START *Selected Topics in Assurance Related Technologies*

Volume 8, Number 1

MicroElectroMechanical Systems (MEMS)

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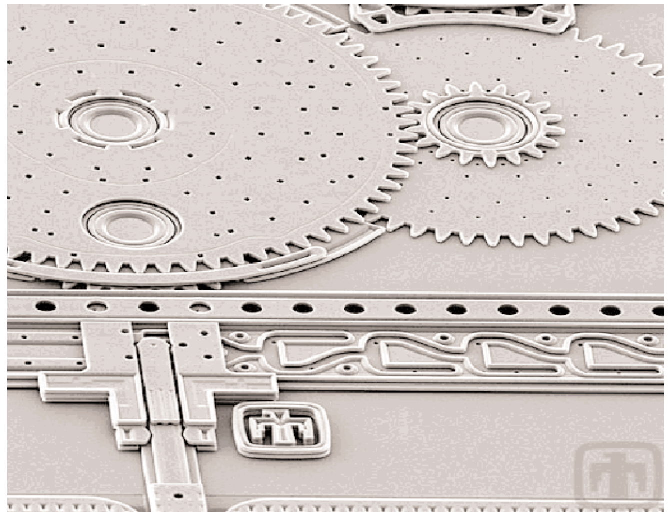

A linear, 24-bit locking mechanism. Courtesy, Sandia National Labs - MEMS, S&T Department, <www.mems.sandia.gov>.

Introduction

MicroElectroMechanical Systems, or MEMS, represent an extraordinary technology that promises to transform whole industries and drive the next technological revolution. These devices can replace bulky actuators and sensors with micron-scale equivalents that can be produced in large quantities by fabrication processes used in integrated circuit photolithography. This reduces cost, bulk, weight and power consumption while increasing performance, production volume, and functionality by orders of magnitude. For example, one well-known MEMS device is the accelerometer for a car airbag – a $3 chip that replaced a system of conventional mechanical sensors costing over $80.

Furthermore, it is clear that current MEMS products are simply precursors to greater and more pervasive applications to come, including genetic and disease testing, guidance and navigation systems, power generation, RF devices (especially for cell phone technology), weapons systems, biological and chemical agent detection, and data storage. Micromirror-based optical switches have already proven their value; several start-up companies specializing in their development have already been sold to large network companies for hundreds of millions of dollars. The promise of MEMS is increasingly capturing the attention of new and old industries alike, as more and more of their challenges are solved with MEMS.

Background

MEMS are, in their most basic forms, diminutive versions of traditional electrical and mechanical devices – such as valves, pressure sensors, hinged mirrors, and gears with dimensions measured in microns – manufactured by techniques similar to those used in fabricating microprocessor chips. The first MEMS products were developed in the 1960s, when accurate hydraulic pressure sensors were needed for aircraft. Such devices were further refined in the 1980s when implemented in fuel-injected car engines to monitor intake-manifold pressure. In the late 80s, MEMS accelerometers for car airbags were developed as a less expensive, more reliable, and more accurate replacement for a conventional crash sensor. Taking the spotlight today are optical MEMS (also known as Micro OptoElectroMechanical Systems, or MOEMS), primarily micromirrors, which are used as digital light processors in video projectors and as switches in optical network equipment.

After extensive development, today's commercial MEMS – also known as Micro System Technologies (MST), Micro Machines (MM), or M3 (MST, MEMS & MM) – have proven to be more manufacturable, reliable and accurate, dollar for dollar, than their conventional counterparts. However, the technical hurdles to attain these accomplishments were often costly and time-consuming, and current advances in this technology introduce newer challenges still. Because this field is still in its infancy, very little data on design, manufacturing processes, or reliability are common or shared.

MEMS Types and Characteristics

To understand the basic principles of MEMS reliability, it must first be noted that very little is understood about mechanics and materials at the microscopic level. At this scale, many common physical principles – such as inertia and gravity – have insignificant effects, and atomic and surface forces dominate micromachine behavior. Even when the material is known to have fully-understood properties at the macro scale, such as friction and wear, almost completely new tribological data must be catalogued when dealing with micron-sized features.

