NEMSIC

Hybrid Nano-Electro-Mechanical / Integrated Circuit Systems for Sensing and Power Management Applications

Grant Agreement Number:	**224525**
Project Acronym:	**NEMSIC**
Project Title:	**Hybrid Nano-Electro-Mechanical / Integrated Circuit Systems for Sensing and Power Management Applications**
Funding Scheme:	**Collaborative project**
Thematic Area:	**Information and Communication Technologies**
Project start date:	**01/06/2008**

Deliverable D4.1: Failure mode and effect analysis (FMEA) for the envisaged NEM devices

Nature[1]: R

Dissemination level[2]: PU

Due date: Month: M3

Date of delivery: M3

Partners involved: IMEC, IMEC-NL, EPFL, UNIGE, SOU

Authors: Vladimir Cherman (IMEC), Ingrid De Wolf (IMEC), Silvia Armini (IMEC) Dimitrios Tsamados (EPFL), Daniel Bertrand (UNIGE), Sywert Brongersma (IMEC-NL), Hiroshi MIZUTA (SOU)

Document version: 5.2

---

[1] R = Report, P = Prototype, D = Demonstrator, O = Other

[2] PU = Public, PP = Restricted to other programme participants (including the Commission Services, RE = Restricted to a group specified by the consortium (including the Commission Services), CO = Confidential, only for the members of the consortium (including the Commission Services)

Table of Contents

Executive summary

This deliverable summarizes and discusses the possible reliability issues and failure modes, which can affect the functionality and long-term stability of nano-electro-mechanical (NEM) devices envisaged in the NEMSIC project. The theoretical analysis of failure mechanisms reported in this deliverable is based on the strong experience and theoretical background of NEMSIC partners in the field of micro-electro-mechanical systems (MEMS) and on the knowledge of physical phenomena and processes taking place in nano-sized mechanical systems.

This deliverable consists of three parts:

- In the first part, the general definitions of the "FMEA" discipline are introduced.
- The second part of the deliverable discusses different failure mechanisms, which may deteriorate the stability and functionality of NEMSIC nano-devices. The importance of every failure mechanism is also discussed.
- In the third part, the discussed failure mechanisms are summarized in a table and arranged according to the given priority number (P.N.).

1 Definitions

In this chapter the terminology of the failure mode and effect analysis is introduced [1, 2]:

Failure Mode is a measurable deviation of the property of an object from its specified value or range. For a resonator, for example, it can be a shift of the resonance frequency, a drop of the quality factor etc.

Failure Defect is a signature of the defect, which can be seen (observed optically, by SEM, TEM and other techniques). Examples: stiction, fracture, particles…

Failure Mechanism is the physical or chemical process responsible for the failure. Example: capillary forces, fatigue, wear…

Failure cause is what is initiating the failure mechanism. As a failure cause one can consider a change in the environmental and exploitation conditions, or another failure mechanism. Examples: increased humidity, high temperature, shock,… The failure cause can also be an error in the design or errors occurring during the processing (example: a non-complete release).

Failure analysis is an investigation performed after the failure has occurred by performing electrical, optical and other measurements with the aim to determine the failure mechanism and finally to figure out the cause of the failure.

Failure Mode and Effect Analysis (FMEA) is an opposite action of failure analysis consisting of a theoretical investigation (prediction) of failure, which can be initiated by one particular cause, and the possible effects of this failure on the functioning of the device.

2 Failure mechanisms in NEMSIC devices

In this chapter the possible failure mechanisms, which may occur in NEMSIC devices are discussed. Namely, two kinds of devices are considered:

1. NEM-FET sensor. This is a biological or gas sensor based on field effect transistor (FET) operation with the resonating nano-beam as a gate electrode. The surface of this gate electrode is chemically modified (functionalized) in a way that it is selective to a certain kind of bio- or gas-molecules. When the device is used as a resonating structure, the resonance frequency is expected to decrease due to mass loading. The NEM-FET sensor is a threefold system having electrical (FET), mechanical (NEM), and chemical (CHEM) components. Therefore, the failure mechanisms associated with all three fields of science are to be considered.

2. NEM-FET switch. This device has a mechanical structure similar to the one used for the bio- and gas-sensing applications but the suspended NEM gate electrode works in the switching mode and not in the resonating mode as in the case of the NEM-FET sensor.

Although the structures of these two devices are pretty similar, different failure mechanisms can contribute differently to the functionality of NEM-FET sensors and NEM-FET switches, and therefore they have to be considered separately.

