MEMS Sensors -
Reliability and Standardisation Challenges

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Abstract

An important challenge in achieving successful MEMS sensors is associated with MEMS reliability and standardistion. In comparison to Integrated Circuits, reliability and standardistion is much more complex for MEMS. Many of the MEMS failure mechanisms are not well understood. This lack of understanding presents a challenge in developing practical reliability techniques and stadardisation solutions for MEMS sensors.

There are industry standard tools and techniques for understanding and quantifying reliability for integrated circuits. However, in the case of MEMS, this knowledge base is much more limited. In most cases, knowledge for quantifying reliability is a competitive advantage, and is not available for sharing.

In order to develop reliable MEMS sensors, reliability must be considered at the earliest stages of sensor development. Decisions made in the design stage can result in sensors that will never be reliable. Reliability must be understood at a fundamental physical and statistical level.

There is often a perspective that MEMS will be unreliable because they have moving parts. However, it is rubbing surfaces and not the moving parts that kill reliability. Avoiding rubbing surfaces is one of the key elements in achieving reliable MEMS sensors.

A second primary issue affecting reliability is the issue of packaging. Again, it is useful to consider the case of integrated circuits, which are known for their reliability. Integrated circuits are packaged in such a way so as to protect the sensitive transistors on the surface of the chip from the environment. The chips are typically packaged in a hermetic environment, or are potted to protect the sensors. For the case of MEMS, some sensors by their very nature require them to be exposed to the environment, creating a reliability challenge.

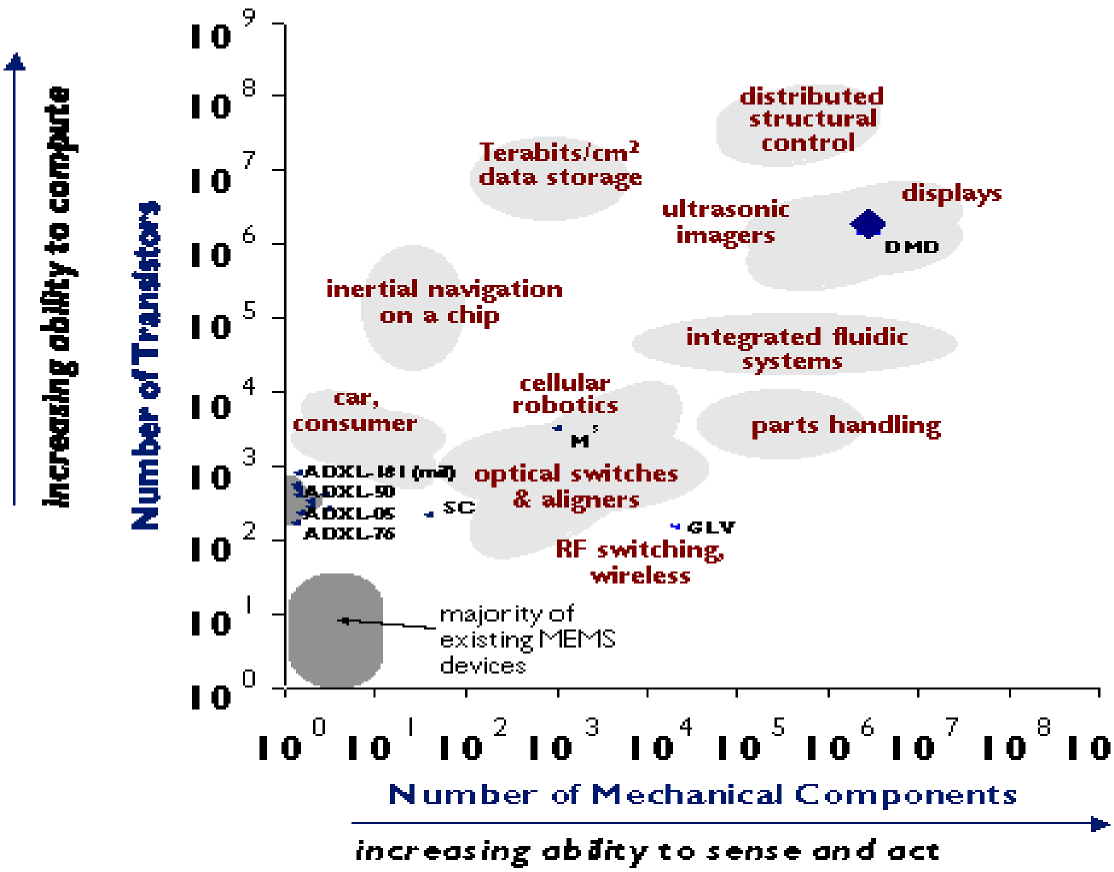
MEMS based accelerometers, microphones, pressure sensors, antennas, are being integrated with Integrated Chip (IC) products leading to new applications. Yet to reach the end-user, MEMS technology must become commercialized enough, which happens when some level of standardization is present.

