MICROSYSTEMS AND RELIABILITY

Titu-Marius I. Băjenescu, prof. Dr.eng.
Elveția

1. INTRODUCTION

The advancement of microdevices technologies (Figure 1) in recent decades has resulted in innovation to the automotive, communication and medical industries where size and mass reduction have improved performance of microsensors and microactuators, such as accelerometers for inertial measurement, mass-flow sensors, bio-chips for microfluidics, RF switches and automotive pressure sensors.

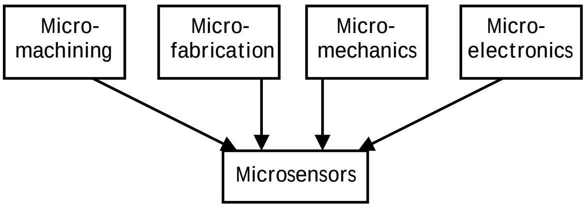


Figure 1. *Basic engineering areas involved in microdevices technology.*

Microelectromechanical systems (MEMS), or microsystems, have expanded in every possible direction as shown in Figure 2.

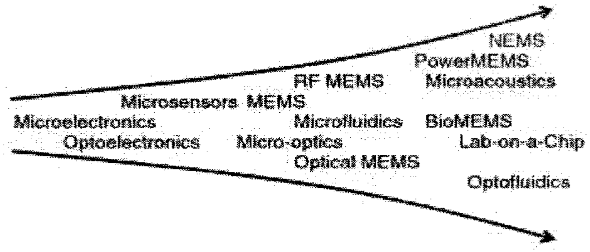


Figure 2. *Evolution of microtechnology subfields.*

MEMS are an electromechanical integrated system where the feature size of components and the actuating range are within the micro-scale. Unlike traditional mechanical processing, manufacturing of MEMS device uses the semiconductor production process, which can be compatible with an IC, and includes surface micromachining and bulk micromachining. Due to the increasingly mature process technology, numerous sophisticated micro structural and functional modules are currently available.

In MOEMS, or optical MEMS, silicon can be machined to make tilting mirrors, adjustable gratings and adaptive optical elements. The micromirror of figure 3 takes advantages of silicon's smoothness and flatness for optics and its mechanical strength for tilting.

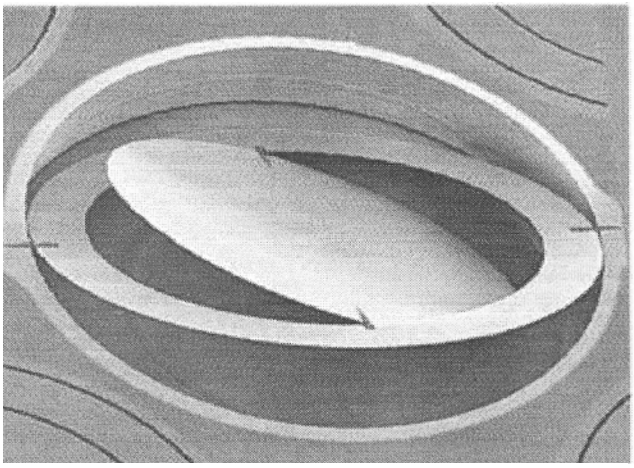


Figure 3. *Micromirror made of silicon, 1 mm in diameter, is supported by torsion bars 1.2 μm wide and 4 μm thick (after [1]).*

The advent of the nanotechnologies has provided unlimited possibilities for molecular sensors design and applications, but the fast moving frontiers have also made it a daunting task for learners to capture the essential design principles and methods behind the implementations. The design and construction of molecular systems capable of performing complex logic functions is of great scientific interest now. Logic operations from the simplest to small-scale integrated cases are now available on molecular level.

With applications ranging from medical diagnostics to environmental monitoring, molecular sensors (also known as biosensors and chemical sensors – Figures 4 and 5), along with emerging nano-technologies, MEMS offer not only valuable tools but also unlimited possibilities for engineers and scientists to explore the world.

The reliability of MEMS has increased rapidly in the past 12 years, with highly reliable micromachined devices being used by the dozens in modern automobiles, and with MEMS accelerometers and gyroscopes becoming commonplace in many consumer handheld devices. MEMS devices are sold by the hundreds of millions per year, with failure rates below ppm. MEMS devices are sold by the hundreds of millions per year- with failure rates below ppm. In modern cars microsensors and micromechatronic actuators play an essential and still increasingly important role as the interface between the vehicle with its complex functions of motor management, chassis systems, safety as well as comfort and convenience on the one hand and the respective electronic control units on the other hand. They have to fulfil their task in a harsh environment over the entire lifetime of an automobile. Therefore reliability aspects have moved more and more into the focus of engineering and research activities in microsystem technology.

