An Inventive Framework of Micro-Electromechanical System (MEMS)

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***Abstract*— MEMS is an enabling technology allowing the development of smart products, enhancing the computational ability of microelectronics with the perception and control capabilities of micro sensors and micro actuators and expanding the space of possible designs and applications. MEMS is a relatively new technology which exploits the existing microelectronics infrastructure to create complex machines with micron feature sizes. MEMS promises to revolutionize nearly every product category by bringing together silicon based microelectronics with micro machining technology, making possible the realization of complete systems on a chip. Micro-electromechanical systems (MEMS) technology enable us to create various useful sensing and actuating devices integrated with other microelectronic, optoelectronic, microwave, thermal and mechanical devices for advanced Microsystems. Micromachining and micro electro mechanical systems (MEMS) technologies can be used to produce complex structure, devices, and systems on the scale of micrometers. MEMS products based on piezoelectric and capacitance sensing now include pressure and flow sensors, accelerometers, gyroscopes, microphones, digital light projectors, oscillators, and RF switches. MEMS devices are used in virtually all areas of industrial activity, health care, consumer products, construction, and military and space hardware. The future of MEMS is multifaceted, complex, and subject to change, in response to the prevailing winds of investment by government and commercial entities. This diversification of product offerings and globalization of the industry has been accompanied by strong revenue growth and growing private investment. Much of the growth in MEMS business is expected to come from products that are in early stages of development or yet to be invented.**

Keywords- Sensor, Micromachining, Biological Sensor, Chemical sensor, Mechanical sensor, Optical sensor, High aspect ratio (HAR) Silicon micromachining, Micro Sensor.

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I. INTRODUCTION

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro-fabrication. Many of the same techniques that are used to create microscopic electronic devices can also be used to construct microscopic mechanical devices and fluidic devices. MEMS are separate and distinct from the hypothetical vision of molecular nanotechnology and molecular electronics. MEMS are made up of components between 1 to 100 micrometers in size (i.e. 0.001 to 0.1 mm), and MEMS devices generally range in size from 20 micrometers (20 millionths of a meter) to a millimeter (i.e. 0.02 to 1.0 mm). They usually consist of a central unit that processes data (the microprocessor) and several components that interact with the outside such as micro sensors. At these size scales, the standard constructs of classical physics are not always useful. Because of the large surface area to volume ratio of MEMS, surface effects such as electrostatics and wetting dominate over volume effects such as inertia or thermal mass.

Figure 1. Applications area of MEMS

A. Sensor

A sensor is basically a convertor that measure physical parameter (for example: temperature, blood pressure, humidity, speed, etc.) and convert it into a signal which can be measured electrically. Let us explain an example of temperature, the mercury in the glass thermometer expands and contracts the liquid to convert the measured temperature which can be read by a viewer on the calibrated glass tube. Sensors are used in everyday objects such as touch-sensitive elevator buttons (tactile sensor) and lamps which dim or brighten by touching the base. There are also innumerable applications for sensors of which most people are never aware. Applications include cars, machines, aerospace, medicine, manufacturing and robotics.

B. MEMS

MEMS or Micro Electro Mechanical Systems is a technique of combining Electrical and Mechanical components together on a chip, to produce a system of miniature dimensions. MEMS is the integration of a number of micro components on a single chip which allows the microsystem to both sense and control the environment. The components typically include microelectronic integrated circuits (the "brains"), sensors (the "senses" and "nervous system"), and actuators (the "hands" and "arms"). The components are integrated on a single chip using micro fabrication technologies similar to those used for integrated

circuits. MEMS-based sensors are a crucial component in automotive electronics, medical equipment, hard disk drives, computer peripherals, wireless devices and smart portable electronics such as cell phones and PDAs.

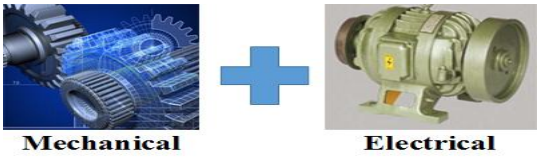

Figure 2. Diagrammatical explanation of MEMS

MEMS extend the fabrication techniques developed for IC industry to add mechanical elements such as beams, gears, diaphragms, and springs to devices. A pressure transducer usually outperforms a pressure sensor made using the most precise macro scale level machining techniques. It is possible to not only achieve stellar device performance, but to do so at a relatively low cost level. More recently, the MEMS research and development community has demonstrated a number of micro actuators including: micro valves for control of gas and liquid flows; optical switches and mirrors to redirect or modulate light beams; independently controlled micro mirror arrays for displays, micro resonators for a number of different applications, micro pumps to develop positive fluid pressures, micro flaps to modulate airstreams on airfoils, as well as many others. Surprisingly, even though these micro actuators are extremely small, they frequently can cause effects at the macro scale level; that is, these tiny actuators can perform mechanical feats far larger than their size would imply. For example, researchers have placed small microactuators on the leading edge of airfoils of an aircraft and have been able to steer the aircraft only by using these microminiaturized devices.[4]

