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SURVEY OF QUALITY AND RELIABILITY PROBLEMS IN DESIGN OF MEMS

Keywords: MEMS, Quality, Reliability, Failure Modes, Fault Simulation

The interdisciplinary nature of MicroElectroMechanical Systems (MEMS) utilizes design engineering and manufacturing expertise from a wide and diverse range of technical areas.

In order to produce a high reliability and quality MEMS we must not only examine the device itself, but must also examine the entire process surrounding the devices, from conception to finish. This means that the process must be qualified, with the supplier fully investigated, the design verified, and the packaging certified.

The paper presents a survey of the various aspects of MEMS, with emphasis on its reliability and quality features in the design phase.

1. INTRODUCTION

The essence of MEMS is that they are small devices that perform mechanical tasks in ways and, more importantly, in quantities that conventional devices cannot.

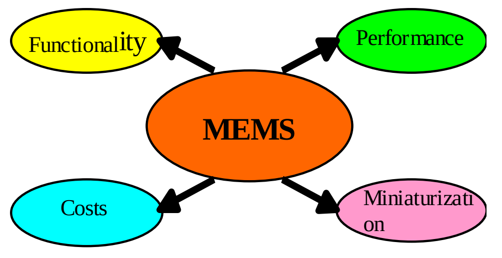

Fig. 1. The potentials of MEMS

The interdisciplinary nature of MEMS including integrated circuit fabrication technology, mechanical engineering, materials science, electrical engineering, chemistry and chemical engineering, as well as fluid engineering, optics, instrumentation and packaging.

The complexity of MEMS is expressed in the extensive range of markets and applications In order to produce a high reliability MEMS the manufacturers must not only examine the device itself, but must also examine the entire process surrounding the device, from conception to finish [1]. This means that the process must be qualified, with the supplier fully investigated, the design verified, and the packaging certified. While the potentials of MEMS (Figure 1) are al most limitless, production of commercial devices has been heretofore limited. MEMS, as products of a young industry, remain largely prototypical The MEMS reliability will need to rapidly mature. The main goal of this paper is to point the MEMS special features and basic similarities in design requirements to provide a means of developing high quality and reliability MEMS devices.

2. DESCRIPTION OF MEMS BASIC FEATURES

In the most general form, MEMS is shown schematically in Figure 1.

The main advantages of MEMS are:

- Interdisciplinary nature of technology, micro machining techniques and application
- Increased performance and reliability
- Reduced physical, size, volume, weight, and cost.
- Provided the basis for the manufacture of products that cannot be made by other methods.

Figure 3 illustrates the classifications of microsystems technology (MST). Although MEMS is also referred to as MST, strictly speaking, MEMS is a process technology used to create these tiny mechanical devices or systems, and as a result, it is a subset of MST.

Despite the many similarities between IC and MEMS fabrication, MEMS makers, or foundries, are still in their adolescence. The widening variety and increasing complexity of MEMS products make the MEMS foundry business extremely problematic. Although the fabrication technology is similar, the technology is on a different scale.

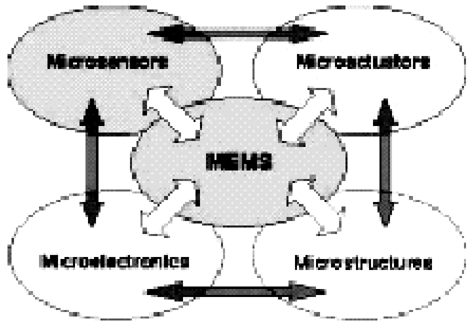

Fig. 2. Schematic illustration of MEMS components

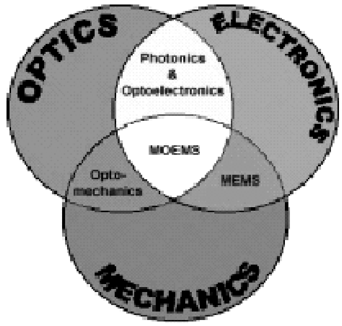

Fig. 3. Classifications of microsystems technology [1]

3. MEMS MATERIAL PROPERTIES, PROCESSING TECHNIQUES AND DEVICE ELEMENTS

MEMS are constructed out of a multitude of materials, each of which has unique reliability implications. Different materials have different responses to failure mechanisms that need to be understood to better device reliability.

