RELIABILITY ASPECTS OF MEMS AND RF MICROSWITCHES

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1. INTRODUCTION

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. 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 behavior 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. Figure 1 illustrates the functional block-diagram of MEMS.

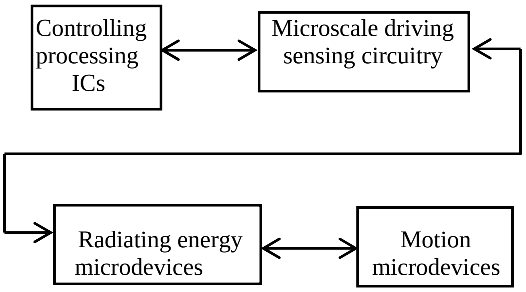

Figure 1. Functional block-diagram of MEMS

Recent fundamental and applied research and development in nano- and microelectromechanics, informatics, and nanotechnology have notably contributed to the current progress of NEMS and MEMS. Leading edge basic research, software and hardware, novel technologies are integrated to devise new systems. These prominent trends provide researchers, engineers and students with the needed concurrent design of integrated complex MEMS and NEMS. Two important historical dates: first MEMS publication in 1967 [1] and first MEMS products: pressure sensors (Si diaphragms and diffused piezo-resistors). MEMS applications: ultrasound transducer, gyroscope, microphone, accelerometer, optical scanner, two-axis micromirror.

2. MEMS SWITCHES

MEMS switches utilize mechanically moving parts to physically vary the distance between two conductive elements of a signal line in order to make or break an ohmic contact[1] (in the case of ohmic switches), or to increase or decrease the enclosed capacitance (in the case of capacitive switches). Figure 2 illustrates the two different switching principles.

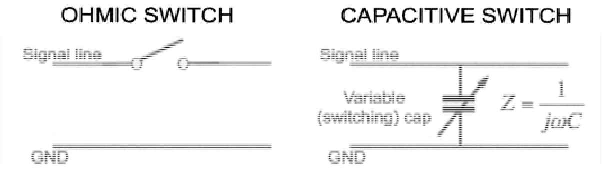

Figure 2. Switching principles for ohmic and capacitive devices.

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.

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[1] The two main failure mechanisms observed during aging of the devices are the stiction of the free-standing element and the increase of the electrical contact resistance. The mechanisms leading to failure are plentiful and localized at the metal contact interface. The root causes of those issues stem from interactions between the deformation of the contact asperities, the current flow and the heating at the contact [21], and lead to melting, material transport, adhesion, friction, wear, arcing, fracture, built-up of insulating film.

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].

3. SOME PROBLEMS TO BE SOLVED

The problems to be solved range from high-yield mass production, assembling, and self-optimization to devising novel high-performance NEMS and MEMS. For example, micro- and nanoscale switches, logic gates, actuators and sensors should be devised, studied, optimized and fabricated.

In work [3], a study of ETM effects was performed to minimize the Joule heat effects on the contact areas, thus improving performance of the microswitch. By optimizing mechanical, thermal, and electrical characteristics of the microswitch, its resistance can be minimized assuring lower operational temperatures. Thermal analyses done computationally, using Thermal Analysis System (TAS) software, on a cantilever-type RF MEMS switch indicate heat-affected zones and the influence that various design parameters have on these zones. Results obtained in [3] also showed that a microswitch with contact resistance equal to 50% of that in the baseline design achieves maximum temperatures of 409ºC leading to a higher operational reliability than that of the baseline design of the microswitch.

MEMS devices are currently used in telecommunications, wireless networking, global positioning systems, cellular, auto, and even toy industry [4, 15-19]. Microcomponents greatly reduce size and weight of many products, while reducing their cost and improving performance [5]. Although, at this time, MEMS bring large number of advantages to a range of industries, much can still be done to improve their reliability. Microswitches are an important part of all MEMS devices. These microswitches fit two major design groups: capacitive and resistive [6, 7]. The capacitive design of a microswitch refers to membrane type microswitches that use difference in capacitance between two electrodes as means of actuation. Resistive, or contact, cantilever type microswitches use electrostatic force as means of actuating the switch and consequently making a metal-to-metal contact.

Contact MEMS switches present a major reliability concern. The Joule heat generated when the current is passed through the microswitch causes its temperature to reach hundreds of degrees Celsius which, in turn, makes the contacts to wear at an increased rate or, at the extreme, weld. Changing certain design parameters, e. g., materials, dimensions, and/or surface finish of contacts, can enhance the life of the microswitch. Modifying the ICs featuring, the microswitches have been proven as a successful technique for decreasing the current passing through the microswitch, thus may be used as another promising method of improving the microswitch reliability.