Microelectronic integrated circuits can be thought of as the "brains" of a system and MEMS augments this decision-making capability with "eyes" and "arms", to allow microsystems to sense and control the environment. Sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena. The electronics then process the information derived from the sensors and through some decision making capability direct the actuators to respond by moving, positioning, regulating, pumping, and filtering, thereby controlling the environment for some desired outcome or purpose.[10]

Nanotechnology is the ability to manipulate matter at the atomic or molecular level to make something useful at the nano-dimensional scale. Basically, there are two approaches in implementation: the top-down and the bottom-up. In the top-down approach, devices and structures are made using many of the same techniques as used in MEMS except they are made smaller in size, usually by employing more advanced photolithography and etching methods.

C. Benefits of MEMS:

- Low Cost
- Low Power
- Miniaturization
- High Performance
- Integration

II. MEMS SENSOR

Of course, history teaches us that integration is the most cost effective and high performance solution. So Analog Devices pursued an integrated approach to MEMS where the sensor and signal conditioning electronics are on one chip. . The electronic design of MEMS sensors is very challenging. Most MEMS sensors mechanical systems are designed to realize a variable capacitor. Electronics are used to convert the variable capacitance to a variable voltage or current, and amplify or linearize it and in some cases, temperature compensates the signal. This is a challenging task as the signals involved are very minute. Advancements in IC technology and MEMS fabrication processes have enabled commercial MEMS devices that integrate micro sensors, micro actuators and microelectronic ICs, to deliver perception and control of the physical environment. These devices, also known as 'Microsystems' or 'smart sensors'.

III. FABRICATION

Materials used in fabrication process:

A. Silicon

Silicon is the material used to create most integrated circuits used in consumer electronics in the modern world. It is also an attractive material for the production of MEMS, as it displays many advantageous mechanical and chemical properties: Single crystalline silicon is an almost perfect Hookean material. This means that when silicon is bent there is virtually no hysteresis and hence almost no energy loss. This property makes it to the ideal material, where many small motions and high reliability are demanded, as silicon displays very little fatigue and can achieve service lifetimes in the range of billions to trillions of cycles.[8]

B. Polymers

Polymer materials have been used in MEMS in several capacities, including substrates, structural thin films, functional thin films, adhesion and packaging, coating, and surface chemical functionalization. The following polymer materials are used in MEMS today with relative high frequency today: Parylene, polyimide, acrylics (PMMA), photopatternable epoxy, and polydimethylsiloxane (PDMS) elastomer. In addition, a number of other materials are also being used, including liquid crystal polymer (LCP), liquid crystal elastomer (LCE), biodegradable Polymers, functional hydrogels, Paraffin, piezoelectric polymers, fluorocarbon thin films, and conductive polymers.[1]

C. Metals

Metals can also be used to create MEMS elements. While metals do not have some of the advantages displayed by silicon in terms of mechanical properties, when used within their limitations, metals can exhibit very high degrees of reliability. Metals can be deposited by electroplating, evaporation, and sputtering processes. Commonly used metals include gold, nickel, aluminum, copper, chromium, titanium, tungsten, platinum, and silver.[2][8]

D. Ceramics

Micro-electro-mechanical systems (MEMS) can be fabricated with a variety of technologies and from a wide range of materials. MEMS are normally made by micro-machining silicon, but in some applications ceramic materials are a very useful alternative, especially in harsh environments and at high temperatures. The laminated 3D structures made using low-temperature co-fired ceramic (LTCC) are especially practical for so-called Ceramic MEMS. Ceramic packages are suitable for use in sensors due to the high modulus of elasticity and low coefficient of thermal expansion of ceramic materials.

IV. MEMS BASIC PROCESSES

There are three basic building blocks in MEMS technology, which are the ability to deposit thin films of material on a substrate, to apply a patterned mask on top of the films by photolithographic imaging, and to etch the films selectively to the mask. A MEMS process is usually a structured sequence of these operations to form actual devices.