Consider two of the major categories of MEMS devices: sensors and actuators. Sensors, such as accelerometers and gyroscopes, tend to have no moving parts that operate under the conditions of sliding friction. As such, many of their performance characteristics may be measured with conventional tools used in the microelectronics industry. On the other hand, actuators such as micromirrors, microengines and gears represent an entirely different class of devices that requires the characterization of their electrical *and* their mechanical properties. Therefore, custom tools are required to analyze and measure their performance and reliability. Laboratories and companies have written proprietary software and developed test stands for this purpose. Furthermore, the material properties in both device categories are still relatively unknown, and conventional methods for determining them are largely ineffective. In order to mitigate some of the undesirable effects of these unknown factors, tight process controls are implemented to ensure consistent performance (and thus a calculable failure rate) of the MEMS device; however, the difficulty in improving that failure rate remains, and more research must be done to properly model material behavior.

MEMS devices are fabricated using a number of materials, depending on the application requirements. One popular material is polycrystalline silicon, also called “polysilicon” or “poly”. This material is sculpted with techniques such as bulk or surface micromachining, and Deep Reactive Ion Etching (DRIE), proving to be fairly durable for many mechanical operations. Another is nickel, which can be shaped by PMMA (a form of plexiglass) mask plating (LIGA), as well as by conventional photolithographic techniques. Other materials – such as diamond, aluminum, silicon carbide and gallium arsenide – are currently being evaluated for use in micromachines for their desirable properties; e.g., the hardness of diamond and silicon carbide. To create moveable parts, several layers are needed for structural and electrical interconnect (ground plane) purposes, with so-called “sacrificial” oxide layers in between. The current manufacturing record is five layers, making possible a variety of complex mechanical systems. These capabilities, developed over the last several years, are beginning to unlock the almost unlimited possibilities of MEMS applications.

Failure Issues

The primary obstacle to overcome in MEMS is adhesion – that is, one moving part sticking to another part or to the ground plane. Also known as stiction, adhesion occurs under various conditions: e.g., two clean surfaces in contact, the surface tension of an etchant (pulling two structures together) during the etching release of a MEMS device, or an electrostatic attraction due to a trapped charge. Some solutions to the adhesion problem are relatively straightforward (such as increasing the number of layers of a poly spring to minimize out-of-plane movement) and some require more effort (such as coating a device with a self-assembling monolayer to eliminate capillary action).

Another concern is operational wear in actuators. Although some MEMS have been shown to operate for billions of operating cycles, the erosion of sliding surfaces – and the particulate contamination that results from such action – must be controlled for MEMS to realize their commercial potential. Various solutions include: using harder structural materials (e.g., diamond instead of poly), liquid and solid lubricants, optimizing device design, and optimizing the frequency of the operational cycle. Unfortunately, the effectiveness of many of these approaches is determined by trial and error, the effects of which varies from application to application, and may introduce new, unexpected difficulties as well. It is expected that the field of microtribology and nanotribology will have to be expanded in order to adequately address the needs of microsystems.

A third major issue is packaging, a problem that appears to be the focus of numerous failure modes. Normal IC packaging is hermetically sealed to prevent contamination. A few MEMS devices (such as accelerometers) may be packaged with similar standards, but others require interaction with the outside world – e.g., gas detectors, medical “lab-on-a-chip” systems, and optical switches (requiring optical windows) – and are therefore subject to intrusion by unwanted factors through those openings. A dust mote can wreak serious havoc on an actuator of comparable size, and stray radiation can similarly damage sensitive components; solutions must maintain functionality while minimizing vulnerability. Similarly, a micromachine that requires free space to function is in additional danger to contamination during manufacture. Also, a MEMS device must contend with heat dissipation, power supply, input and output signals, and other factors. Companies have produced various solutions to deal with these; few, if any, are standardized (except for those borrowed from the IC industry). Packaging standards must be further developed if there is to be widespread acceptance of MEMS in conventional systems.

Although these challenges in adhesion, wear, and packaging have led to an abundance of research, companies have met with very limited commercial success. Institutional researchers are making significant headway into these issues, but the momentum towards commercialization is still slow; MEMS will require time to gain more substantial interest – and therefore resources – from industry.

Monolithic Integration of MEMS with CMOS

One sought-after potential of MEMS is the ability to integrate the functions of sensing, actuating, control and processing on one piece of real estate – reducing cost, size, and possible points of failure. However, MEMS require processing steps that are incompatible with some CMOS fabrication processes when combined on the same chip: if the MEMS were fabricated first, the processing would make the remaining surface finish unacceptable for CMOS photolithography; on the other hand, if the CMOS were fabricated first, then the heat from the MEMS processing would cause the aluminum to contaminate the stoichiometry of the doped silicon and cause it to fail. These problems make "system-on-a-chip" integration a difficult feat.

