so on.

(5) Creep (TMF). Creep failures take place mainly in metal layers that have to undergo time dependent loading at elevated temperatures. A typical example of devices prone to this failure mode are RF-MEMS switches, as they heat up when closed due to the traveling RF power [59].

(6) Dielectric charging (ELF). Presence of large electric fields across thin dielectric films leads to accumulation of charges within them [60]. Entrapped charges generate spurious DC levels that can modify the MEMS pull-in/pull-out characteristic (i.e. voltage screening [2]), or even lead to stiction (i.e. failure) [61], namely, the missed release of the switch to the rest position when the DC bias is removed (i.e. zeroed).

(7) Electromigration (ELF). This is a well-known phenomenon in Integrated Circuits (ICs), as it leads to the formation over time of voids or hillocks due to high current densities in thin-film conductors [62].

(8) Electrostatic Discharge (ELF). MEMS structures, because of very small gaps, are prone to non-uniform high electric fields that lead to ElectroStatic Discharge (ESD) [63], dielectric breakdown [64], corona effects, and other electrically-driven irreversible failures.

(9) Microwelding (ELF). Current flowing through a closed ohmic MEMS switch combined with surface roughness of metals electrodes in physical contact leads to accumulation of high current density in very small areas. In such spots, the heating melts metals and the joints can be strong enough to cause stiction of the micro-relay in the actuated position [65].

(10) Self-heating (ELF). This issue takes place when large current and/or RF power flows through the MEMS device and results in increase of device temperature that can be significant [66]. This opens the floor to occurrence of TMFs previously discussed, like for instance contact wear and creep.
List of a few approaches to improve MEMS reliability discussed in literature. For each case MEMS device, targeted reliability issue/s and proposed solution are briefly discussed.

<table>
<thead>
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<th>MEMS device</th>
<th>Targeted reliability issue/s</th>
<th>Proposed solution</th>
<th>Refs.</th>
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<td>1 Accelerometer</td>
<td>Mechanical failures due to high frequency shocks</td>
<td>Design level (PS) Flexible stops</td>
<td>[74]</td>
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<tr>
<td>2 Resonator</td>
<td>Resonant frequency long-term stability</td>
<td>Technology level (PS) Low-temperature processing of Silicon thin-films</td>
<td>[75]</td>
</tr>
<tr>
<td>3 Micro-mirror</td>
<td>Performance drifts due to technological uncertainties</td>
<td>Design level (PS) Robust design optimization</td>
<td>[76]</td>
</tr>
<tr>
<td>4 Lateral comb-drive resonator</td>
<td>Performance drifts due to mass and elastic constant changes because of aging, device defects, harsh conditions, etc.</td>
<td>Sub-system level (AS) Custom active adaptive controller</td>
<td>[77]</td>
</tr>
<tr>
<td>5 MEMS with cyclic contact</td>
<td>Contact wear and stiction</td>
<td>Technology level (PS) Atomic Layer Deposition (ALD) of thin-film coatings</td>
<td>[78]</td>
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<tr>
<td>6 Coriolis vibratory gyroscope</td>
<td>Performance instabilities due to variations of system parameters</td>
<td>Sub-system level (AS) Active control electronics combining three calibration methods: 1) Frequency temperature self-sensing; 2) Sideband-ratio detection; 3) Quadrature compensation</td>
<td>[79]</td>
</tr>
<tr>
<td>7 Resonator in a vacuum</td>
<td>Quality factor (Q-factor) decrease due to degradation of the in-package vacuum</td>
<td>Technology level (PS) Use of getter films within the sealed cavity to absorb gases</td>
<td>[80]</td>
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<tr>
<td>8 RF-MEMS capacitive switch</td>
<td>Charge accumulation in the dielectric film, leading to voltage screening and failure for stiction</td>
<td>Technology level (PS) Deposition of SiO₂/Si₃N₄ double layer dielectric stacks instead of SiO₂ single layer</td>
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<td>Design level (AS and PS) Design of an active restoring mechanism (i.e. micro-heater integrated in the MEMS) to be activated with an electric current in case of stiction</td>
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<td>10 RF-MEMS capacitive switch</td>
<td>Stiction due to charge accumulation</td>
<td>Design level (AS and PS) Toggle design enabling both push and pull active electrostatic control</td>
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<td>Control level (AS) Shaping of the voltage waveform applied to the MEMS switch to achieve soft-landing and soft-contact of surfaces at pull-in</td>
<td>[84]</td>
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<td>12 RF-MEMS capacitive switch</td>
<td>Contact wear and other mechanical failures induced by the cycled abrupt pull-in contact</td>
<td>Design level (PS) Resistive and capacitive braking schemes by suitable design of device-intrinsic loading resistor and of capacitor plate geometry</td>
<td>[85]</td>
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<td>13 Lateral Bulk Acoustic Resonator (LBAR)</td>
<td>Drift of resonant frequency due to temperature variations</td>
<td>Control level (AS) Temperature compensation active control circuitry</td>
<td>[86]</td>
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<td>14 Resonator</td>
<td>Drift of resonant frequency due to temperature variations</td>
<td>Technology level (PS) Reduction of the resonator Temperature Coefficient of Frequency (TCF) by exploiting heavy n-type and p-type doping</td>
<td>[87]</td>
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<td>15 MEMS vibration Energy Harvester</td>
<td>Mechanical irreversible damage induced by excessive vibrations and shocks</td>
<td>Design level (PS) Design of the package shape in order to provide mechanical stoppers to limit the amplitude of the MEMS oscillations and avoid high stress concentration in specific device’s spots</td>
<td>[88]</td>
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**Table 2**

