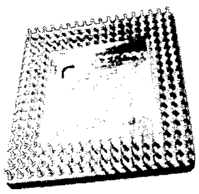

AN INTRODUCTION TO MICRO ELECTRO MECHANICAL SYSTEMS (MEMS)

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ABSTRACT

The remarkable progress of MEMS (Micro Electro Mechanical Systems) research has reached the stage where practical applications are intensely pursued. Based on high-performance systems commercial products have made remarkable progress in many fields. This paper discusses the underlying principles for MEMS, going over the materials and processes used for their fabrication. It also presents two state of the art examples, under development in the industry. A brief discussion of terminology is also included.

1.INTRODUCTION

Micro Electro Mechanical Systems (MEMS), also known as Micromechanics, Microsystems technology (MTS) or nanotechnology, is an interdisciplinary field of study committed to the physical integration of micromechanical systems with microelectronics, resulting in miniature embedded system that involve micromachined components and structures.

MEMS have been studied since the 1960's. The first devices appeared in the 70's and the public interest gave MEMS a boost in the 80's. During the last decade, the research has grown through funding from governmental agencies, involving researchers from universities and industries all over the world (MEMS Exchange, 2003). Most of this research and development has been directed toward the replacement of conventional technologies to increase functionality, reduce cost, and improve reliability.

The strong demand of these systems in different fields of work makes the study and general understanding of MEMS required for any engineer. This paper introduces the general concepts of this technology, by summarizing the materials and processes involved in fabrication, and provides a closer look at two applications where MEMS have been successfully implemented.

2.MEMS

Since their first appearance, Micro Electro Mechanical Systems have been studied for research groups around the globe. Their numerous applications have made their market grow exponentially.

2.1.Microengineering

The design and development of MEMS requires knowledge not only of one single field, but of different disciplines of science. This knowledge includes quantum mechanics, molecular theory of matter, mechanics thermo fluids and chemistry, just to mention a few. Figure 1 illustrates the relationship between some of these fields. The technology and techniques involved in MEMS are grouped in what is called Microengineering referring to the technologies and practice of making three dimensional structures and devices with dimensions in the order of micrometers.

2.2.State-of-the-art

The application of MEMS can be grouped in three major categories: passive structures, sensors and actuators. Currently, they are being used for many industries such automobile, aerospace, telecommunications and health care. The dominant applications are pressure and inertial sensors, and inject print heads. Work is also being done on high resolution displays and high-density storage devices. Figure 1 shows some of these applications.

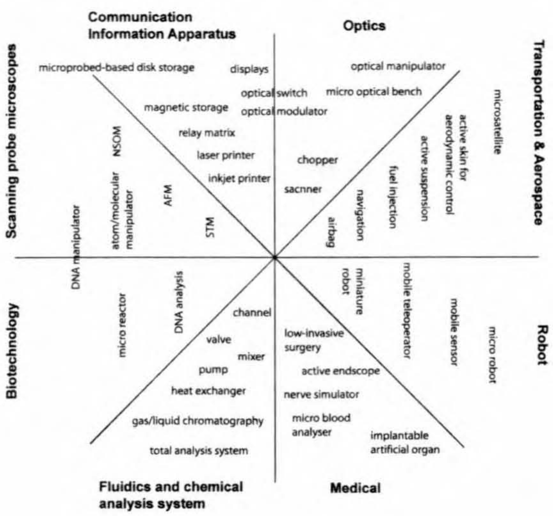


Figure 1.Applications of MEMS

Recent efforts have been directed towards biomedical and genetic engineering, developing new medical diagnostic tools and drug delivery systems. The market for MEMS has grown exponentially during recent years reaching 82 billion dollars in 2000.

3.MEMS FABRICATION

The origin of MEMS fabrication takes place in the integrated circuit (IC) industry. Most of the processes used to produce IC are used to develop MEMS. Some recent devices require certain specific processes or a combination of them for their elaboration. All these processes are referred to as Micromachining. Micromachining adds layers of material over a silicon wafer and etches precise patterns in these layers or in the underlying substrate.