2.1 Mechanical failure mechanisms

Mechanical failure mechanisms are initiated when an external or internal static or dynamical mechanical load is applied to materials. This load can be expressed in terms of strain, i.e. the relative deformation of the object, or in terms of stress, i.e. the force. The force can have different origins: electrical, chemical or mechanical. The amplitude of the load, the dynamics of the load and the environmental conditions determine the failure mechanism acting in the particular system.

2.1.1 Elastic deformation

At relatively small mechanical loads, a reversible alteration of the shape or dimensions of a solid body occurs. This deformation is called elastic deformation and it involves reversible stretching of the atomic bonds. Elastic deformation itself is not considered as a failure mechanism. Moreover, it is one of the main mechanical means that are used together with electrostatic forces to build electromechanical systems including micro- and nano- systems. Nevertheless, in complex mechanical systems the elastic deformation in one material can have an effect on other components of the system mechanically coupled with it, thus initiating failure. For example, large elastic deformation of a beam or cantilever can lead to an electrical short, or to the plastic deformation or even fracture in a more rigid material mechanically coupled with it, or to delamination, or stiction if the deformed member touches other materials. The priority number that can be attributed to this mechanism highly depends on the exact design and on the materials used for the NEMSIC devices. If they mainly consist of Si, the problem is probably small. If they consist of Si and metallic parts, the problem might be important.

The elastic deformation should be considered especially for the NEMSIC switch. As the thickness of the suspended gate and the air gap will be extremely small in the out-of-plane NEMSIC switch, small elastic deformation, which is not considered as a failure in the MEMS, could be a trigger of unwanted pull-in and stiction in the NEMS switch. On the other hand, such failures should be less frequent for the in-plane NEMSIC sensors as the oscillation amplitude of the suspended nanowires (NWs) will be designed small enough compared to the NW-actuation gap so that the unexpected pull-in phenomenon can be avoided more easily.

2.1.2 Plastic deformation

At higher mechanical loads, i.e. above the yield strength, the atomic bonds in the material start breaking. The atoms are irreversibly slipping past each other thus changing the shape of the body. Such irreversible (permanent) change in shape or size of a solid body without fracture and resulting from the application of increasing stress is called plastic deformation. Plastic deformation involves a permanent change of the elastic modulus of the material affecting the functionality of the mechanical system and thus initiating failure. Failure modes which can be attributed to this mechanism are a shift of the pull-in and pull-out voltages, short circuit, a change of the resonance frequency, etc. During manufacturing of the device, plastic deformation of suspended structures may occur due to differences in thermo expansion coefficients of materials composing the multi-layer suspended structures (both for high and for low temperatures). To prevent this kind of deformation, a temperature compensated design for suspended structures can be used. Silicon is a brittle material and does not show plastic deformation. However, if metals are used in the MEMS/NEMS devices, the stress levels induced in these materials during operation or during reliability testing can be high enough to consider the plastic deformation as having a high priority number. As a result, also for this failure mechanism its priority number will highly depend on design and on the materials used for the devices.

2.1.3 Creep

Creep is a time-dependent plastic deformation of a material under constant mechanical load, which is below the yield strength of the material. The creep is controlled by different mechanisms such as dislocations movement or diffusion. It is accelerated with temperature and mechanical stress and is becoming important at temperatures above 30-50% of the melting point of the material. That is, materials with low absolute melting point, aluminum for example, are prone to creep even at relatively low temperatures. The creep, thus, depends on the kind of the material, on its quality, on the ambient temperature and the stress acting on the material. In NEMSIC devices creep- related reliability issues have to be taken into account at the design level (i.e. materials selection) as well as at the technological level (control of the material's quality). Failure modes similar to the ones considered in the previous paragraph can be attributed to the creep.

In addition, the "creep" behavior of the functional self assembled monolayer (SAM) is not known and its importance has to be determined during the course of the project.

2.1.4 Fracture

Fracture is a breaking (or separation) of the material into two or more pieces under an application of mechanical loads. In plastic materials fracture takes place after the strain in the material has exceeded the ductility limit. On the other hand, brittle materials such as silicon break before the plastic deformation takes place. Failure defects attributed to the fracture can be observed as cracks in the material or as its complete separation into two or more pieces. Fracture can be initiated by external loads, such as shocks and vibrations, or it can be a result of other failure mechanisms inducing high local mechanical stresses in the system. The first fracture mechanism, which is due to the external forces, has a low priority number in the NEMSIC devices because the mechanical structures are extremely small and light, thus being almost insensitive to the typical external (environmental) mechanical loads (ex. vibrations, shock). However, fluids can cause rather high forces on materials, and they might result in fracture. So, the effect of moving or drying fluids on the NEMS has to be studied.