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<td>Technology level (PS) Atomic Layer Deposition (ALD) of thin-film coatings</td>
<td>[78]</td>
</tr>
<tr>
<td>6 Coriolis vibratory gyroscope</td>
<td>Performance instabilities due to variations of system parameters</td>
<td>Sub-system level (AS) Active control electronics combining three calibration methods: 1) Frequency temperature self-sensing; 2) Sideband-ratio detection; 3) Quadrature compensation</td>
<td>[79]</td>
</tr>
<tr>
<td>7 Resonator in a vacuum</td>
<td>Quality factor (Q-factor) decrease due to degradation of the in-package vacuum</td>
<td>Technology level (PS) Use of getter films within the sealed cavity to absorb gases</td>
<td>[80]</td>
</tr>
<tr>
<td>8 RF-MEMS capacitive switch</td>
<td>Charge accumulation in the dielectric film, leading to voltage screening and failure for stiction</td>
<td>Technology level (PS) Deposition of SiO₂/Si₃N₄ double layer dielectric stacks instead of SiO₂ single layer</td>
<td>[81]</td>
</tr>
<tr>
<td>9 RF-MEMS ohmic switch</td>
<td>Stiction failure due to microwelding induced by large current densities</td>
<td>Design level (AS and PS) Design of an active restoring mechanism (i.e. micro-heater integrated in the MEMS) to be activated with an electric current in case of stiction</td>
<td>[82]</td>
</tr>
<tr>
<td>10 RF-MEMS capacitive switch</td>
<td>Stiction due to charge accumulation</td>
<td>Design level (AS and PS) Toggle design enabling both push and pull active electrostatic control</td>
<td>[83]</td>
</tr>
<tr>
<td>11 Single Pole Single Throw</td>
<td>Contact wear and other mechanical failures induced by the cycled abrupt pull-in contact</td>
<td>Control level (AS) Shaping of the voltage waveform applied to the MEMS switch to achieve soft-landing and soft-contact of surfaces at pull-in</td>
<td>[84]</td>
</tr>
<tr>
<td>12 RF-MEMS capacitive switch</td>
<td>Contact wear and other mechanical failures induced by the cycled abrupt pull-in contact</td>
<td>Design level (PS) Resistive and capacitive braking schemes by suitable design of device-intrinsic loading resistor and of capacitor plate geometry</td>
<td>[85]</td>
</tr>
<tr>
<td>13 Lateral Bulk Acoustic Resonator (LBAR)</td>
<td>Drift of resonant frequency due to temperature variations</td>
<td>Control level (AS) Temperature compensation active control circuitry</td>
<td>[86]</td>
</tr>
<tr>
<td>14 Resonator</td>
<td>Drift of resonant frequency due to temperature variations</td>
<td>Technology level (PS) Reduction of the resonator Temperature Coefficient of Frequency (TCF) by exploiting heavy n-type and p-type doping</td>
<td>[87]</td>
</tr>
<tr>
<td>15 MEMS vibration Energy Harvester</td>
<td>Mechanical irreversible damage induced by excessive vibrations and shocks</td>
<td>Design level (PS) Design of the package shape in order to provide mechanical stoppers to limit the amplitude of the MEMS oscillations and avoid high stress concentration in specific device’s spots</td>
<td>[88]</td>
</tr>
</tbody>
</table>

(11) **Self-actuation (ELF).** RF power delivered to RF-MEMS switches and varactors (i.e. variable capacitors) generates an effective DC voltage with respect to ground. Depending on the design and on the RF power amplitude, such spurious DC level can be large enough to actuate the MEMS device despite no bias is applied [67]. The latest three items, i.e. microwelding, self-heating and self-actuation, are failure mechanisms typical of RF-MEMS devices that fall under the category of power handling [68].