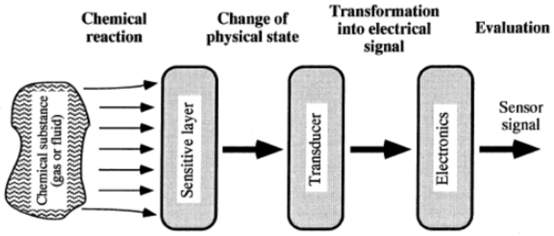


Figure 4. *The structure of a chemical sensor system (after [2]).*

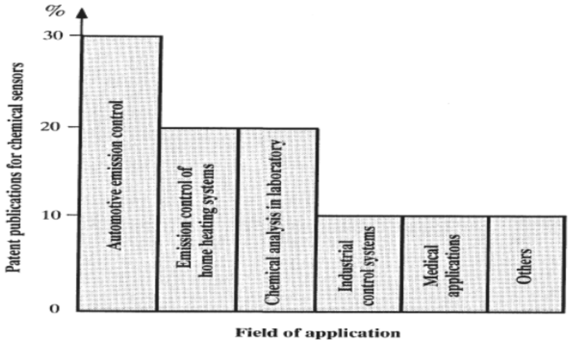


Figure 5. *Fields of application of chemical sensors [2].*

2. MICROSENSORS

A sensor (Figure 6) is a device that converts a non-electrical physical or chemical quantity into an electrical signal; it detects or measures some physical phenomenon such as heat or pressure. Most microsensors are fabricated on a silicon substrate using the same processing technologies as those used for ICs. Microsensors have been developed for measuring force, pressure, position, speed, acceleration, temperature, flow, and a variety of optical, chemical, environmental, and biological variables.

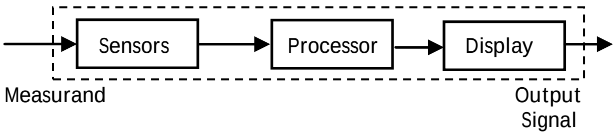


Figure 6. *The block scheme of a microsensor.*

3. MICROACTUATORS

An actuator converts a physical variable of one type into another type, and the converted variable usually involves some mechanical action. An actuator (Figure 7) causes a change in position or the application of force. Examples of microactuators: pumps, valves, positioners, switches, rotational and linear motors.

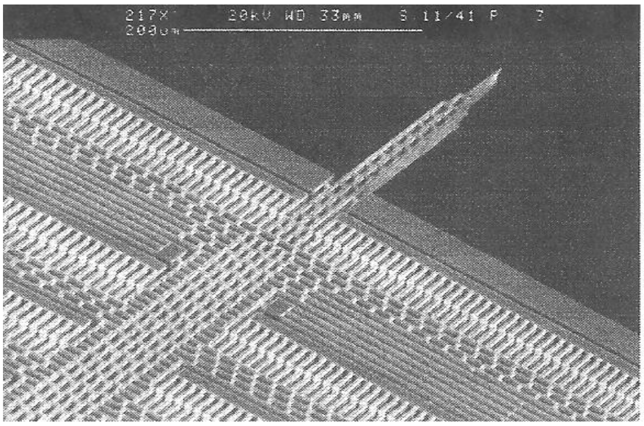


Figure 7. *SEM detail view of an electrostatic silicon actuator with integrated tip for lateral atomic force microscopy (AFM) measurement (after [3]).*

Microstructures and microcomponents: Micro-sized parts that are not sensors or actuators. Examples: microscopic lenses, mirrors, nozzles, and beams; these items must be combined with other components in order to provide a useful function.

Microsystems and micro-instruments: Integration of several of the preceding components with the appropriate electronics package into a miniature system or instrument. They tend to be very application specific. Examples: micro-lasers, micro-spectrometers, optical chemical analyzers. The economics of manufacturing these kinds of systems have tended to make commercialization difficult.

Industrial applications of microsystems: thin-film magnetic heads, compact disks, automotive components, ink-jet printing heads, medical applications, chemical and environmental applications.

4. INK-JET PRINTING HEADS

- Currently one of the largest applications of microsystem technology.
- A typical ink-jet printer uses up several cartridges each year.
- Today’s ink-jet printers have resolutions of 1200 dots per inch (dpi).