2.1.5 Delamination of the functional layer

Delamination is a failure mechanism of multi-layer structures. During repeated cyclic mechanical or temperature stresses or under a static stress, the functional layer (or the part of the layer) deposited on the Si-NW may separate. These can lead to the degradation of the performance of the functional layer or to the complete failure of the device (see paragraph 3.3.3). Because of very small thickness of the functional coating comprising the self-assembled monolayer (SAM) and the layer of bio-molecules (in the order of 1 nm) the delamination failure mechanism is very unlikely to appear.

2.1.6 Fatigue

Fatigue is a destructive failure mechanism which involves the formation of cracks (which can lead to fracture) in the material exposed to relatively low (below the ductility or even yield limit) but cyclic mechanical stresses. Fatigue failure mechanism can have a very high priority number in the NEMSIC switch and especially in the NEMSIC sensor, which works in the resonating mode, if the gate material is a metal. In the case of Si-gate, the stresses required for fatigue are in the GPa range, values which are nearly never encountered during MEMS/NEMS operation. However, a problem that can occur in crystalline silicon is stress-corrosion cracking where the crack originates and propagates in the native oxide on the silicon. This oxide grows into the silicon due to local tensile stress at the crack tip, and the crack will grow with it, leading eventually to fracture. This probably also requires GPa stresses, but we cannot exclude that this problem might occur in the NEMSIC devices.

2.1.7 Wear and friction

Wear is an abrasion of the material due to its friction against another material. This action results in wearing out the material thus creating particles and changing its mechanical properties and initiating failure. This failure mechanism can be considered as having middle to high priority number for the NEMSIC switch if it is designed in a way that the switching action involves pulling–in of the beam followed by its sliding against a static surface (channel of the FET transistor, for example). In contrast, the “NEMSIC sensor” does not involve any mechanical contact action and, therefore, wear is not present. Nevertheless, the sensing organic film, which is coating the resonating beam, is in contact with the tested liquid. Wearing of the functional layer due to friction against liquid environment can take place and should be investigated (see also paragraph 3.3.3). Moreover, friction between liquid and the sensor can also induce additional heat. This, in turn, can lead to the elastic deformation of the beam, its fracture, to the degradation of the functional layer or to electrical charging.

2.1.8 Micro welding

When two surfaces come into contact with large forces, or if there is friction between two contacting surfaces in the NEMSIC switch which can locally heat them, or high currents running through them, the surfaces can stick together due to welding. One should notice that only plastically deformable surfaces (ex. metals) are prone to welding. In NEMSIC devices welding will not be considered as one of the possible failure mechanisms.

2.1.9 Unwanted material deposition

An unwanted (non-controlled) material deposition, which may occur during exploitation of NEMSIC devices, can originate from the environment seen by the device. In the case of the NEMSIC sensor, unwanted particles can be delivered to the resonating beam by the sensed liquid or gas and they will cause a shift of the resonance frequency of the sensor. In the case of the NEMSIC switch, unwanted material deposition has to be minimized at the manufacturing level and via a proper packaging. Also the packaging materials can give outgassing which can affect the mass of the NEMS and cause a shift of its properties (ex. resonance freq, pull-in/pull-out voltages). Moreover, the unwanted material deposition can be a result of other failure mechanisms. For example, unwanted particles can be produced by mechanical wear or by heating up and evaporation controlled by short circuit, breakdown or fusing failure mechanisms. These particles can be deposited onto the contact surface of the NEMSIC switch thus changing its “ON-state” performance or onto the resonating beam changing its resonance frequency and quality factor. These particles can also deteriorate the properties of functional layers deposited onto the surfaces of the resonator.

2.1.10 Remarks: material properties

The impact of "mechanical" mechanisms such as plastic deformation, fatigue, creep, fracture etc. on the NEMS/MEMS functionality and reliability, is determined by the relationships between stresses and strains induced in the materials and the mechanical properties of the materials such as yield strength, modulus of elasticity, ductility limit etc. These properties are, in general, not constant for every material and depend on the quality of the material and on the dimensions of mechanical structures. In polycrystalline materials, the yield stress is reversely proportional to the square root of the grain size. This phenomenon is known as Hall-Petch strengthening [3]. It means that one can improve the reliability of the mechanical system by fabricating strengthened materials with nano-grains. However, when the typical size of the system is becoming comparable to the size of the grain, as can be in the case of nano-systems, the stress-strain characteristic can deviate from the Hall-Petch prediction thus influencing their reliability. In addition, it was shown that the ductility limit of the mechanical structure decreases when its size is becoming comparable to the grain size [4].