(12) **Corrosion (ENF).** It takes place depending on the environmental characteristics within which MEMS devices operate (e.g. moisture, microorganisms, presence of contaminants), and can lead to a variety of failures [29].

(13) **Humidity (ENF).** Presence of humidity in the MEMS operation environment can lead to various degradation effects and failures. Among them, one of the most serious is stiction (i.e. missed release of pulled-in devices) induced by capillary forces acting on the surfaces coming into contact to each other [69].

(14) **Radiation (ENF).** When MEMS operate in harsh environments, like it happens in space, presence of radiations can modify the electromechanical properties of the device in a spectrum spanning from reversible/irreversible slight performance drifts to catastrophic failure [70,71].

In conclusion, as mentioned above, the just discussed list of MEMS failures mechanisms at functional level includes the most relevant items, but it does not represent a unique way to frame and categorize all the possible physics of failure. To this regard, the reader willing to build up more exhaustive knowledge on Microsystem functional failures can refer to relevant literature contributions like [72,73].
4. Approaches to enhanced reliability

Based on the intricate scenario depicted throughout this contribution on MEMS failure mechanisms and physics of failure, it results to be rather intuitive that methods and approaches to improve reliability of Microsystem devices are multiple and diverse, as well. In addition, it should be kept in mind that solutions to enhance reliability of a certain MEMS device are always chosen depending on its final exploitation, both in terms of intrinsic characteristics (e.g. number of cycles, voltage applied) and environmental conditions (e.g. temperature of operation, presence of mechanical vibrations, contaminants). In light of these considerations, once again it results rather tricky to group the available approaches to improve reliability of MEMS according to well-defined schemes and categories. In this paper, subdivision among passive and active strategies is proposed, according to the following rationale:

- Passive strategies are considered to be all the measures that make a MEMS device intrinsically and physically more reliable versus certain failure mechanism/s, typically acting at technology and design level. For instance, deposition of insulating layers less prone to charge accumulation, or design of suspended membrane geometries that reduce non-planarities induced by residual stress, are valuable example of passive strategies to improve reliability of Microsystem devices.
- Active strategies, on the other hand, are all those measures in which additional components or specific procedures (i.e. other than the physical Microsystem itself) are integrated and/or applied to the MEMS device in order to improve its reliability. For instance, application of a package to protect MEMS devices from stiction induced by moisture, or bias waveform shaping to preserve a MEMS relay from contact wear, are significant examples of active strategies aimed to reliability improvement.

Leaving shortly out the just reported distinction and going more into technical details, one can act at different levels in order to improve reliability of a certain MEMS device. As mentioned before, it is possible to act at design and technology level, the latter one encompassing measures related both to process flow characteristics and material properties. Furthermore, the MEMS product developer can act at packaging and integration level, as well as at sub-system and operation level in order to enhance long-term functionality of a certain Microsystem device. In addition to that, it is also possible to incorporate within the MEMS (or nearby it) active mechanisms dedicated to recover device performance stability and/or operability, to be exploited in case of need. The actuation of one of these options, or of a combination of them, depending on specific cases can be regarded as a passive or active strategy to enhance reliability of Microsystem devices. In fact, in some circumstances the same action type (e.g. design level) can be exploited to implement both active and passive strategies. The following Table 2 summarizes a few significant examples of adopted approaches to improve MEMS reliability documented and available in literature. As a matter of fact, the exploitation of Microsystem devices in the field of displays typically exposes such components to a wide variety of reliability issues and failure mechanisms that are in common with other types of applications of MEMS. Thereafter, most part of the items reported in Table 2, despite not directly related to displays, can be considered as relevant examples of measures and solutions to improve reliability of MEMS also in such a field of technology, as well.