This resolution converts to a nozzle separation of only about 21 μm, certainly in the microsystem range.

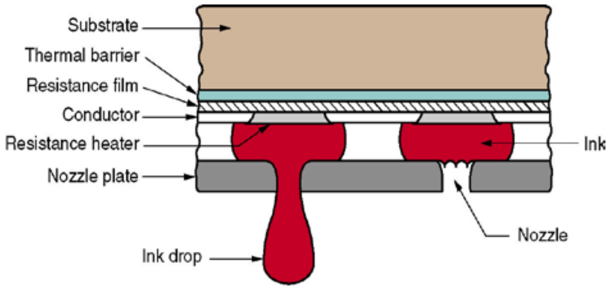
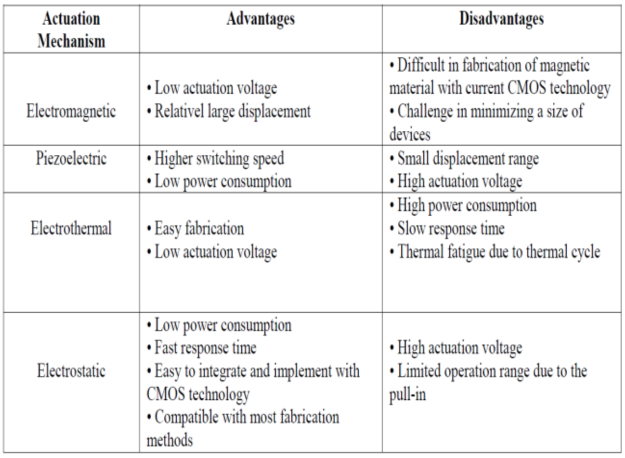


Figure 8. *Diagram of an inkjet printing head.*

5. ACTUATION MECHANISM

There are several actuation mechanisms present today which can be classified as direct and indirect actuation methods. For direct methods, the most common is by the use of a PZT (Pb-Zr-Ti transducer or, as it is sometimes called, piezoelectric z-axis actuating transducer), which is capable of vibrating at different frequencies very accurately depending on the driving voltage. Indirect methods may include using acoustic vibration to shake a microsensor much like a piece of paper in front of a speaker vibrates from the compression waves in the air. Another indirect method has a magnetic coat deposited on a microsensor such as a cantilever and an inductance coil underneath it to generate magnetic fields that attract and repel the cantilever into vibration [5].

Table 1. *Summary of Actuation Mechanisms [5].*



Actuation Mechanism	Advantages	Disadvantages
Electromagnetic	• Low actuation voltage • Relativel large displacement	• Difficult in fabrication of magnetic material with current CMOS technology • Challenge in minimizing a size of devices
Piezoelectric	• Higher switching speed • Low power consumption	• Small displacement range • High actuation voltage
Electrothermal	• Easy fabrication • Low actuation voltage	• High power consumption • Slow response time • Thermal fatigue due to thermal cycle
Electrostatic	• Low power consumption • Fast response time • Easy to integrate and implement with CMOS technology • Compatible with most fabrication methods	• High actuation voltage • Limited operation range due to the pull-in

Different fabrication processes allow us to build microactuators that can be actuated in different manners; i.e., electromagnetic actuation requires ferromagnetic materials, usually Ni, to be deposited on microactuators, and this process is not compatible with standard CMOS processes. Hence, a custom process is usually employed to build electromagnetic actuators. Even though many unique actuation methods are developed, the conventional actuation methods are electromagnetic, piezoelectric, electro-thermal and electrostatic actuation (Table 1).

6. ELECTROSTATIC MEMS

Electrostatic MEMS is a special branch with a wide range of applications in sensing and actuating devices in MEMS. It is necessary to understand the effects of electrostatic forces in MEMS [4] and then many phenomena of practical importance, such as pull-in instability and the effects of effective stiffness, dielectric charging, stress gradient, temperature on the pull-in voltage, nonlinear dynamic effects and reliability due to electrostatic forces occurred in MEMS can be explained scientifically, and consequently the great potential of MEMS technology could be explored effectively and utilized optimally.

Electrostatic actuation is one of the most popular actuation methods for microactuators fabricated by MEMS technologies, despite its high actuation voltage and limited operation range due to the pull-in phenomenon. Another advantage is that electrostatic actuators can be easily built by many fabrication methods, which are compatible with most CMOS technologies that are employed in order to manufacture modern analog and digital devices [5].