The scaling MEMS devices down to nano- dimensions involves also changes in the aspect ratio of typical mechanical structures, such as beams and cantilevers. This can also influence the redistribution of the priority numbers between different mechanical failure mechanisms compared to the case of MEMS. For example, it was reported that the change of the aspect ratio affects the ductility level of the structure [4].

It is clear that more information is needed on the material properties of the nanostructures to be able to predict and optimize their reliability. When poly-crystalline structures become of the size of some grains, material properties will deviate from the ones of bulk materials and the orientation of the grains will affect the properties of the device. It is very likely that this will give an increased statistical variation amongst the devices: a device which consists for example of 5 silicon grains oriented along a [100] direction will have different mechanical properties than a devices with grains oriented in the [110] direction because silicon is a anisotropic material (Young's modulus depends on the grain orientation). These devices will have different pull-in voltages, different resonance frequencies etc. There is still a lot of research required to describe and understand these issues for different materials. If crystalline silicon is used, this problem might be smaller. However, we should not underestimate the effect of the native oxide in this case, which will highly affect the mechanical properties of the device.

2.2 Electrical failure mechanisms

The failure mechanisms attributed to MEMS and NEMS devices and being initiated by the action of constant or alternating charges, electric fields or electric currents are discussed in this section.

2.2.1 Breakdown

Electrical breakdown is a sudden passage of an electrical current between two isolated conducting surfaces. In MEMS/NEMS devices one can distinguish between the electrical breakdown in gases, solid dielectrics, liquids and vacuum depending on the kind and the quality of dielectrics and on the environmental conditions. The breakdown is initiated when the voltage applied between two conductors separated by a specified gap exceeds a certain limit, called the dielectric strength. In the case of dielectrics, the dielectric strength is determined by their quality and the density of grains. Thus, porous (less dense) dielectrics can break down easily compared to their denser counterparts.

Breakdown of dielectrics can be a result of the accumulation of electron or hole traps due to a small leakage current through the dielectric during operation or test. When enough traps are present, breakdown takes place (percolation model). In gases, the dielectric breakdown is controlled by the mechanism of ionization of gas molecules due to the induced electric field. It mainly depends on the gas pressure and on the distance between the electrodes. In the macro- and partially in the micro-world the distances between the electrodes are much larger than the mean free path of an electron in the gas (0.5 µm in the case of air at atmospheric pressure). In this case the breakdown voltage is well explained by Paschen's law [6], which takes into account the distance between the electrodes and the gas pressure. However, when the distance between two electrodes is becoming smaller than a few microns, which is a typical situation in the case of NEMS, the Paschen's law can not be used to determine the breakdown conditions [9]. Instead, the mechanisms associated with the breakdown in vacuum have to be considered [5]. In [7] and [8] it was pointed out that the breakdown mechanism in vacuum "arises from a 'cold-' or field- electron emission process occurring at isolated 'point' sites on the cathode surface". It was also shown that the finishing of the surface plays an important role in vacuum breakdown.