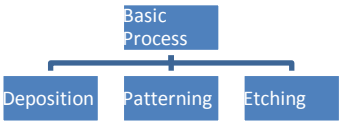

Figure 3. Basic MEMS Process

A. Deposition Process

One of the basic building blocks in MEMS processing is the ability to deposit thin films of material. In this text we assume a thin film to have a thickness anywhere between a few nanometers to about 100 micrometer. MEMS deposition technology can be classified in two groups:

- Depositions that happen because of a chemical reaction. These processes exploit the creation of solid materials directly from chemical reactions in gas and/or liquid compositions or with the substrate material.
- Depositions that happen because of a physical reaction. Common for all these processes are that the material deposited is physically moved on to the substrate. In other words, there is no chemical reaction which forms the material on the substrate.

B. Patterning

Lithography in the MEMS context is typically the transfer of a pattern to a photosensitive material by selective exposure to a radiation source such as light. A photosensitive material is selectively exposed to radiation (e.g. by masking some of the radiation or not). If the resist is placed in a developer solution after selective exposure to a light source, it will etch away one of the two regions (exposed or unexposed). If the exposed material is etched away by the developer and the unexposed region is resilient, the material is considered to be a positive resist. If the exposed material is resilient to the developer and the unexposed region is etched away, it is considered to be a negative resist.

C. Etching Process

In order to form a functional MEMS structure on a substrate, it is necessary to etch the thin films previously deposited and/or the substrate itself. In general, there are two classes of etching processes:

1) Wet Etching: where the material is dissolved when immersed in a chemical solution.

2) Dry Etching: where the material is sputtered or dissolved using reactive ions or an etching agent. The dry etching technology can split in three separate classes called reactive ion etching (RIE), sputter etching, and vapour phase etching.

V. MEMS MANUFACTURING TECHNOLOGY

A. Bulk Micromachaning

This technique involves the selective removal of the substrate material in order to realize miniaturized mechanical components. Bulk micromachining can be accomplished using chemical or physical means, with chemical means being far more widely used in the MEMS industry. Anodic bonding of glass plates or additional silicon wafers is used for adding features in the third dimension and for hermetic encapsulation.

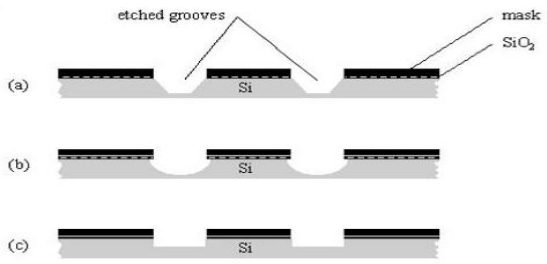

Figure 4. Etched grooves using (a) Anisotropic Etchants, (b) Isotropic Etchants, (c) Reactive Ion Etching (RIE)[11]

A widely used bulk micromachining technique is chemical wet etching, which involves the immersion of a substrate into a solution of reactive chemical that will etch exposed regions of the substrate at measurable rates. Chemical wet etching is popular in MEMS because it can provide a very high etch rate and selectivity. Furthermore, the etch rates and selectivity can be modified by: altering the chemical composition of the etch solution; adjusting the

etch solution temperature; modifying the dopant concentration of the substrate; and modifying which crystallographic planes of the substrate are exposed to the etchant solution.[3]

The etch rate of some isotropic wet etchant solution mixtures are dependent on the dopant concentration of the substrate material. The etch rate selectivity with respect to dopant concentration is highly dependent on solution mixture.

B. Surface Micromachining

In surface micromachining, the MEMS sensors are formed on top of the wafer using deposited thin film materials. These deposited materials consist of structural materials that are used in the formation of the sensors and sacrificial layers that are used to define gaps between the structural layers. Many of the surface micro-machined sensors use the capacitive transduction method to convert the input mechanical signal to the equivalent electrical signal. In the capacitive transduction method, the sensor can be considered to be a mechanical capacitor in which one of the plates moves with respect to the applied physical stimulus. This changes the gap between the two electrodes with a corresponding change in the capacitance. This change in capacitance is the electrical equivalent of the input mechanical stimulus.

Surface micromachining enables the fabrication of complex multicomponent integrated micromechanical structures that would not be possible with traditional bulk micromachining. This technique encases specific structural parts of a device in layers of a sacrificial material during the fabrication process. The substrate wafer is used primarily as a mechanical support on which multiple alternating layers of structural and sacrificial material are deposited and patterned to realize micromechanical structures. The sacrificial material is then dissolved in a chemical etchant that does not attack the structural parts. The most widely used surface micromachining technique, polysilicon surface micromachining, uses SiO_2 as the sacrificial material and polysilicon as the structural material.