Without an understanding of the effects of electrostatic forces in MEMS, many phenomena of practical importance, such as instability, nonlinearity and reliability in MEMS cannot be explained scientifically, and consequently the great potential of MEMS technology could neither be explored effectively nor utilized optimally. Therefore, it is important and necessary to investigate the dynamic characteristics of the electrostatic force and its nonlinear effects on MEMS devices in microscale.

Reliability of sensing and actuating devices due to electrostatic forces is a very young and important field in MEMS. A failure is said to occur when an electrostatic microstructure or its system no longer performs the required functions under the specific conditions within the stated period of time. There have two main failures: irreversible failures and degradation failures. Figure 9 illustrates the methodology of the reliability analysis for electrostatically actuated MEMS devices. Table 2 shows the common failure modes and mechanisms of the electrostatically actuated devices in MEMS.

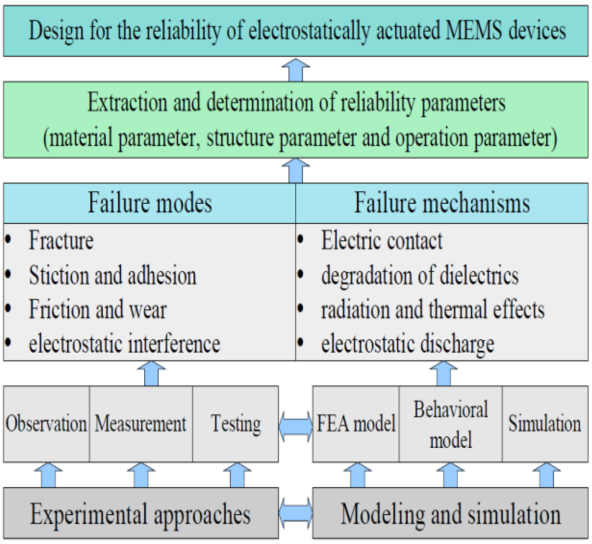


Figure 9. *Methodology of reliability analysis for the electrostatically actuated MEMS devices (after [6]).*

Table 2. *Common failure modes and mechanisms of the electrostatically actuated devices in MEMS (after [6])*

Failure mode	*Failure mechanism*	*Example*	*Ref.*
Stiction and adhesion	Surface contact	Comb finger actuator beam	7, 8
Electrostatic Interference	Electrical contact	Electrostatic micromotor	9, 10
Dielectric changing and breakdown	Nuclear radiation	Accelerometer RF MEMS switch	11,12, 13
Wear and friction	Surface contact and rubbing	Micromotor microengine	14, 15
Fracture	Implicit and applied Stress	Comb finger actuator	16

Nearly all RF MEMS switches are based on an in-plane suspension bridge or cantilever design under electrostatic actuation. Many electrostatically actuated MEMS devices involve surfaces contacting or rubbing against one and other, resulting in friction and wear [17]. The operation of micromachined devices that have contacting joints and bearings is significantly affected by friction and wear of the contact surfaces involved (Figure 10). Severe wear of the pin joint and wear debris near the rubbing surfaces was evident. Wear of rubbing surfaces was the dominant mode of the failure for the microengine.

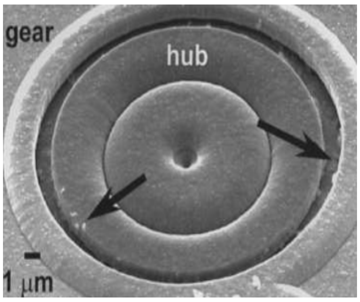


Figure 10. *SEM image of characteristic wear debris on the drive gear and the hub (after [15]).*

7. MICROFABRICATION PROCESSES

Microfabrication is the collection of techniques used to fabricate devices in micrometer range; its applications include ICs, MEMS, microfluidics, micro-optics, nanotechnology and countless others.

Many microsensor technology products (MST) are based on silicon; reasons why silicon is a desirable material in MST: *(i)* Microdevices often include electronic circuits, so both the circuit and the device can be made on the same substrate. *(ii)* Silicon has good mechanical properties: high strength and elasticity, good hardness, and relatively low density. *(iii)* Techniques to process silicon are well-established.

8. OTHER MATERIALS AND MST PROCESSING

MST often requires other materials in addition to silicon to obtain a particular microdevice. Example: microactuators often consist of several components made of different materials. Thus, microfabrication techniques consist of more than just silicon processing: *(a)* LIGA (*in German:* Lithographie, Galvanoformung, Abformung) process; *(b)* Other conventional and nontraditional processes accomplished on a microscopic scale.