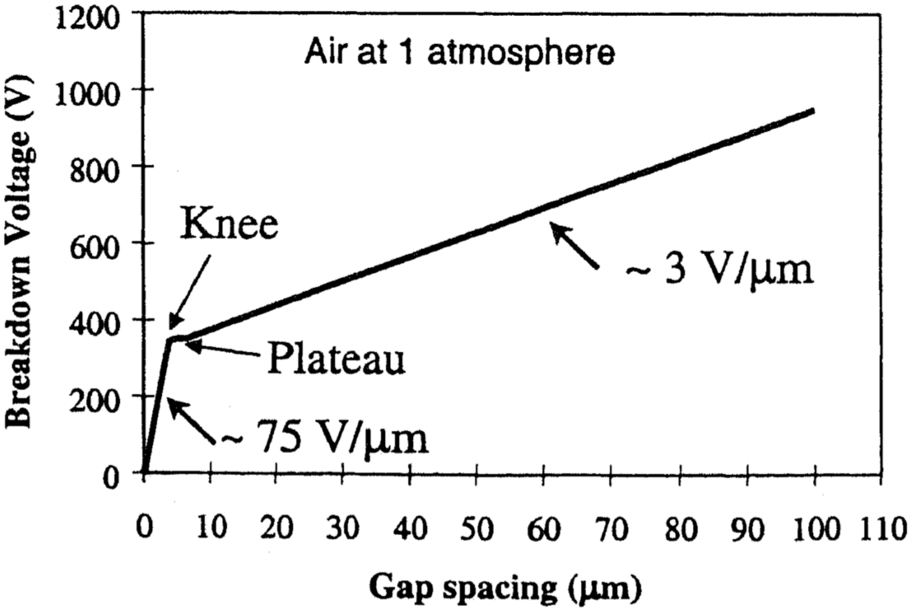

Fig. 1. [9] Modified Paschen curve: breakdown voltage vs. gap spacing.
Note: plateau, knee and steep decline of the breakdown voltage for a gap less than 5µm.

In the case of NEMSIC devices, where the distances between conducting surfaces are on the level from few tens to few hundreds of nano-meters, electrical breakdown can be considered as having a high priority number, although the risk of breaking down has to be minimized at the design level (proper selection of working voltages and dimensions) and during the fabrication (surface finishing etc.).

In addition, if there are insulators present in the NEMSIC designs, the breakdown of these insulators (and their charging sensitivity) has to be studied.

2.2.2 Short circuit

Short circuit is usually not considered as a failure mechanism itself but as a result of other failure mechanisms resulting in a contact between of two or more conductors. Nevertheless, the short circuit can occur due to particle contamination at contacting surfaces during fabrication or exploitation of the devices. In the case of NEMSIC sensor these particles can be delivered to the near-by-resonator area by the sensed liquid and initiate the failure. In addition, the liquid itself can be the cause of a short circuit.

2.2.3 Fusing

Fusing is one of the possible results of a short circuit or an electrical breakdown, involving the generation of high dc or ac electrical currents which heat the structures and melt them.

2.2.4 Electromigration

Electromigration is the movement of ions in a conductor under the influence of an electrical current. It is a typical problem in Al or Cu conductors with high current density (i.e. narrow lines). In the "NEMSIC sensor", electromigration will have a negligible effect because no currents with high densities are present in the system. However, special care should be taken when designing NEMSIC switch to avoid electromigration-related reliability problems.

2.2.5 Self actuation

Self actuation is an actuation of the movable MEMS/NEMS structure without an application of the actuation signal. For example, a high power RF signal can actuate a RF MEMS switch. Another source of the actuation force can be Lorenz forces acting on the conductors with electrical current at the presence of electromagnetic waves. For NEMSIC devices, the "self-actuation" failure mechanism is not relevant except for the cases if it operates in an environment polluted by high electromagnetic fields.

2.2.6 Charging

Charging is an injection of charges into the bulk or on the surface of a dielectric. There are different sources of dielectric charging. In MEMS/NEMS devices containing dielectric materials this process mainly occurs when there is a strong electric field in the dielectric. Under an action of such a high electric field, tunneling of charges from electrodes into the dielectric occurs. This phenomenon is similar [10] to Poole-Frenkel emission in dielectric materials, where the conduction occurs due to field-enhanced thermal excitation of trapped electrons into the conduction band [11]. In SiO2 charging can also be due to Fowler-Nordheim tunneling or other defect assisted tunneling/hopping mechanisms.

The dielectric charging mechanism will have a different effect on the reliability of the NEMSIC switch and the NEMSIC sensor. The NEMSIC sensor design does not utilize any solid dielectric in the sensitive area of the device and therefore the discussed failure mechanism should have a negligible effect on its reliability. However, the sensor is supposed to work in a liquid environment. The electrical and the dielectric properties of this liquid are not enough investigated for the moment and an effect of possible charging of this liquid during sensor operation should not be excluded from the consideration beforehand. Charging could be particularly serious for the Si-nanowire

(SiNW) devices used as a single-electron transistor because any background charge can vary the Coulomb oscillation of the current in the channel of the transistor.

Contrary to the sensor operation, the NEMSIC switch contains a dielectric, which forms a metal-insulator-semiconductor (MIS) capacitor when the suspended nano-beam is in the actuated position. Charging of this dielectric may occur and result in shifting of the pull-in and pull-out voltages as well as of the semiconductor threshold voltages, or even in stiction of the beam to the dielectric and should be investigated.