3.1.Materials

The variety of materials used in MEMS is very broad. These materials are used as substrate material, where Silicon is by far the most commonly used. Exploration and development of new techniques drive the research in the use of new compounds, and thin films of silicon nitrides, oxides, glass, organic polymers and some shape-memory alloys.

The control of the mechanical properties and its extensive use, make silicon and polysilicon the materials of preference in industry (Petersen 1982). Figure 2 shows some silicon ingots and the crystal structure of this element.

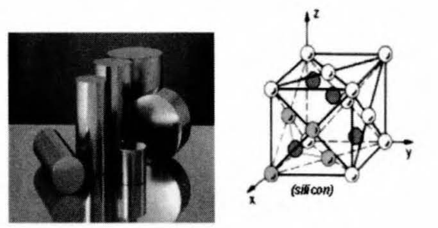


Figure 2. Silicon ingots and crystalline structure of silicon.

The study of crystallography and solid state physics are strongly encouraged for people interested in working with MEMS. The properties of a selected group of materials used on MEMS can be found in table 1.

3.2.Processes

Micromachining processes are divided into basic tools (well-established methods available

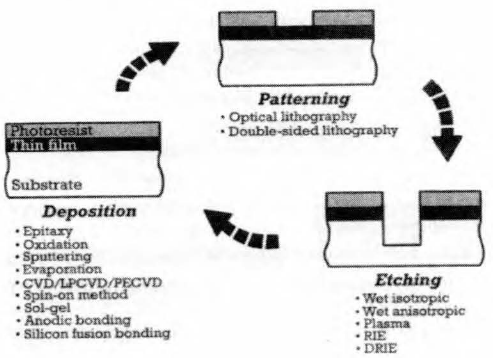
Table 1. Properties of selected materials

Property	Si	SiO_2	Si_3N_4	Quartz	SiC	AlN
Density (g/cm^3)	2.4	2.3	3.1	2.65	3.2	3.26
Specific Heat (J/g*K)	0.7	1.0	0.7	0.787	0.8	0.71
Hole mobility ($cm^2/V*s$)	400	-	-	-	40	-
Electron mobility	1500	-	-	-	1000	
Relative permittivity (ε_0)	11.8	3.8	4	3.75	9.7	8.5
Dielectric strength ($V/cm x 10^6$)	3	3-5	5-10	25-40	4	13
Melting temperature C	1415	1700	1800	1610	2830	2470

in most foundries) and advanced tools (unique in their nature and limited). Figure 3 show the basic process flow in micromachining. As previously mentioned, micromachining layers are deposited; photoresist is lithographically patterned, and then used as a mask to etch the underlying material.

The patterning is made by means of photolithography with three sequential steps: application of photoresist (photosensitive emulsion), its optical exposure to print an image of a mask (made using CAD tools) onto the resist, and the immersion in an aqueous developer to dissolve the exposed resist and render the image visible. More advanced techniques entail double-side lithography that requires a high degree of accuracy.

Figure 3. Basic process flow in micromachining



One of the most important processes in micromachining is etching, which involves the removing of materials in desired areas by chemical and physical methods. Chemical etching uses diluted chemicals like HF or Si3N4 to dissolve substrates. Two kinds of etching are available, isotropic (uniform in all directions) and anisotropic (just in preferred directions). Physical etching or plasma etching uses a stream of positive-charged-carrying ions of a substance with a large number of electrons. These ions bombard the surface of the target, gnawing out the substrate material from its surface (Hsu, 2002).

Figure 4 shows the use of these basic processes for the fabrication of a micromotor. Layers are deposited; photoresist is lithographically patterned and then used as a mask to etch the underlying material.