4. MICROSWITCH CLASSIFICATION

The RF MEMS switches can be categorized based on the contact type, actuation method, and configuration. The two types of contacts present in RF MEMS switch designs are the metal to metal contacts and metal-insulator-metal contacts. The metal to metal contacts, also referred to as ohmic or direct contacts, can be found in cantilever-type MEMS switches. The signal in this microswitch is propagated when the two metal contacts come together and electrical current passes through the established interface (figure 3). A sample cantilever-type microswitch manufactured by Cronos is shown in figure 4.

The metal-insulator-metal contacts – sometimes referred to as capacitive or indirect contacts – are found in membrane microswitches. The capacitance built up between the metal on a membrane and metal on the substrate, via applied voltage, is used as means of actuating the microswitch. An ambitious research program of the Packaging Research Center of Georgia Institute of Technology has four main directions [1]: *(a)* Electrical design: design for wafer-level packaging, design of chip-to-package rigid / compliant lead transitions, power distribution with minimum noise and electromigration, signal integrity; *(b)* Interconnects: lead-free solder, nano links, nano interconnections, MEMS-fabricated interconnects; *(c)* Test and burn-in: interposer with built-in test-support processor and large bandwidth capability, mixed signal test at ultra-high optical signal rate; *(d)* Reliability: micro scale and nano-scale material characterization, fatigue modeling and DfR [18].

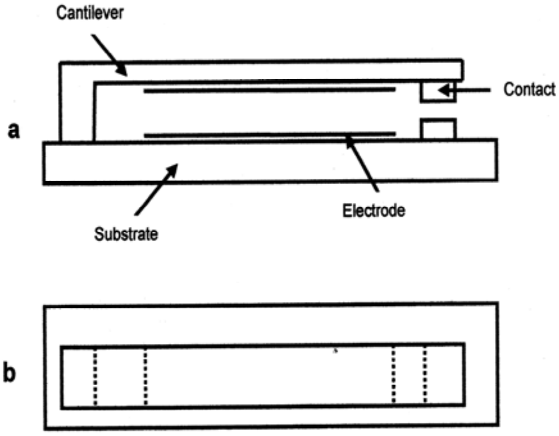

Figure 3. A sample cantilever-type microswitch:
(a) longitudinal cross section;
(b) top view

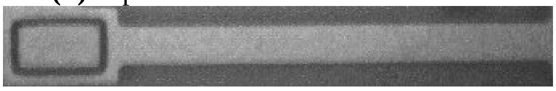

Figure 4. Top view of a sample contact RF microswitch.

Palladium contacts do not oxidize or sulfidate, but have a very low electrical conductivity. The palladium life is ten times that of fine silver, which makes it a good choice for a contact from the reliability stand point.

Both the reaction force and the slip force have great effect on the wear of the contact. Their values then have a direct impact on the overall reliability of the microswitch.

The interferometric images aid greatly in determining the manufacturing reliability of the RF MEMS switches.

The electrostatic force, along with other parameters, like surface finish or material properties of the conductor, directly affects the electrical resistance of the contacts. By increasing contact force the electrical resistance can be minimized. Low electrical resistance has an impact on power dissipation through the switch, thus the thermal resistance. Controlled thermal resistance directly affects the operational temperatures and, therefore, reliability of the RF MEMS switches.

The increases in the actual contact area(s) lead to lower interfacial resistance(s) that, in turn, result in lower temperature raises due to Joule heating, thus increasing reliability of the RF MEMS switches.

Increased force, however, also results in greater wear of the contacts. Greater wear, eventually, leads to tribological failure of the microswitches, adversely affecting their reliability. Therefore, careful considerations of multiple effects, frequently conflicting, of a change in a specific parameter, characterizing functional operation of the RF MEMS switches, must be made before the change is recommended for implementation.

The heat-affected zones are the contact interfaces between the shorting bar and the traces. Temperatures of these areas reached the magnitudes of about 700°C, for the design and operating conditions considered in thesis [3]. However, the maximum temperatures reduced to about 400°C when contact resistance was reduced to half of its original value. At these high temperatures, the material used for contacts, in this case gold, softens and tends to migrate, causing material transfer between the contacts, which leads to a premature wear. These are cumulative temporal effects that should be avoided in order to increase reliability and life expectancy of the microswitch.