Moreover, it was recently shown that MEMS devices can also suffer from dielectric charging of the substrate [12]. Due to the FET architecture and nano-meter dimensions of NEMS structures, the effect of dielectric charging of the substrate on the reliability of the device is minimized and low priority number can be attributed to this particular charging mechanism.

A last possible source of charging problems is the native dielectric present on silicon. If the resonators are made of silicon, this oxide will be present and can charge. If this happens, it can cause also shifts of the electrical characteristics of the NEMS.

2.2.7 Casimir forces and Van der Waals forces

The Casimir and Van der Waals forces are short range (nano-scale) forces acting on objects and originating from the existence of co-called "zero-point vacuum oscillations of the electromagnetic field". These forces are well described by the quantum field theory and are becoming of very high importance when MEMS devices are scaled down to nanometer dimensions. For example, in [13] it was shown that the Casimir force can be two orders of magnitude higher than the electrostatic force at working distances below 150 nm (as in Fig.2).

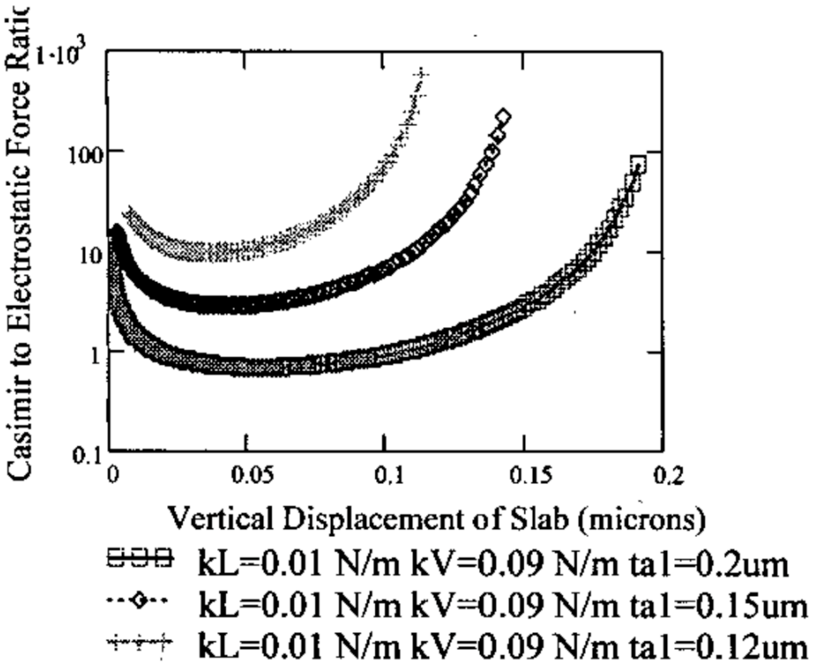

Fig. 2. [13] Ratio of Casimir force to electrostatic force
as a function of the displacement of the movable dielectric slab.
("ta1" is the air gap, kL and kV are lateral and vertical spring constants of the slab, respectively)

As the distance between plates increases, the Casimir force rapidly vanishes. The strength of the Casimir force is reversely proportional to the fourth power of the distance. The Van der Waals force, although having a similar nature, decreases slowly and is proportional to the third power of the distance [14], [15]. In [14] it is also noted that "…van der Waals and Casimir forces cannot in general be considered to simultaneously act in MEMS…".

Taking into account the large contribution of Casimir and Van der Waals forces in nano-meter scale devices, high priority numbers have to be attributed to these forces for both NEMSIC devices.

2.3 Chemical failure mechanisms

The failure mechanisms which may occur in nano-electromechanical systems due to chemical interactions between different components of the system are discussed in this section.

2.3.1 Corrosion

Corrosion is a chemical or electrochemical process between the metals and an environment, which deteriorates the properties of the former. In the situation when the micro/nano electromechanical system is exposed to a chemically "active" environment (i.e. non-inert gases, humidity or liquid), corrosion can play an important role affecting the reliability of the device [16]. Corrosion is not so relevant to the NEMSIC switch application if proper attention is paid to the packaging of the device. However, the sensed liquid (or gas) is a working environment for the NEMSIC sensor. This should get a high priority number when discussing bio- (gas-) sensing application.

Oxidation is sometimes also listed under corrosion problems. Oxidation of a nano-device will change its weight, deteriorating the functionality of the device and possibly resulting in failure. Oxides can also trap charges and in this way affect the reliability, as was discussed previously.