9. DIFFERENCES BETWEEN MICROFABRICATION AND IC FABRICATION

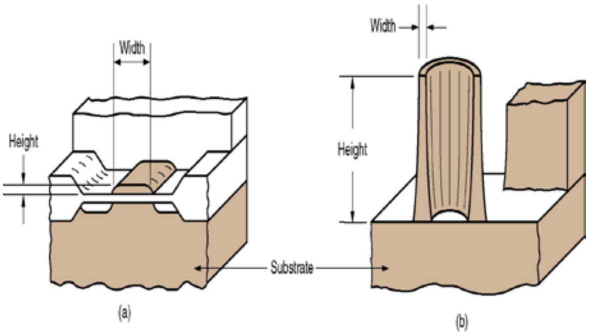


Figure 11. *Aspect ratio (height-to-width ratio) typical in* ***(a)*** *fabrication of integrated circuits and* ***(b)*** *microfabricated components (after [18]).*

– Aspect ratios (height-to-width ratio of the features) in microfabrication are generally much greater than in IC fabrication;

– The device sizes in microfabrication are often much larger than in IC processing;

– The structures produced in microfabrication often include cantilevers and bridges and other shapes requiring gaps between layers.

10. 3D FEATURES IN MICROFABRICATION

- Chemical wet etching of polycrystalline silicon is isotropic, with the formation of cavities under the edges of the resist. However, in single-crystal Si, etching rate depends on the orientation of the lattice structure.
- 3-D features can be produced in single-crystal silicon by wet etching, provided the crystal structure is oriented to allow the etching process to proceed anisotropically.

11. RELIABILITY ASPECTS

As scaling of the oxide thickness continues, it is obviously desirable to reduce the leakage current. It is also desirable to maintain or increase the reliability of such films. Continued scaling of the gate dielectric has precipitated the need for a greater and more detailed understanding of the issues pertaining to integration and reliability.

Reliability assessment of components, integrated circuits or micro-assembled devices, is one of the major factors conditioning the on-going development of microelectronics. In the same way, growing market penetration by nanotechnologies is clearly related to the imperative demonstration of satisfactory built-in operational reliability with respect to actual severe standards. This situation requires a specific effort on built-in reliability. These considerations must be integrated, as early as possible at the beginning of the development 'top-down' and the 'bottom-up' approaches.

Reliability issues cover extremely large scientific fields such as physics, material science, electrical transport, thermal phenomena, coupling interfaces between optics and electronics, statistical models, etc.

MEMS/MEOMS working in harsh conditions arising from the environment (space, corrosive gas, high pressure, high temperature >150°C, liquids, shocks) or from their operation (high current density – figure 12 -, large deflections, high voltages) are severely prone to reliability issues.

Reliability is of concern if MEMS/MEOMS machinery is used in critical applications. MEMS are usually a combination of electronic circuits and micro-machinery. The reliability aspect includes both the electronic and the mechanical parts, complicated by the interactions. Different from mechanical systems, inertia is of little concern; the effects of atomic forces and surface science dominate. Wafer level reliability (WLR) has received increasing interest in recent years. We still have limited knowledge on how MEMS/MEOMS devices fail. Limited tools and models are available. How to model the reliability of MEMS/MEOMS is a challenge.

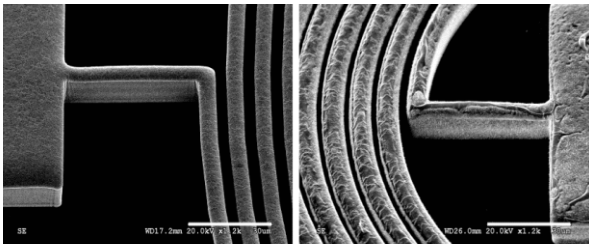


Figure 12. *Comparison between two identical on-wafer Cu-microcoils: an original one (left) and one after high current density stress (right) (after [19]).*