5. Reliability of MEMS: a different perspective

According to what was discussed in the paper up to here, reliability has emerged through years as a rather articulated issue that should better be considered a transversal discipline MEMS product developers are called to get accustomed to, already commencing from early phases of Microsystem technology based products development. Albeit, further thinking about reliability from a different point of view might help reconsider the concepts of device malfunctioning and failure. Very likely, the most intuitive approach is to frame both of them as unexpected and unpredictable circumstances that might somehow take place. Nevertheless, is it appropriate to consider the fact that, for instance, losses and parasitic effects of an RF-MEMS device get worse after it is packaged, as an unforeseen situation? Or, again, is it really unexpected that mechanical performance of a MEMS accelerometer might change after the thermal stress it undergoes during final chip assembly? Most probably, if MEMS device, package, electronics and their integration within the hybrid chip are considered standalone physical parts and subsequent steps to be performed in-line, the correct answer is “Yes”. From a different perspective, if one pursues the targets of efficiency, effectiveness and timeliness in development of innovative MEMS devices, the just discussed
strategy results to be largely sub-optimal. Graphical representations might help discuss details of this topic. To this regard, Fig. 4 shows the block diagram of a typical development flow in which MEMS, package and electronics are modeled, designed (and tested) independently from each other.

When MEMS and package are fabricated, they are integrated (i.e., the MEMS is encapsulated) and subsequently tested. Results of experiments might lead to the need for additional runs of refined modeling, simulation, design and fabrication of both components, in order to mitigate the issues risen during the testing phase. Subsequently, the MEMS in-package is integrated to active control electronics and tested. Once again, drifts with respect to initial expected performance can lead to further simulation, fabrication, etc., of the three parts. At the end of the process, hybrid functional chips are tested for reliability (refer to Fig. 3 for more details), leading to further simulation, fabrication, etc., cycles, and possibly also to update and review of initial requirements and specification set (broken double arrow in Fig. 4). On the other hand, a completely different approach is depicted in the scheme of Fig. 5.

In this case, MEMS and package are modeled and simulated as a unique component from the beginning. Subsequently, MEMS in-package models are linked to design of electronics (i.e., sub-system simulation), and a first review/update of requirements’ set is already performed, in order to identify possible specifications hard to achieve. Subsequently, the design of MEMS in-package is performed taking into account all the possible failure mechanisms that might occur during its final operation (i.e., design for reliability). Afterwards, MEMS and package are fabricated, encapsulated, and the MEMS in-package is interfaced to active circuitry. Thereafter, the integrated chip is tested for reliability (refer to Fig. 3 for more details), and, as before, possible additional runs of design/fabrication are performed, as well as review/update of specifications. Eventually, in light of the two radically different scenarios depicted in Figs. 4 and 5, two fundamental considerations seem to be straightforward. On one side, a significant number of reliability issues can be effectively taken into account before they show up during testing, simply considering them already in the preliminary design phase. Furthermore and eventually, a synergic system-oriented approach (as reported in Fig. 5) enables to achieve significant reduction of costs, complexity and TTM in the development of innovative MEMS based products.

6. Conclusions

In this paper, multiple facets of the articulated topic of MEMS reliability have been addressed, following a blended approach typically not pursued in most part of the review articles currently available in literature. First, basic information and formal definition of reliability have been provided to the reader. Thereafter, the most common failure modes of MEMS devices arising at design, technology, integration and functional level were introduced and discussed. A review of some valuable adopted solutions to improve reliability of MEMS versus specific failure mechanisms was then presented. Eventually, some considerations lying on the plane of methodology and general approach to the development of MEMS have been expanded in order to stimulate the reader to develop a synergic and system-linked interpretation of reliability. Such reading aggregates around a fundamental query, i.e., if malfunctions, performance drifts and failures arising from integration of MEMS components are to be considered as unforeseen unknowns, or if they must be more wisely accounted for already from the beginning of the development phase, according to a system-oriented vision. As discussed in the paper, the latter circumstance allows reducing significantly costs, effort and time to be invested in development of a novel MEMS based product, it being a best practice to be kept in mind and pursued by Microsystems designers and product developers. Eventually, it is worth stressing that the experience on MEMS technology and on the related reliability issues gained both at scientific and industrial level, enables nowadays mass-market exploitation of a significant variety of Microsystems based sensors and actuators solutions. Moreover, based on such extensive know-how it can be forecasted that emerging novel exploitations of MEMS devices will require reduced TTM if compared to the first attempts to commercialize Microsystems back in the 90s. This will finally make possible a full exploitation of all the advantageous features that MEMS technology brings with itself as a dowry. Among them, the possibility to scale-down and miniaturize complex devices and geometries, to exploit innovative materials, to integrate sensors/actuators and electronics within tiny chips, as well as low manufacturing costs, much reduced weight and area occupation, certainly represent the most relevant aspects.

References


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