2.3.2 Capillary forces and hydrodynamic effect

Capillary forces are attractive forces between liquids and other materials. The attraction action takes place when the intermolecular forces inside the liquid are lower than the attraction forces between the molecules of the liquid and the molecules of other substances. Similarly to the corrosion, the effect of capillary forces on the reliability of NEMSIC switch has to be minimized by using hermetic packaging; while in the sensing application stiction or fracture due to capillary forces has to get a very high priority number.

The liquid flow can result in forces acting on the nano-beam. This could mechanically deform the beam inducing stresses, elastic or plastic deformations, fractures etc. We call this effect as "hydrodynamic effect".

2.3.3 Degradation of the functional layer

The properties of the functional layer may change with time during storage, transportation and exploitation of the sensor. For example, the functionalized Si-NW can be contaminated during the experiment, the measurement procedure may affect the biological properties of the functional layer, or vice versa the change of biological properties of the layer during the measurement cycle may affect electrical and mechanical properties of the sensor other than those detected as a shift of the resonance frequency.

3 FMEA analysis

In this section of the report the failure mechanisms discussed before are summarized in a table and the priority number of every failure mode is calculated separately for the NEMSIC switch and NEMSIC sensor.

The priority number is calculated as a product of 'severity' and 'occurrence'. These two parameters are ranked between 1 and 10.

- **Severity** is a measure of the importance of the effect of a particular failure mechanism on the functionality of the device or of the higher hierarchical order system. Severity, which equals to 1 means that the mechanism gives no or a negligible danger while a severity equal to 10 means that this failure mechanism will certainly cause complete dysfunction of the device.
- **Occurrence** is the probability of the failure to happen during storage or operation of the device. Occurrence equal to one means that the probably that this failure occurs is negligibly small even at certain and hard exploitation conditions. Occurrence equal to 10 means that the failure mechanism always occurs even at normal conditions.

In this work the **Risk Priority Number (RPN)**, which is the product of the priority number (PN) and the detectability, will not be calculated. This is because the **"detectability"** is an ability of the failure to be detected before the usage of the device. This number is very important for the manufacturers allowing them to minimize the number of failures, which would happen at their customer's sides. They mostly screen for such failures using burn-in techniques. However, in the case of NEMSIC devices it is too early to speak about "detectability" as no design neither technology for the particular NEMSIC nano-devices has been developed so far.

An important note has to be considered before deciding on the degree of the importance and that of the occurrence for every failure mechanism:

In general, a failure or a chain of failures may occur due to:

1. non-optimized or wrong design (for example the combination of materials with large difference in thermo-coefficients, high currents/voltages used for actuation, wrong choice of materials etc.);
2. non-optimized technological process or sudden deviation of the technology from the optimized one (for example non-optimized temperature regimes may induce stresses in the materials, residual particles may contaminate the surface of NEMS, residual water may result in stiction of the beam etc.);
3. aging and different environmental and exploitation conditions during storage and usage of the device (for example storage at high temperature, application of many actuation cycles, working in harsh environment, electrostatic discharge etc.).

In this deliverable we consider all sources of possible failure mechanisms, but we assume that the device is designed and manufactured in a way that it is fully functional in the beginning of the reliability study. In other words, only the reliability issues, related to post-production life of the device will be considered. This means that in the next table we do not take into consideration failure mechanisms caused by a non-proper design of the switch or sensors or by a technology deviation which result in a fully non-functional device after its fabrication (for example surface contamination, residual water on surfaces etc.).

The results of the FMEA analysis are collected in the table below.

Table 1: Failure mode analysis of the NEMSIC switch (in the green fields), and the NEMSIC sensor (in the blue field). SE = severity number; OC = occurrence number; PN= Priority Number.

No	Failure Mechanism	NEMSIC Sensor			NEMSIC Switch		
		SE	OC	PN	SE	OC	PN
1	Elastic Deformation	8	6	48	5	6	30
2	Plastic Deformation	8	1	8	8	1	8
3	Creep	5	1	5	5	1	5
4	Fracture	10	3	30	10	3	30
	Functional layer delamination	9	2	18	-	-	-
5	Fatigue	8	4	32	8	4	32
6	Wear and friction	6	3	18	4	1	4
7	Micro Welding	10	0	0	10	0	0
8	Unwanted material deposition	8	3	24	8	3	24
9	Electrical Breakdown in the gap	8	3	24	8	5	40
10	Electrical Breakdown in the dielectric	10	0	0	10	4	40
11	Short Circuit	5	6	30	10	1	10
12	Fusing	10	1	10	10	1	10
13	Electromigration	8	2	16	8	0	0
14	Self Actuation	6	1	6	6	1	6
15	Charging	9	4	36	8	8	64
16	Casimir and Van der Waals Forces	8	8	64	8	8	64
17	Corrosion	6	3	18	6	0	0
18	Capillary and hydro-dynamic Forces	9	7	63	9	3	27
20	Degradation of functional layer	7	5	35	-	-	-

4 References

[1] I. De Wolf, “Reliability of MEMS”, Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems, 2006. EuroSime 2006. 7th International Conference on , pp. 1-6, 24-26 April 2006.