3.1. Material properties

A) Substrates

The most common substrate material for micro machining is silicon (Si). Other crystalline semiconductors including germanium (Ge) and gallium arsenate (GaAs) are used as substrate materials due to similar inherent features.

B) Additive Films and Materials

- Silicon-single crystal, polycrystalline and amorphous
- Silicon compounds (Si_xNy, SiO_2, SiC etc.)
- Metals and metallic compounds (Au, Cu, Al, ZnO, GaAs, IrO_x, CdS)
- Ceramics (Al_2O_3 and more complex ceramic compounds)
- Organics (diamond, polymers, enzymes, antibodies, DNA etc.) [1]

3.2. Processing Techniques

Adaptations in the processes used to manufacture integrated circuits have led to the development of MEMS and will continue to define the dimensional limitations in devices. It is ultimately these technologies that determine the specifications and reliability characteristics of any given device. As such, they are critically important to understanding MEMS. In the fabrication of common MEMS devices, there are two basic techniques employed: bulk and surface micromachining. These two processes, are the basis for any MEMS fabrication technology.

I. Microfabrication Processing Steps

There is a variety of processing techniques that are often used in all MEMS processes [2]. The degree to which they are successfully implemented in any given technology determines the viability of the technology. They are listed below to give a basic description of MEMS processing.

A. Thin Film Growth and Deposition: Spin Casting, Evaporation, Sputtering. Reactive Growth, Chemical Vapor Deposition, Plasma Deposition

B. Photolithography: Mask Fabrication, Alignment and Exposure

C. Etching and Patterning Techniques: Lift-off, Wet Etching, Dry Etching

II. MEMS Fabrication Processes

Bulk micromachined devices have reliability concerns that vary with the processes used to fabricate them. While bulk materials have well understood properties, the mechanical attributes of surface micromachined devices depend upon thin film processing conditions. The LIGA process can have great variability across process runs. Another problem with LIGA is that the injection molding process and mold separation processes require almost perfectly vertical structures. This issue has become a strong factor in the device yield of LIGA technology. One issue that is an area of concern in GaAs processing is the internal film stresses created by thermal mismatch in GaAs-AlxGa1-xAs heterostructures. As well as using CAD for mask design, CAD and finite element analysis (FEA) are important simulation tools for the design of MEMS applications. Unfortunately there is a lack of adequate advanced software based design tools to fully model, analyse and simulate MEMS. Despite certain successful high volume applications, high yields are difficult with MEMS devices due to their mechanical complexity and their integration with the necessary micro-electronics. Assembling and packaging complex microscopic parts is also extremely difficult. If semiconductor microfabrication was seen to be the first micromanufacturing revolution, MEMS is the second revolution.

Table 1

MEMS fabrication processes

MEMS FABRICATION PROCESSES
A.Bulk Micromachining *1) Wet Etch 2) Dry Etch 3)Wafer Bonding 3a) Anodic, 3b)Low-Temperature, 3c)Glass ,3d)Fusion*
B. Surface Micromachining
C. LIGA
D. GaAs Processing
E. Computer Aided Design (CAD)
F. Assembly and System Integration

Table 2

Classification of the common device elements

COMMON MEMS DEVICE ELEMENTS
Structural Beams
Thin Membranes
Hinges
Piesoresistive *Transdusers* *Sensors*
Tunneling Tips
Electrostatic Actuators and Transducers *Parallel Plate Capacitors Comb Drivers Micromotors*
Magnetic Actuators
Thermal Actuators *Bimetallic Strips* *Shape Memory Alloys*
Piezoelectric Actuators and Devices

3.3. Common Device Elements

While a completed MEMS is a complicated device, the individual components of any given system are much simpler to understand. Due to the nature of MEMS processing, no single component can be very complex. This is turn means that understanding of a MEMS device can be gained through knowledge of few simple parts and understanding how they interact. To ensure the reliable operation of a MEMS device is it sufficient to ensure the reliable operation of all the constituent parts.