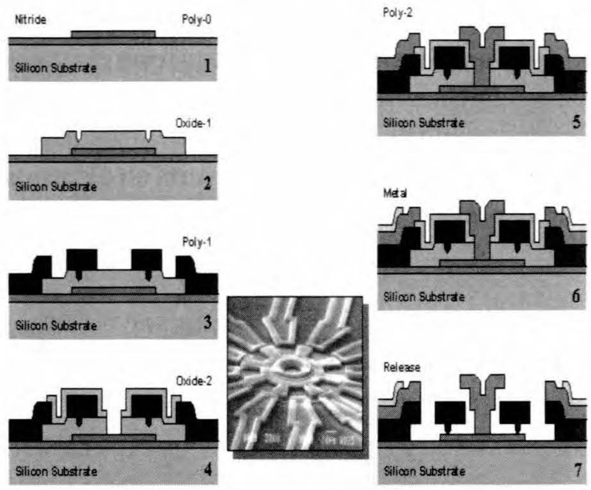


Figure 4. Micromotor design and processes steps.

More advanced techniques are used for the manufacturing of different devices. This group includes Lithography Electroforming and Molding (LIGA), Silicon Fusion Bonding and Reactive Ion Etching (SFB-DRIE) and Single Crystal Reactive Etching And Metallization (SCREAM). Given that the objective of this paper is to give an introduction, a more detailed explanation of every single one of all processes can be found in the references for this paper. It is important to note that the potential complexity of the systems increases with the number of unique process features and independent structural layers, as shown in figure 4.

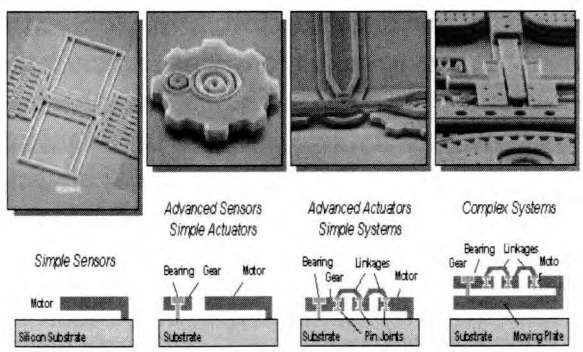


Figure 5. Device complexity by structural layers. From left to right 2, 3 , 4 and 5 levels of complexity.

4.MEMS STRUCTURES AND SYSTEMS

To have a better understanding of MEMS, it is important to go over the commonly used principles of applications: sensing and actuation.

4.1.Sensing and actuation

Sensors and actuators are special types of transducers. A sensor is a device that converts one physical or chemical quantity to an electrical one; some times an intermediate step takes place, for processing by the microsystem. Similarly, an actuator is a device which converts an electrical quantity into a physical or chemical one. (Banks, 1999)

Some of the sensing techniques rely on the properties of the materials used. One commonly used principle is the dependency of most materials' properties on temperature; piezoresistivity and piezoelectricity effects. Some other applications have their origin on capacitive sensing, relying on external parameters, changing the spacing or the relative dielectric constant between two plates of a capacitor (acceleration and relative humidity sensors). More over, another approach is its use of electromagnetic signals to detect and measure physical parameters (e.g. Magnetoresistive sensor in the read heads of high-density computer storage systems). Table 2 shows the characteristics of these methods.

Actuation methods can be grouped in five primary categories: electrostatic actuation, the attractive force between two plate elements carrying opposite charges (opposite in sign) in such way that an applied voltage results in a attractive electrostatic force; piezoelectric actuation; thermal actuation, which relies on the difference of the coefficients of thermal expansion between two joined layers, causing the structure to bend with temperature changes; magnetic actuation, based on the principle that an electrical current in a conductive element that is located within a magnetic field reacts to an electromagnetic force (Lorentz force) perpendicular to the current and magnetic field; and lastly actuation by Shape-memory alloys. Table 3 compares these actuation techniques on basis of the maximum energy output density.

Actuation	Max energy density	Physical & material parameters
Electrostatic	$\frac{1}{2}\varepsilon_0 E^2$	E = Electric field ε_0 = dielectric permittivity
Thermal	$\frac{1}{2}Y(\alpha\Delta T)^2$	α = coefficient of expansion ΔT = temperature rise Y = Young's modulus
Magnetic	$\frac{1}{2}B^2/\mu_0$	B = magnetic field μ_0 = magnetic permeability
Piezoelectric	$\frac{1}{2}Y(d_{33}E)^2$	E = Electric field Y = Young's modulus d_{33} = piezoelectric constant
Shape-memory alloys	-	Critical temperature

Table 3. Actuation techniques based on maximum energy density.