5. FAILURE MECHANISMS

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 RFMEMS 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.) [2, 5]. A list of common degradation/failure mechanisms of MEMS is given in Table 1 [8].

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 into contact. The most important surface forces in MEMS are the capillary force, the molecular van der Waals force, and the electrostatic force.

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.

We distinguish four classes of failure mechanisms [20]:

Class I

No moving parts; *Failure mechanisms:* particle contamination, shock induced stiction;

Applications: accelerometers, pressure sensors, ink jet print heads, strain gauge, integrated circuits.

Class II

Moving parts, no rubbing or impacting surfaces; *Failure mechanisms:* mechanical fatigue, particle contamination, shock induced stiction;

Applications: gyros, combined drives, resonators, filters.

Class III

Moving parts, impacting surfaces; *Failure mechanisms:* stiction, mechanical fatigue, particle contamination, shock induced stiction, impact damage.

Applications: TI DMD, relays, valves, pumps.

Class IV

Moving parts, impacting and rubbing surfaces; *Failure mechanisms:* particle contamination, shock induced stiction, stiction, mechanical fatigue, friction, wear.

Appplications: RF switches, shutters, scanners, optical switches.

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

In paper [10], 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.

The RF MEMS components, designed for switching applications, are suitable candidates for telecommunications due to their low power consumption, RF performances, compactness and lightness. A MEMS is fabricated using processes of integrated circuit manufacturing that makes its cost relatively low. Few of these components are commercially available and more are expected to be in the market as soon as reliability issues will be solved. 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.

6. 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.

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 well as some MEMS structures.
Creep (plastic deformation)	Temperature, applied strain	Well understood materials science field.
Stiction	Humidity, shock, vibration	Difficult to model. Surface conditions are critical.
Shorting and open circuits	Electric field, temperature, humidity 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.
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.
Fracture due to shock and vibration	Acceleration, frequency (resonance), vacuum	Models exist for this failure mechanism in mechanical engineering texts and literature, as well as some MEMS structures. Micro-scale materials properties are needed.

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
Satellite comm. Systems	12…35 GHz	Switching networks with 4x4 and 8x8 configurations and reconfigurable Butler matrices for antenna applications Switched filter banks Phase shifter for multi-beam	0.1 million 0.1…100 million 10…20 million
Wireless comm. Systems	0.8…6 GHz	Switched filter banks for portable units Switched filter banks for base stations General SP2T to SP4T switches Transmit/receive switches Antenna diversity SP2T 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

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].

It is important to notice that creep is accelerated with temperature but it is generally not considered for temperatures below 0.3 time the melting temperature of the material (in Kelvin). Despite the fact that the structure recovers a bit once the load is removed (because of the viscoelastic behavior of materials), the deformation of the structure is irreversible even if the yield strength is not reached.

Under constant constraint and temperature the deformation of a beam is divided into three modes. The primary mode occurs directly once a load ε_0 is applied at time $t = t_0$, it is the transient deformation usually described by a power law, which begins fast and then slows down until the secondary mode. The secondary is the steady state mode known as the linear part of creep strain versus time. During this mode the deformation is, for a part, compensated by recovery mechanisms. This information explains the slowness of the deformation. Most of the models developed in literature are expressed in this region because of the long-term use in commercial applications. 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 micro-structure under constant constraint and temperature over time is given in figure 5.

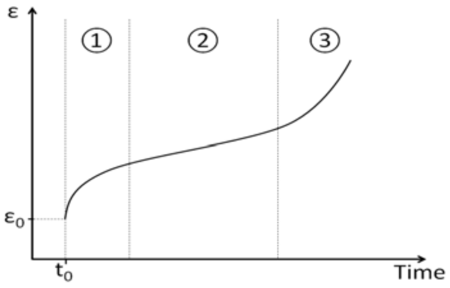

Figure 5. The typical curve of strain versus time to represent creep behavior at constant constraint and temperature. Creep is divided in three regimes.

Creep phenomenon is associated with some types of mechanism involved at grains, molecular and atomic scales. Depending on temperature and stress, these reactions are preponderant or not. The secondary mode has the longest duration (not truly representative in figure 5).

Less the activation energy is and more the structure will be susceptible to temperature, leading to big deformations [13]. In macroscopic structures, creep is divided in two families, one is related with dislocation glide and the other is related with diffusion of defects.

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 [14].

Failure mode	***Underlying causes / Examples***
Mech. fracture 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

7. INSTEAD OF CONCLUSIONS

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.

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