1.0 **Introduction**

Micro Electro-Mechanical Systems (MEMS) are integrated micro devices or systems combining electrical and mechanical components fabricated using Integrated Circuit (IC) compatible techniques. These systems can sense, control, and actuate on the micro scale and function individually or in arrays to generate effects on the macro scale. Using similar fabrication techniques as for ICs, we can build sensors and actuators on the same chip. They indeed compose a 'system on a chip'. Polysilicon is still the prevailing material used in both mechanical parts and electronic parts in MEMS sensors. Issues like strength, tear and wear, corrosion, are new challenging topics. The future trends of MEMS technology are shown in Figure 1.

Just like IC technology 30 years ago, MEMS technology is still in its juvenile age. Most of the MEMS sensors are still prototypes. How MEMS sensors would fail is not very well understood. At microscopic level, assumptions of macroscopic level will not always hold. Factors that can be ignored in macro scale become important in micro scale. Without sufficient attention on these factors, reliability and quality of MEMS sensors can be so impaired that they are unusable or even destroyed the moment after fabrication. Reliability is the hindering factor to prevent utilization of MEMS sensors in critical applications.

The challenging issues in MEMS technology development are reliability and standardisation. The reliability issues of MEMS sensors are more than a simple combination of electrical reliability, material reliability and mechanical reliability. Fabricating multiple devices on the same chip will have to deal with more failure modes. Complex interactions of cross-domain signals, interference and substances induce new failure modes. For sensor inputs, the chip will have to be exposed to environmental stimuli, such as heat, humidity, vibration, etc. one of the ways of understanding reliability and standardization issues of MEMS is to understand the details of the MEMS Fabrication Process.



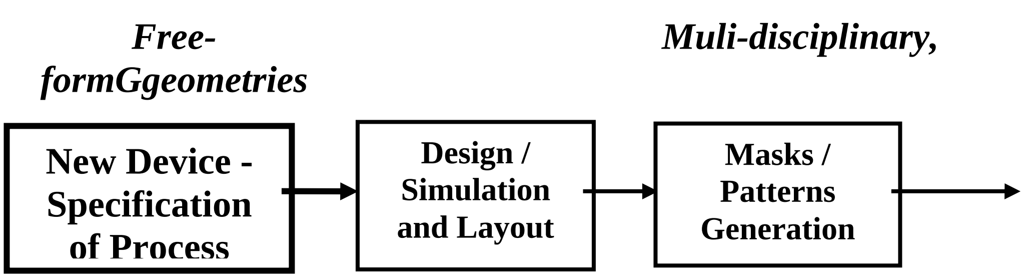
MEMS Technology Advances Across Various Applications

Figure 1

2.0 **MEMS Fabrication Process**

Many MEMS device failures are introduced in the fabrication process, and many failure modes and reliability issues in operation are also related to the fabrication process. Being miniature embedded systems themselves, MEMS sensors are usually batch fabricated using a process similar to those used in IC technology, using silicon wafers as the material and etching techniques to build components. MEMS fabrication process is more complicated, as it has to have mechanical parts and electro-mechanical parts integrated with electronic parts on the same die. They usually have more complex shapes, have moving joints and pivots, need more material strength, and may even need lubrication.