5.APPLICATIONS

To illustrate the applicability of this technology this paper presents two of the most prominent applications, Radiation Sensors and Digital Micromirror Devices.

Radiator sensor for infrared imaging (Sensing). The basic approach is to measure the change in temperature of a suspended sense-resistor. This temperature change is due to incident infrared radiation. The intensity level is then proportional to the change in resistance of the device. Figure 6 shows a single element in the infrared imaging array from Honeywell. This model achieves high sensitivity to radiation by providing extreme thermal isolation. (Cole, 1998).

Piezoresistive	Capacitive	Electromagnetic
Simple fabrication	Simple mechanical structure	Structural complexity varies
Low cost	Low Cost	Complex Packaging
Voltage or current drive	Voltage drive	Current drive
No need for circuits	Requires circuitry	Simple control circuits
High temperature dependence	Low temperature dependence	Low temperature dependence
Small sensitivity	Large dynamic range	Sensitivity a magnetic fields
Medium power consumption	Low power consumption	Medium power consumption

Table 2. Characteristics of Piezoresistive, Capacitive and Electromagnetic sensing methods.

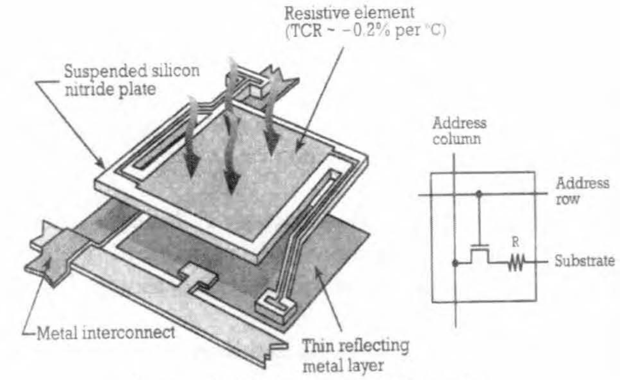


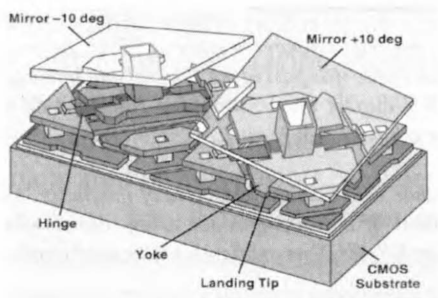
Figure 6. Single radiation sensor for infrared imager. (HoneyWell)

The square of silicon nitride is used as sense-resistor, 50μm by 50μm and 0.5μm thick. Its fabrication process relies on a surface micromachining approach, involving an organic layer, polyimide, rather than polysilicon. The fabrication is made in arrays of 240 by 336 pixels; the electronics offers multiplexing, scan and read-out operations, in exchange for the difficulties of having a single lead to each pixel.

Digital Micromirror Device (Actuation). This device consist in a two dimensional array of optical switching elements (pixels) on a silicon substrate. Each pixel consists of one mirror supported from a central post, mounted in a lower platform, suspended by two other compliant torsional hinges anchored directly to the platform.

Two electrodes positioned underneath the platform provide electrostatic actuation. This device DMD is a trademark of Texas Instruments (TI), U.S. patent #4615595. The angle of tilt is geometrically limited to 10°. Its control (state ON, +10°, or OFF, -10°, and duration) is made by a CMOS static-random-access-memory (SRAM) cell underneath the device. Every pixel measures 17μm x17 μm.