A number of solutions attempt to address these problems. One is to fabricate the CMOS design using tungsten instead of aluminum, thereby allowing the chip to undergo a subsequent MEMS fabrication without adversely affecting the CMOS portion. Another solution is to fabricate the MEMS portion first, placing the assembly in a "trench" slightly below the surface of the wafer. Once the MEMS devices are finished, the entire trench is filled and sealed with an oxide. The wafer is then planarized by chemical-mechanical polishing, thus making the wafer surface acceptable for conventional CMOS photolithography. After the fabrication of the circuit, the oxide is etched away, freeing the MEMS devices. A third solution involves an analysis of the MEMS and CMOS architecture to develop a complex, interleaved, custom process that allows the manufacturer to fabricate both simultaneously. Although innovative, each of these solutions creates their own unique set of manufacturing challenges; the benefits of any approach must be weighed against its costs and complexity.

Remaining Challenges

Despite the widely published excitement about MEMS and the emergence of new MEMS-based products, there are still a number of fundamental challenges to overcome before microsystems enjoy the same prevalence and manufacturability as is attributed to the integrated circuit. One prevailing obstacle is the inadequate characterization of materials at the micron level. There is significant controversy today about the accuracy of various methods for determining fracture strength, for example. Also complicating matters is the fact that different fabrication methods yield different properties using the "same" material. Without a more thorough understanding of materials' behavior at this scale, model development will be excruciatingly slow and consequently, technological progress will be stunted.

Another challenge is the lack of data on MEMS, especially the lack of standards and of reliability data shared among the current industry players. Although it is reasonable to expect companies to guard their data in order to maintain their competitive advantage, it is also true that cooperation will facilitate a company's product development much more than if they had acted alone. Typically, government agencies and nonprofit organizations – such as IITRI's Reliability Analysis Center (RAC) – have acted as centers for such collaboration and data reposition, so that companies may anonymously share data with one another while remaining competitive. Companies are forming direct partnerships to consolidate their resources, as well. Once these formidable hurdles are overcome, MEMS development will explode, clearing the way for hundreds of research-stage devices to be developed into commercial products.

Conclusions

MEMS have a tremendous future in replacing the components of many commercial products used today. The medical, wireless (including cellular and network technologies), biotechnology, computer, automotive and aerospace industries are only a few that will benefit greatly from MEMS. Furthermore, this enabling technology promises to not only transform most major industries but to create entirely new categories of products. An almost infinite number of radical applications are possible because of its potential: nearly limitless functionality, infinitesimally small form factor, a phenomenal price/performance ratio, and an architecture that lends itself to mass production, all of which are advantages that drove the success of the integrated circuit. MEMS will be the indispensable factor for advancing technology in the 21st century.

For Further Study

Additional information on MicroElectroMechanical Systems (MEMS) can be obtained from the following web sites:

a. http://mems.sandia.gov
b. http://mems.isi.edu

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- 96-2 Impacts on Reliability of Recent Changes in DoD Acquisition Reform Policies
- 96-3 Reliability on the World Wide Web
- 97-1 Quality Function Deployment
- 97-2 Reliability Prediction
- 97-3 Reliability Design for Affordability
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- 00-3 Environmental Stress Screening
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Mr. Sunada graduated from Rensselaer Polytechnic Institute with a Management and Technology Master of Business Administration (MBA) in 1998, studying strategic management of emerging and developing technologies. He earned a B.S. in Physics from RPI, completed several reliability courses, and studied the management of information systems (MIS). He also holds a lifetime membership in the Sigma Pi Sigma National Physics Honor Society.

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The Reliability Analysis Center is a Department of Defense Information Analysis Center (IAC). RAC serves as a government and industry focal point for efforts to improve the reliability, maintainability, supportability and quality of manufactured components and systems. To this end, RAC collects, analyzes, archives in computerized databases, and publishes data concerning the quality and reliability of equipments and systems, as well as the microcircuit, discrete semiconductor, and electromechanical and mechanical components that comprise them. RAC also evaluates and publishes information on engineering techniques and methods. Information is distributed through data compilations, application guides, data products and programs on computer media, public and private training courses, and consulting services. Located in Rome, NY, the Reliability Analysis Center is sponsored by the Defense Technical Information Center (DTIC). Since its inception in 1968, the RAC has been operated by IIT Research Institute (IITRI). Technical management of the RAC is provided by the U.S. Air Force's Research Laboratory Information Directorate (formerly Rome Laboratory).