The design process flow for MEMS is shown in Figure 2 and MEMs Fabrication Process is shown in Figure 3. The distinctions between MEMS and ICs are in bold italics. In the design phase, complex CAD tools having the ability to model complex 3D objects have to be used for MEMS. The challenge is the simultaneous modeling of devices in many domains, including electronic, mechanical, chemical, and the ability to analyze cross-domain effects.



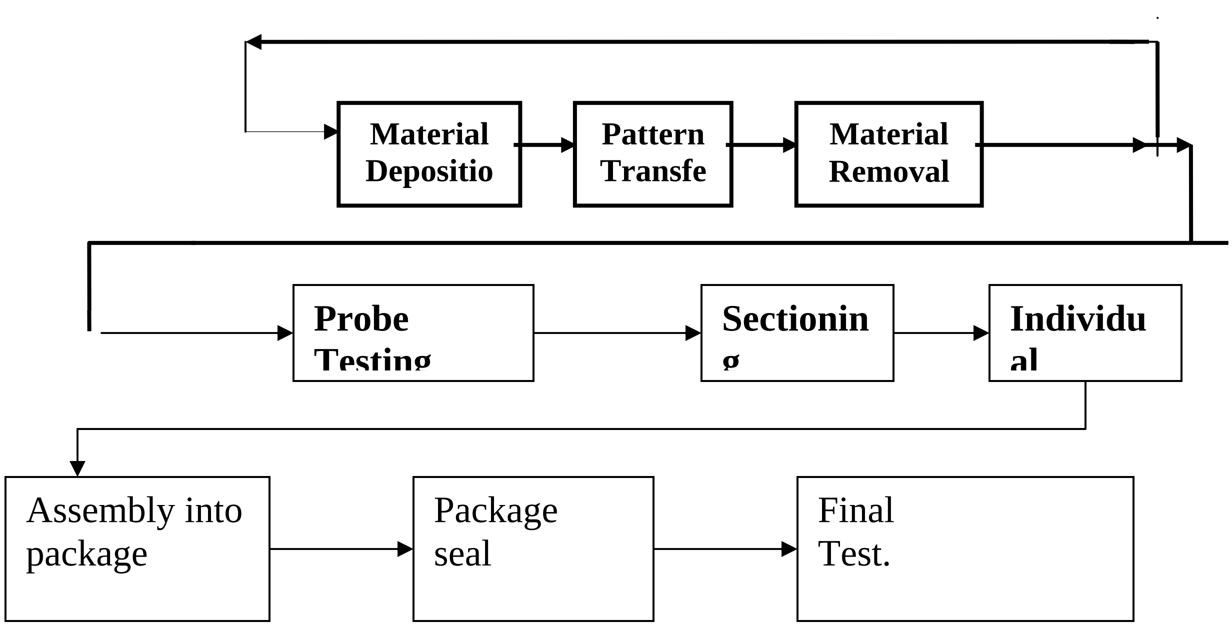
MEMS Design Process Flow

Figure 2

In the cycle from material deposition to material removal, mechanical parts need special attention. Mechanical parts may have complex shapes and may require material with special strength, and will have mechanical parts that can move freely. So the film of material deposited must be thick enough to form the mechanical layer. The process is repeated multiple times until the required device is constructed. Common processing techniques to sculpt mechanical structures include bulk micro-machining, wafer-to-wafer bonding, surface micro-machining, and high-aspect ratio micro-machining.

Removal of underlying material

to release mechanical parts.