4. FAILURE MODES AND MECHANISMS OF MEMS

One of the great obstacles to qualifying MEMS is the individuality of the devices. The roots of reliability are namely failure. In order to accurately study MEMS reliability, the nature of failures must be quantified. Failure may be separated into two distinct categories:

- Degradation failure, which consists of device operation departing far enough from normal conditions that the component can no longer be trusted for reliable operation;
- Catastrophic failures, which are, as the name implies, the complete end of device operation.

Table 3

Classification of MEMS failure modes and mechanisms

<table>
<tr><th colspan="9">FAILURE MODES AND MECHANISMS</th></tr>
<tr><td colspan="9">A) Mechanical Fracture</td></tr>
<tr><td rowspan="2">Stress Indused Failure</td><td colspan="3">Point Defects</td><td rowspan="2">Ftige</td><td colspan="2">Dislocation</td><td rowspan="2">Fracture Strength</td><td>Precipitates</td></tr>
<tr><td>Vacancies</td><td>Intertitial</td><td>Point replacement</td><td>Edge</td><td>Screw</td><td></td></tr>
<tr><td colspan="9">B) Stiction</td></tr>
<tr><td colspan="9">C) Wear</td></tr>
<tr><td colspan="9">D) Delimination</td></tr>
<tr><td colspan="9">E) Stray Stresses</td></tr>
<tr><td colspan="9">F) Electrostatic Parasitic Capacitance</td></tr>
<tr><td colspan="9">G) Dampening Effects</td></tr>
<tr><td colspan="9">H) Environmentally Induced Failure Machanism</td></tr>
<tr><td>Vibration</td><td>Radiation</td><td>Humidity effects</td><td>Temperature changes</td><td>Particulate</td><td>Shock</td><td colspan="3">Electrostatic discharge</td></tr>
</table>

The identification and mitigation of failure mechanisms in MEMS is both one of the most important and one of the newest issues in MEMS. A critical part of understanding the reliability of any system comes from understanding the possible ways in which the system may fail. In MEMS, there are several failure mechanisms that have been found to be the primary sources of failure within devices. In comparison to electronic circuits, these failure mechanisms are not well understood nor easy to accelerate for life testing.

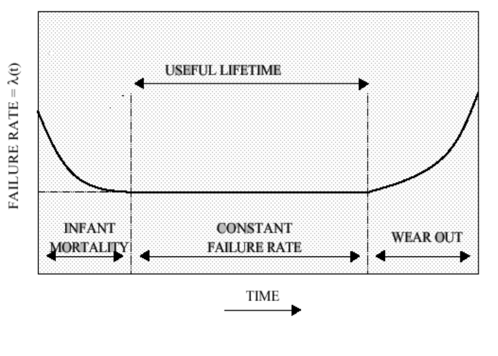

Fig. 4. The MEMS failure rate curve

5. QUALITY ASSRANCE AND QUALIFICATION

To accomplish the leading manufacturers of MEMS enforce the quality control from three standpoints: design, production and finished product. The reliability of MEMS [3} is represent by a failure rate curve as shown in Figure 4. By looking at a plot of failure rate over time, it is possible to derive substance in formation about reliability. A decreasing failure rate will typically justify initial testing and burn-in.

5.1. Quality Assurance

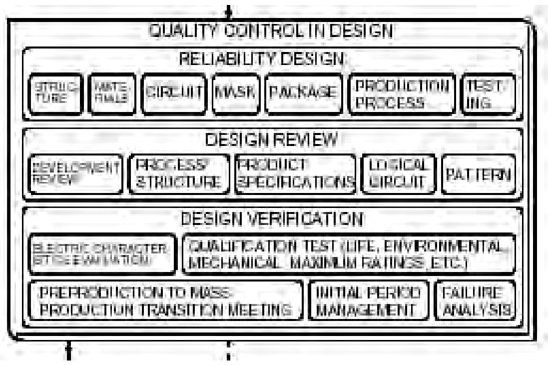

Fig. 5. *Procedure of MEMS Quality control in design phase*

A typical quality assurance system that covers quality control in design is shown in Figure 5. The quality control in design builds the specifications and quality of the product. It focuses on optimization and review of structure, materials, circuit design, packaging and production process. For each device product type, a prototype is fabricated to verify the characteristics and reliability before mass production begins. Three development levels can be defined for MEMS:

- *Level I*: Developing products with new design rules, materials, and process technology;
- *Level II*: Modifying the design to mass-produced products, or partially modifying processes, packages, materials, and equipment;
- *Level III*: Using the current processes and packages or those of similar or slightly modified quality levels;

Fault three analysis (FTA) or another method can be used to review the design. After a prototype is fabricated then MEMS undergoes a qualification test that checks whether their electrical characteristics, maximum ratings, and reliability meet the quality target.