Another important challenge issue in achieving successful commercial MEMS products is associated with MEMS reliability. Reliability and qualification can be much more complex than for ICs. Many of the MEMS/MEOMS failure mechanisms are not yet well understood. This lack of understanding presents a challenge in developing practical qualification techniques for MEMS products. For the world of ICs there are industry standards tools and techniques for understanding and quantifying the reliability. For the world of MEMS this knowledge base is much more limited. In many cases, companies that do have a firm grip on techniques for quantifying reliability view that knowledge as a competitive advantage and are hesitant to share it. In order to develop reliable MEOMS devices, reliability must be considered at the earliest stages of product development. Decisions made in the design stage can result in devices that will never be reliable. Reliability must be understood at a fundamental physical and statistical level. That is often a perspective that by there very nature MEMS will be unreliable because they have moving parts. The truth is this: it is no moving parts that kill reliability, but rubbing surfaces. MEMS can be designed with moving surfaces, but no rubbing parts, and can be very reliable. Avoiding rubbing surfaces is one of the key elements in achieving reliable MEMS devices. Environmental parasites (such as feed through capacitance, eddy currents and molecular contaminants) are identified as major performance limiters for RF MEMS. In general, the smaller the actuator, the smaller its force becomes, but measurement of such small force is difficult and dependable instruments are not currently available.

With the latest advances in wireless communications, new monitoring and supervisory control tools have been designed for industrial systems, avoiding unexpected failures and greatly improvising system reliability and maintainability.

12. FACTORS AFFECTING THE MICROSENSORS RELIABILITY

There are a number of factors that contribute to the reliability of MEMS/MEOMS, in particular: packaging, in bonding and sealing, material characterization relating to operating and environmental conditions, credible design considerations, the technique for mitigating intrinsic stresses / strains induced by fabrication and testing for reliability are a few of these factors.

A primary issue affecting the reliability is the packaging problem. Again it is useful to consider the case of ICs, while ICs are known for their reliability. It should be noted that ICs are packaged in such a way 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 devices. As with semiconductor dies, MEMS/MEOMS devices require to be attached to a package substrate. This requirement is very important in optical and sensor applications. Any die movement causes misalignment in optical packages. Also sensing is usually done through use of electrostatic actuators which are very sensitive to movement. Any die movement causes faulty sensing. Therefore the die attach material should be carefully chosen, so that the CTE differences are minimized as much as possible. As with semiconductors, the thermal expansion mismatch between MEMS/MEOMS and substrate induces stress on the package, which may cause reliability issues.

Packaging requirements of MEMS tend to be very diverse and at present no standardized packaging processes exist. This lack of standards in packaging processes has made it very difficult to develop generic models to predict the effects of packaging on micromachined devices. Packaging processes also influence the performance of the overall system. Packaging processes involving high temperatures, or using high TCE die attach materials can easily affect the thermo-mechanical behavior of the micromachined structures. In addition, special tools to handle MEMS devices with fragile micromechanical structures on them may be required. Some packaging processes such as wafer dicing, die attach etc. are quite intensive in generating particles. Common to all packaging efforts are the requirements of minimizing induced stresses in the micromachined parts from the package and packaging processes, meeting the required I/O needs of these systems, minimizing cost, and improving manufacturability. Pressure sensors and accelerometers were the first MEMS devices to be successfully commercialized. Yet the packaging needs of these systems are very different and exemplify the diversity of MEMS packaging needs.

While the precision of die mounting within the package is relatively unimportant, the package needs to isolate all the other parts of the microsystem except the pressure sensitive membrane from the sensing ambient. The use of intermediate layers introduces further uncertainties in the overall performance of the devices. Additional complexity is introduced in the packaging of differential or gage pressure sensors, from the need to interface the micromachined part to two pressure signals [20].

For the case of MEMS, some devices by their very nature require them to be exposed to the environment, creating a reliability challenge. The package that is designed for an electrostatic actuator (which is a moving device) follows different principles than a micro-fluidic channel. All MEMS packages used for electrostatic actuators must provide protection against moisture. Moisture dampens the microscopic movement of the actuator. Many MEMS devices are fabricated with ICs on a single substrate. Due to the heat generated by ICs, the properties of the material which MEMS are built upon them, change [21].

The type of MEMS devices that are the most reliable and the easiest to qualify are devices that can be packaged in such a way as to protect them from the environment. An excellent example of this is the case of optical MEMS devices. These devices can be packaged in a traditional ceramic package with a glass lid. The glass lid, hermetically attached to the ceramic package, creates a “safe” environment for the sensitive MEMS chip, while still allowing photons to interact with the MEMS device. The development of a robust MEMS DFM (design for manufacturability) strategy is realized by three capabilities that enable the so called concurrent engineering [22] of MEMS/MEOMS devices:

(*a*) Test structures with corresponding models and measurement setups that allow the extraction of material properties and determine process capabilities;

(*b*) Software capable to incorporate these materials and process specific variables and statistical data into the design and simulation stream;

(*c*) Stable processes proven for various common classes of MEMS devices supported by test structures that are dedicated to manufacturing analysis and yield improvement.