MEMS Fabrication Process Flow

Figure 3

Bulk micro-machining is the term applied to a variety of etching procedures that selectively remove material, typically with a chemical etchant whose etching properties are dependent on the crystallographic structure of the bulk material. Wafer-to-wafer bonding is a strategy commonly employed to get around the restrictions in the type of structures that can be fabricated using bulk micro-machining. Because anisotropic etching, by definition, only removes material, bonding of wafers allows for the addition of material to the bulk micro-machining repertoire. High-aspect ratio micro-machining is a newer technique, which allows the fabrication of thick (usually greater than hundreds of microns and up to centimeters thick), precision, high-aspect ratio MEMS structures (structures with near-vertical sides). In surface micro-machining (SMM), alternating layers of structural (usually Polysilicon) and sacrificial material (usually silicon dioxide) are deposited and etched to form the shape required. Surface micro-machining enables the fabrication of free-form, complex and multi-component integrated electromechanical structures, giving freedom to fabricate devices and systems without constraints on materials, geometry, assembly and interconnections. Surface micro-machining is at the heart of the current activity in MEMS.

Testing is very important for quality and reliability purposes. Testing MEMS sensors is unique. Compared to electronic devices, that have electric voltage/current as input and electric voltage/current as output, MEMS sensors may have a closed loop, from sensors to actuators. The input can be temperature, humidity, loudness, acceleration, etc., and the output can be various electrical or mechanical responses. Testing MEMS sensors require the proper setup of inputs and accurate measure of the outputs.

Packaging is the Achilles heel of MEMS manufacturing. Unlike IC packaging, MEMS packaging is an application-specific task. MEMS packages must have the ability to meet at least one or more of the following criteria:

a) Isolate non-sensing areas from the sensing areas, often in harsh, corrosive, or mechanically demanding environments;
b) Not impede mechanical action, such as tilting, twisting, rotating, sliding, or vibrating;
c) Allow the transfer of fluids from one region to another;
d) Allow the coupling of energy, motion, or momentum from one region to another; and

e) Not transfer mechanical strain, heat, pressure, moisture, and so on to the part in the package.

3.0 **Reliability issues**

Following the same path taken in IC technology, Wafer Level Reliability (WLR) has received increasing interest in recent years. Polysilicon is the major material used to construct both the electric and mechanical parts of MEMS sensors. It is an ideal material, not only because it is the most abundant solid element in the Earth's lithosphere, but also because of its high strength. At least presently, material strength is not a key limiting factor in MEMS performance and reliability, i.e. fracture, wear and tear of the material are not the dominant causes of MEMS failures. The material can endure sustained high stress so that it can be used in joints, beams and springs. However, failures induced by wear can be found in parts that involve sliding motion and operate in stress. Little evidence was found in support of corrosion wear. Surface fatigue, deformation and impact wear typically require forces in excess of those for abrasive wear. Again such forces were not applied. Fretting wear occurs where machine elements experience fluctuating loads, leading to microcracks and fatigue failure.

4.0 **MEMS Common Failure Modes**

A summary of common failure modes for MEMS structures include:

External Particulate Contamination

Particles, which might be internally generated, or present in spite of a clean room environment, could naturally be expected to have a detrimental mechanical or electrical effect on devices where small gaps exist between bearing surfaces or elements with large potential differences.

Fused Components due to Overdriving

Overdriving (when large voltages are applied), leading to inadvertent contact of structural and electrical members leading to fused components suchas in springs and comb fingers. Overdriving occurs when large voltages are applied.

Sticking and Static Overload

Sticking occurs between contacting surfaces. It can affect even elements that are not powered. Many MEMS operate at stress levels in the vicinity of 1 GPa. In several cases high stresses are necessary to overcome stiction in membrane geometries. Small defects that act as critical cracks at these stress levels can be introduced by etching, polishing, or rough handling.

Electrostatic Clamping of Gears (Links)

Clamping of gears due to electrostatic charges takes place at certain energy levels, preventing the gears from moving.