Figure 7. A pair of DMD pixels of Texas instrument



The fabrication used by TI uses surface micromachining on wafers which incorporate de CMOS electronics. The release of the mechanical structures is done by etching. A typical DMD includes 1.3 Million micromirrors and is used for digital projection TV and cinema. (Texas Instruments, 2003)

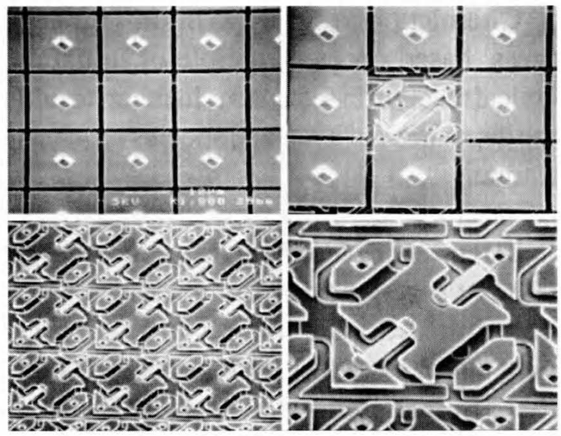


Figure 8. Details of the complete array.

6.FUTURE PERSPECTIVE AND SUMMARY

After a brief overview of MEMS' technology, it is obvious that this extremely diverse technology could significantly affect every category of commercial products. The nature of this technology and its diversity of useful applications make it potentially more pervasive than even integrated circuit microchips.

Also, MEMS blurs the distinction between complex mechanical systems and integrated circuit electronics. Costly and unreliable parts of a macroscale electronics system, as sensors and actuators, increase reliability and decrease their cost using batch fabrication techniques in micro electro mechanical systems. The performance of MEMS is expected to be superior to macroscale systems, and the price is predicted to be much lower.

MEMS are already used for tasks ranging from in-dwelling blood pressure monitoring to active suspension systems for automobiles. Their great promise lies in their potential to enable a new range of applications, a mojor growth industry. Some of these applications under development are: miniature biomechanical chambers for DNA synthesis and addressing, optical communication switches, thermomagnetical data storage systems, as well as new and improved micropumps and mechanical resonators.

GLOSSARY

Chemical Vapor Deposition (CVD): A process, based on the principle of initiating a chemical reaction in a vacuum chamber, resulting in the deposition of a reacted species on a heated substrate.

Micro Electro Mechanical Systems (MEMS): A generic descriptive term, common in the United States, for a broad technology having the objective of miniaturizing complex systems by integrating a diverse set of functions in a small package.

Micromachining: A term describing the set of design and fabrication tools for the machining of microstructures and very small mechanical features on a substrate.

Piezoelectricity: The property exhibited by a class of materials to develop voltage in response to applied mechanical stress or pressure. Conversely, an external applied electrical voltage strains and deforms this material.

Piezoresistivity: The property of certain type of materials, including impurity doped silicon, to change their electrical resistivity in response to mechanical stress.

Shape memory alloy: Group of materials that have the ability of returning to a predetermined shape when heated above critical "transition temperature." These materials "remember" their original shape after being strained and deformed.

Transducer: A device that converts from one physical quantity to another. One example is the deformation of a piezoelectric crystal under an applied electric field.

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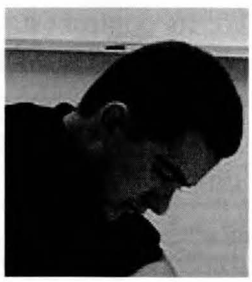
AUTORES

Student member of the IEEE since 1998, Juan Pablo Saenz joined the Cryogenic Electronics Group at San Francisco State University in fall 2002, where he pursued a MS in Engineering. As Graduate Research Assistant he worked on microfabrication processes set up, superconductor materials characterization and device Layout, for MEMS integration with Cryogenic devices.



His MS thesis "Study of processes and materials for MEMS integration with cryogenic devices," recently won the 18th Annual research competition in Engineering and Computer Science at SFSU. Before joined the CEG Juan Pablo was part of the Control and intelligent System Research group at the Universidad Nacional de Colombia, where he got his BS in Electrical Engineering.

He is author with Camilo A. Cortes of the thesis "Design and construction of a walking robot using nitinol wire and the calculator HP 48GX as artificial intelligence platform."