Design for manufacturability (DFM) is the general engineering art of designing products in such a way that they are easy to manufacture. The basic idea exists in almost all engineering disciplines, but of course the details differ widely depending on the manufacturing technology [23].

13. FAILURE MECHANISMS [27]

The development of high adhesion forces at micromachine interfaces during release-etch drying and/or operation often leads to permanent adhesion of contacting surfaces, a phenomenon referred to as *stiction*, hence affecting the micromachine yield and operation life.

For surface micromachining, stiction can occur when removing a chip from die liquid etchant, so that the suspended part is pulled towards the substrate surface where it remains stuck due to capillary forces. Sticking occurs between contacting surfaces. It can affect even elements that are not powered. Hydrophobic coating and improved release etches and drying schemes (such as super-critical CO_2 drying) have done much to lessen its impact. Most typical defects encountered include the break of suspended parts (suspended parts that are not adequately released from the substrate). Several mechanisms can prevent a full release of a suspended part in bulk micromachining [24]. These include the presence of unwanted oxide residuals that prevent adequate etching, insufficient etching, slow etching rate because of an inadequate solution and the formation of hillocks, or re-deposition of etched material that may occur after micromachining. Other typical effects of electrical overstress are circuit breaks due to high operating voltages.

The primary failure mode is directly related to visible wear on bearing surfaces [25].

14. FAILURE ANALYSIS [28]

Microelectronic failure analysis has been an integral part of the development of state-of-the-art integrated circuits. Failure analysis of MEMS is moving from its infancy to assume an important role in the successful design, fabrication, performance and reliability analysis for this new technology. The primary failure mode is directly related to visible wear on bearing surfaces.

Most FA techniques used for MEMS/MEOMS have been applied in the past for ICs; but some techniques are more specific to MEMS, given for instance the fact that they include moving parts. Some of the specific FA techniques include optical microscopy, optical interferometry, scanning electron microscope, focused ion beam, infrared microscopy, atomic force microscopy, acoustic microscopy and emission, scanning laser microscopy, laser cutting, or light emission [26] and Raman spectroscopy. The metrology techniques include profilometry, micro co-ordinate measuring machines, electron microscopy, optical microscopy, white light interferometry and laser Doppler velocimetry.

15. CONCLUSIONS

It is evident that the number of microscale sensors in our environment is set to increase. In some markets they are well established such as pressure sensors, gyroscopes and ink jet nozzles, which currently account for two thirds of the MEMS sensors market. The fabrication techniques are essentially two dimensional while the third dimension is created by layering. Micromachining techniques allow further structuring of devices in the third dimension, although this is limited, and complex three-dimensional fabrication is still in its infancy. Micro assembly promises to extend MEMS beyond the confines of silicon micromachining. Microsystems are rapidly evolving from individual transducer components into highly integrated complete systems on the same chip. While process technologists are obsessed to pursue Moore's curve down to nanoscale dimensions, design technologists are confronted with gigascale complexity. On the other hand, post-PC products require zero cost, zero energy yet software programmable novel system architectures to be sold in huge volumes and be designed in exponentially decreasing time. Conceiving these devices requires significant changes in the design and test flow. Computer-Aided Design (CAD) tools and validation procedures are to be created and prepared to face the new challenge. Looking forward, the success of any DFM approach for MEMS will be measured by the ability to select the best design option. This will result in higher yield and ramp-up to volume production in considerable shorter time scales than traditionally seen in the MEMS industry, exploring and exploiting the many design possibilities quickly and accurately by leveraging proven electronic design automation (EDA) methodologies.