Delamination

High stresses can be associated with multilayer films, introduced by processing, thermal mismatch, or epitaxial mismatch leading to delamination.

Environmental Attack

MEMS are designed for a variety of applications where environmental effects can be important. This includes valves, sensors, and pumps where the contacting fluids, including water, can be corrosive.

Fatigue and Creep

Any process that results in an irreversible repositioning of atoms within a material can contribute to fatigue. Stiction is the mechanism by which released MEMS structures are attracted and stick to each other. The generic route to failure observed for all rotating devices involves sticking of structures that are in sliding contact.

The increasing use of metal as a structural material in MEMS where room temperature creep exists should be of concern to MEMS manufacturers.

5.0 **Failure Analysis (FA) and FA Techniques**

Failure Analysis is one of the methods for improving reliability. Almost all the failure analysis techniques in IC can be used in MEMS. Complete listing of failure analysis techniques are provided.

Optical Microscopy

Optical microscopy is one of the most valuable and widely used tools in the FA of MEMS. The features that can be observed optically include textures, stains, debris, fracture, and abnormal displacements.

Scanning Laser Microscopy (SLM)

Scanning laser microscopy has been used primarily to obtain confocal images. A confocal image is an image with a very limited depth of field (depth of focus) created by inserting an aperture in the optical path. By taking a series of confocal images at different focal planes, an extended depth-of-focus image can be constructed. The extended depth-of-focus image is particularly useful in resolving elements which have abnormal vertical displacements.

Scanning Electron Microscopy (SEM)

The SEM has been useful for imaging defects at high magnification as well as determining electrical continuity in static and operating microengines. Passive and active voltage contrast techniques have identified structures at potentials different from those expected. Passive voltage contrast is defined as contrast which arises from voltage differences induced by rastering the beam causing various elements reach an equilibrium potential through self-charging. Active voltage contrast is defined as that arising from external application of voltage on different structures. In both cases, contrast is generated by differences in secondary electron emission yields caused by differences in surface potential. efficiency.

Atomic Force Microscopy (AFM)

The atomic force microscope (AFM) provides very detailed topographic images and surface traces.

Infrared Microscopy

Infrared microscopy is often used to construct thermal images based on the infrared radiance emitted from the structures. Hot spots can be found using infrared microscopy.

Acoustic Microscopy

Acoustic microscopy was employed on stationary microengines in an attempt to resolve contact between stuck gears and links and the substrate. This technique is more destructive to the sample due to the introduction of water as a coupling fluid. The acoustic signal could not be translated into evidence of sticking, although morphological features were resolved.

6.0 **Techniques for Improving Reliability**

Once MEMS failure modes are identified, techniques targeted to eliminate the corresponding problems can be used to improve the reliability of MEMS sensors.

Chemical surface treatments

Stiction is a major cause of the failures of MEMS sensors. A liquid echant used in fabrication process can cause moving parts to stick when dried. Hydrophobic coating and improved release etches and drying schemes such as super-critical CO_2 drying have done much to lessen its impact. While coupling agents and other coating materials are being investigated to reduce stiction, the long-term effectiveness remains largely unexplored. The development of manufacturable methods to stabilize the properties of surfaces is critical to the continued commercialization of MEMS sensors.

Model-based operational methods

Constraint forces can result in overstress and wear-out of the parts. Improper operational methods, i.e. those not using model-based drive signals designed to minimize parasitic constraint forces, can significantly degrade performance of MEMS. Consequently, the method of operation must be seriously considered when developing MEMS that are to be highly reliable.

Clever design modifications

Clever design modifications to the parts that fail frequently can improve its reliability and prolong its life. Thickness, stiffness, and shape, etc are typical factors of concern. For example, lateral clamping can be mitigated by changing the shape of the interface between the alignment guides and the comb shuttle. Specifically, the gaps at the ends of the comb fingers when they are fully engaged are made large enough that the parasitic force due to the end fringing fields is negligible.