5.2. Qualification

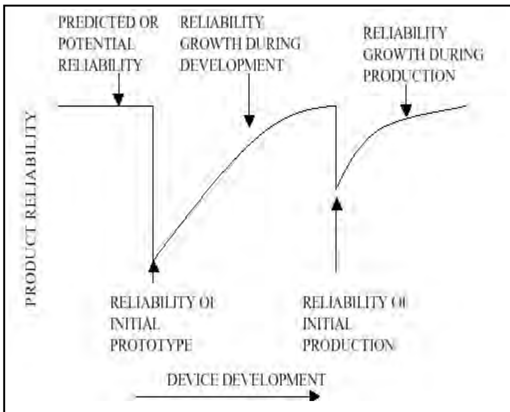

Fig. 6.Reliability over the development cycle

The specifics of qualifying a MEMS device depend upon the specifics of the process, materials, and structures in a device. The reason that specific standards were not set for MEMS is that many people within the electronics community have complained that these standards limit their device development. In order to improve reliability, qualification should begin as early as possible (Figure 6). To decrease initial failure rate and improve reliability the MEMS manufacturers are carrying out production quality control and improvement activities and screening including electrical characteristics testing and burn-in. To reduce random failures they have to enforce quality control in the design stage and formal testing (endurance evaluation with life tests, environmental, mechanical tests, quantitative tests) and design verification.

6. FAULT SIMULATION METHODOLOGY FOR MEMS

To support fault simulation and testability analysis in MEMS, it is necessary to model both the mechatronic and electrical elements within the same simulation environment to ensure the efficient injection and analysis of faults (Figure 7). Failure Mode and Effect Analysis (FMEA) [4], is well accepted by the system design industries, whereas fault simulation tends to be restricted to low level components unless behavioural modelling techniques are used. To illustrate the need for the integration of the two methods, a brief analysis of the types of faults that can occur in MEMS devices reveals the following categories:

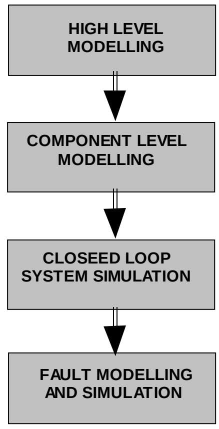

Fig. 7. Flow diagram of MEMS Fault simulation methodology

- Local defects
- Parameters out of tolerance
- Wear (especially in devices with movable parts)
- Environmental hazards
- Problems due to imperfection in the design process (i.e. design validation poor compared to mixed-signal designs)
- Mode coupling / structure oscillation in incorrect modes
- System level faults (for example crosstalk between signals of different modules)

Since the FMEA is performed at different levels of hierarchy, failure modes can be predicted at an early stage of the design. To be able to handle a fault in a closed-loop system simulation it has to be modelled at either the component level or the lumped level.

Since defects and parametric variations occur either within or between components, they can be modelled at the component level.

To enable modelling of FMEA failure modes, it isnecessary to categorise these failures to the level of modelling they require. The following categorisation is proposed:

- Failures that are directly linked to certain components.
- Failures that can be modelled at the lumped level.

5. CONCLUSIONS

In order to increase innovation and creativity, and reduce unnecessary "time-to-market" costs, an interface should be created to separate design and fabrication. As successful device development also necessitates modeling and simulation, it is important that MEMS designers have access to adequate analytical tools. Therefore more powerful and advanced simulation and modeling tools are necessary for accurate prediction of MEMS device behavior. Due to the relatively low number of commercial MEMS devices the pace at which the current technology is developing, standardization has been very difficult. In order to match the projected need for MEMS scientists and engineers, an efficient and low cost education methodology is necessary. One approach is industry driven academic research centers offering, technology-specific programmes with commercial integration, training and technology transfer.

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