[2] Microelectronics failure analysis. Desk reference. Fifth edition. Ed. EDFAS Desk Reference Committee, ASM international, 2004

[3] E.O. Hall, Proc. Phys. Soc., Ser. B, Vol. 64, pp. 747-753, 1951.

[4] T. Connolley, PE McHugh, M. Bruzzi. “A review of deformation and fatigue of metals at small size scales”. Fatigue & Fracture of Engineering Materials & Structures, vol.28, no.12, pp.1119-1152, 2005.

[5] P.G. Slade, ED Taylor. “Electrical breakdown in atmospheric air between closely spaced (0.2 mu m-40 mu m) electrical contacts”. IEEE Transactions on Components and Packaging Technologies,vol.25, no.3, pp.390-396, 2002.

[6] Friedrich Paschen. “Über die zum Funkenübergang in Luft, Wasserstoff und Kohlensäure bei verschiedenen Drucken erforderliche Potentialdifferenz”, Annalen der Physik, vol.273, no.5, pp.69-96, 1889.

[7] R.V. Latham. “Initiation of electrical breakdown in vacuum”. Physics in Technology, vol.9, no.1, pp.20-25, 1978.

[8] P. Kranjec, L. Ruby, “Test of the critical theory of electrical breakdown in vacuum”, J. of Vacuum Science and Technology, Vol.4, no.2, pp.94-96, 1966.

[9] A. Wallash, L Levit, R. Ramesham, DM Tanner. “Electrical breakdown and ESD phenomena for devices with nanometer-to-micron gaps”. Conference On Reliability, Testing, And Characterization Of MEMS/MOEMS II, Jan 27-29, 2003, San Jose, California. Reliability, Testing, And Characterization Of Mems/Moems II, vol.4980, pp.87-96, 2003.

[10] C. Goldsmith, J. Ehmke, A. Malczewski, B. Pillans, S. Eshelman, Z. Yao, J. Brank, M. Eberly, “Lifetime Characterization of Capacitive RF MEMS Switches”, 2001 IEEE MTT-S International Microwave Symposium Digest, vol.1, pp.227 – 230, 20-25 May 2001.

[11] S.M. Sze, “Physics of semiconductor devices”, New york, John Wiley & Sons, 1981

[12] P. Czarnecki, X. Rottenberg, P. Soussan, P. Ekkels, P. Muller, P. Nolmans, W. De Raedt, H.A.C. Tilmans, R. Puers, L Marchand, I. De Wolf. “Influence of the substrate on the lifetime of capacitive RF MEMS switches”. 2008 21st IEEE International Conference on Micro Electro Mechanical Systems - MEMS '08, Tucson, AZ, USA. 2008 21st IEEE International Conference on Micro Electro Mechanical Systems - MEMS '08, pp.172-175, 2007.

[13] H.J. De Los Santos, “Impact of the Casimir force on movable-dielectric RF MEMS varactors”. IEEE Conference on Nanotechnology, San Francisco, CA, USA, 2003 Third IEEE Conference on Nanotechnology. IEEE-NANO 2003. Proceedings (Cat. No.03TH8700), vol.2, pp.900-903, 2003.

[14] R.C. Batra, M. Porfiri, D. Spinello. “Effects of van der Waals force and thermal stresses on pull-in instability of clamped rectangular microplates”. Sensors, vol.8, no.2, pp.1048-1069, 2008

[15] F.W. Delrio, M.P. De Boer, J.A. Knapp, ED Reedy, PJ Clews, ML Dunn. “The role of van der Waals forces in adhesion of micromachined surfaces”. Nature Materials, vol.4, no.8, pp.629-634, 2005.

[16] M. Hon, F.W. DelRio, C. Carraro, R. Maboudian. “Effects of relative humidity and actuation voltage on MEMS reliability”. Transducers '07 & Eurosensors XXI. 2007 14th International Conference on Solid-State Sensors, Actuators and Microsystems, Lyon, France, pp.367-370, 2007.