7.0 **Standardization Motivation**

MEMS based accelerometers, microphones, pressure sensors, antennas, RF switches and embedded memory chips, are being integrated with Integrated Chip (IC) products and leading to new applications. Yet to reach the end-user, MEMS technology must become commercialized enough, which happens when some level of standardization is present.

Radio Frequency (RF) MEMS represent a growing segment of micro system component design and implementation. They are also developed for switching applications such as Transmit/Receive Duplexers (TDD), band/mode selection, time-delay for phased-array, antenna diversity or reconfigurable antennas. MEMS varactors are often used for VCO tuning, variable matching or variable delay line applications. MEMS also provide low loss inductors or filters for band-select filters, IF channel filters, RF filter banks, VCO stabilization or image rejection. Yet the rapid growth of the MEMS industry has been impeded by a general lack of reliable material properties, understanding of processing effects on materials, and process variables. It is often stated that there is no standard process in MEMS. Due to the fact that MEMS offer many more degrees of design freedom than ICs and because approximately 90% of available MEMS sensors are produced in captive fabs, it is possible that there will never be a MEMS “standard process” in the IC sense. What can and should be standardized, however, are methods of characterizing a process and its associated material properties. Standardization of Materials Characterization will enhance accuracy and efficiency of Design and Simulation tasks (or phases) by offering a higher rate of first pass success.

Standardization may also be achieved by adding consistency between measurement techniques. MEMS reliability issues such as yield, fatigue, creep, charging and contact physics must also be investigated. The MEMS Industry Group (MIG), a non-profit industry organization has recently released a MEMS reliability study that indicates that customers demand reliability demonstrations. To help achieve these goals, MIG has embarked on a MEMS reliability initiative that includes a web-based reliability database.

With these issues in mind, any standardization effort must involve identification and selection of relevant material properties, identification of conditions, both processing and ambient, that affect material properties, and specification methods of metrology (measurement). Likewise the industry must extend process control through the use of Standard Test Methods and Statistical Analysis.

8.0 **Conclusions**

MEMS technology will merge the functions of compute, communicate and power together with sense, actuate and control to change completely the way people and machines interact with the physical world. Using an ever-expanding set of fabrication processes and materials, MEMS will provide the advantages of small size, low power, low mass, low cost and high functionality to integrated electromechanical systems both on the micro as well on the macro scale.

MEMS will open up a broad new array of solutions only if they prove to be sufficiently reliable. In order to rapidly take advantage of this technology, reliability must be considered concurrently with technology development. Failures induced by deficiencies in material/mechanical properties are not the majority, such as fracture strength or fatigue-related fracture. Failure causes are typically related to contacting or rubbing surfaces: Stiction and friction-related wear. Corresponding measures to minimize those failures can be taken to improve MEMS reliability. Chemical surface treatments are effective against sticking after drying of liquid etchant. Model-based operational methods can minimize parasitic forces, eliminate overstress and wear-out of critical parts. Clever design modifications will rule out some common failures observed.

MEMS technology is still in its infancy, like IC technology 30 years ago. Focus has been put in wafer level reliability, the same path taken in the IC technology. Presently how MEMS fail is still not well understood. Available tools and techniques are mostly improvised versions from IC tools. Reliability models are scarce.

MEMS technology has strong ties to semiconductor processes and Electronic Design Automation (EDA) tools, such that there is a strong effort to integrate MEMS technology with IC development. This is especially true in RF MEMS design. By developing our own MEMS industry material property methodology, we may borrow much of the processing methodology from the IC world. Design and simulation tools are already at a highly sophisticated level and are prepared for this challenge. In order to expedite MEMS standardization, the industry must design test structures that measure specific material properties and processing effects, derive models in suitable formats, adapt the structures to specific process flows, develop test methods for test equipment and arrange these elements in widely distributed standards.