Bibliography

1. ***Greywall D. S. et al.*** *Crystalline Silicon Tilting Mirrors for Optical Cross-Connect Switches. Journal of Microelectromech. Syst.,* 12(2003), 708–712.
2. *http://mspde.usc.edu/inspiring/resource/sensor/ Microsensors. pdf*
3. ***Geßner T.*** *Recent Progress of Microactuators. Proc. 7th Int. Conf. New Actuators,* Bremen: ASCO-Druck 2000, pp 62-70.
4. Janocha H. *Microactuators – Principles, Applications, Trends.* http://www.lpa.uni-saarland.de/ pdf/a2-1.pdf
5. ***Kumar J. S. J. et al.*** A Study of Why Electrostatic Actuation is Preferred and a Simulation of an Electrostatically Actuated Cantilever Beam for MEMS Applications. www.ijeset.com/.../2N15-IJESET 0605 424_v6_iss5_4...
6. ***Zhang W.-M. et al.*** *Stability, Nonlinearity and Reliability of Electrostatically Actuated MEMS Devices. Sensor Basel,* May 2007, 7(5), pp. 760-796.
7. ***Walraven J. A.*** *Failure Mechanisms in MEMS. ITC International Test Conference,* Charlotte, NC, USA, September 30-October 02, 2003**,** pp. 808-812.
8. ***Spengen W. M. V., Puers R., Wolf I. D.*** *A Physical Model to Predict Stiction in MEMS. J. Micromech Microeng.,* 2002, *12,* pp. 702-713.
9. ***Mehregany M. et al.*** *Operation of Microfabricated Harmonic and Ordinary Side-Drive Motors. Proc. 3rd. IEEE MEMS Workshop,* Napa Valley, CA, Feb. 1990, pp. 1–8.
10. ***Zhang W. M., Meng G., Li H. G.*** *Electrostatic Micromotor and its Reliability. Microelectronics Reliability, 45*(2005), pp. 1230-1242.
11. ***Lee S. et al.*** *Reliability Testing of Flexible Printed Circuit-Based RF MEMS Capacitive Switches. Microelectronics Reliability, 44*(2004), pp. 245–250.
12. ***Wibbeler J., Pfeifer G., Hietschold M.*** *Parasitic Charging of Dielectric Surfaces in Capacitive Microelectromechanical Systems (MEMS). Sensors and Actuators A, 71(1-2),* pp. 74-80.
13. ***Knudson A. R. et al.*** *The Effects of Radiation on MEMS Accelerometers. IEEE Trans. Nucl. Sci.,* Indian Wells, CA, USA, 43(6), pp. 3122-3126.
14. ***Gabriel K. J. et al.*** *In-Situ Friction and Wear Measurements in Integrated Polysilicon Mechanisms. Sensors and Actuators A,* 21-23, pp. 184-188.
15. ***Tanner D. M. et al.*** *Frequency Dependence of the Lifetime of a Surface Micromachined Microengine Driving a Load. Microelectronics Reliability,* 39, pp.401-414.
16. ***Kahn H. et al.*** *Fracture Toughness of Polysilicon MEMS Devices. Sensors and Actuators A***,** *82,* pp. 274-280.
17. ***Zhang W. M., Meng G.*** *Numerical Simulation of Sliding Wear Between the Rotor Bushing and Ground Plane in Micromotors. Sensors and Actuators A, Physical*, 126, pp. 15-24
18. www.ise.ncsu.edu/.../CHAPTER%2036%20-%20MIC...
19. ***Thrieu K.*** *Reliability of MOEMS in Harsh Conditions.* www.engineering.lancs.ac.uk/.../ LancasterMNT_D4
20. ***Tadigadapa S., Najafi N.*** *Reliability of MEMS. Proceedings of SPIE,* Vol. 4558 (2001), pp. 197-205.
21. Băjenescu T. I., Bâzu M. I. *Reliability of Electronic Components. A Practical Guide to Electronic Systems Manufacturing.* Springer, Berlin and New York, 1999.
22. ***Bigdeli S.*** *Material and Reliability Requirements for MEMS Packaging. National Semiconductor*, Santa Clara, CA, USA, 10 May 2003.
23. Băjenescu T. I., Bâzu M. I. *Reliability Engineering for Electronic Component Users.* Artech House, Boston and London, 2009.
24. *Castillejo A. et al. Failure Mechanisms and Fault Classes for CMOS-Compatible MEMS. Proc. of IEEE Int. Test Conference,* Washington DC, USA, pp. 541-550, October 1998.
25. ***Mir S.*** *Integrated Circuit Testing: From Microelectronics to Microsystems. TIMA Lab. Research Reports,* 2003.
26. ***Peterson K. A. et al.*** *Failure Analysis of Surface-Micromachined Microengines. Proc. of Material and Device Characterization in Micromachining Symposium,* Santa Clara, CA, USA, Vol. 3512, pp. 190-200, 1998.
27. ***Băjenescu T.-M. I.*** *MEMS-Based Devices Relevant Failure Modes and Mechanisms. EEA,* vol 61(2013) nr. 3, pp. 16-20.
28. ***Bâzu M., Băjenescu T.-M. I.*** *Failure Analysis – a Practical Guide for Manufacturers of Electronic Components and Systems,* Wiley, 2011.

Recommended for publication: 12.07.2017.