C. High Aspect Ratio (HAR) Silicon Micromachining

HAR combines aspects of both surface and bulk micromachining to allow for silicon structures with extremely high aspect ratios through thick layers of silicon (hundreds of nanometers, up to hundreds of micrometers). The silicon-on-silicon (SOS) process utilizes dielectric barrier discharge surface activated low-temperature wafer bonding and deep reactive ion etching to achieve a high aspect ratio (feature width reduction-to-depth ratio of 1:31), while allowing for the fabrication of devices with a very high anchor-to-anchor thermal impedance ($>0.19 \times 10^6$ K W^{-1}). The SOS process technology is based on bonding two silicon wafers with an intermediate silicon dioxide layer at 400 °C. This SOS process requires three masks and provided numerous advantages in fabricating several MEMS devices, as compared with silicon-on-glass (SOG) and silicon-on-insulator (SOI) technology, including better dimensional and etch profile control of narrow and slender MEMS structures. Additionally, by patterning the intermediate SiO_2 insulation layer before bonding, footing is reduced without any extra processing, as compared to both SOG and SOI. All SOS process steps are CMOS compatible. HARMEMS technology enables a high degree of immunity to high-frequency, high-amplitude parasitic vibrations. HARMEMS technology has also been introduced in dual-axis accelerometers used in electronic stability control (ESC) to measure the lateral acceleration of the vehicle.

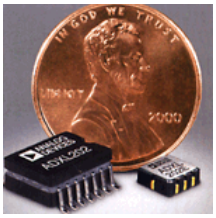

Figure 5. HAR Silicon Micromachaning [12]

VI. TYPES OF MEMS SENSOR

There are many types of MEMS sensor now available in market:

- Mechanical Sensor
- Optical Sensor
- Thermal Sensor
- Chemical and Biological Sensor

A. Mechanical Sensor

MEMS accelerometer is an example of mechanical sensor. Accelerometers are widely used for navigational and airbag deployment safety systems in automobiles. The current generation of accelerometer devices integrates electronic circuitry with a micromechanical sensor to provide self-diagnostics and digital output. It is anticipated that the next generation of devices will also incorporate the entire airbag deployment circuitry that decides whether to inflate the airbag. As the technology matures, the airbag crash sensor may be integrated one day with micromachined sensors to form a complete microsystem responsible for driver safety and vehicle stability.[7][9]

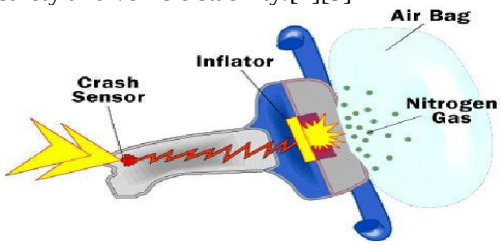

Figure 6. Airbag Inflation

B. Optical Sensor

The sensors have a number of inherent advantages, including small size, light weight, high sensitivity and immunity to EMI noise. These advantages make optical fiber sensors excellent candidates for partical discharges

(PD) acoustic detection.[3] A diaphragm-based interferometric fiber optical microelectromechanical system sensor with high sensitivity is designed and tested for on-line detection of the acoustic waves generated by partial discharges (PD) inside high-voltage power transformers. In principle, the sensor is made according to Fabry Perot interference, which is placed on a micro-machined rectangular silicon membrane as a pressure-sensitive element.

C. *Thermal Sensor*

Thermal sensors detect the temperature & converts it into digital form. Thermal sensors utilize the Seebeck effect in which thermoelectric force is generated due to the temperature difference at the contact points between two different kinds of metal. A thermopile is created by serially connecting thermocouples consisting of N+ poly Si, P+ poly Si, and Al. By creating hot junctions on highly heat-resistant dielectric membranes, and cold junctions on highly heat-conductive silicon, it is possible to achieve high-speed response and high-energy conversion efficiency (infrared rays - temperature - thermoelectric force).

D. *Chemical and Biological Sensor*

A piezoelectric transducer converts mechanical strain into electrical polarization and vice versa, and its sensitivity and sound output depend on the mechanical compliance of the transducer structure. To detect acoustic sound pressure level, a piezoelectric acoustic transducer can be fabricated using a thin, compliant micromachined diaphragm whose bending due to an applied sound pressure causes a stress change in the piezoelectric film, generating an electric polarization in the film. Thus, the residual stresses of the films used in a MEMS diaphragm-based transducer would affect the transducer performance as well as the frequency response of the transducer. Piezoelectric microelectromechanical systems (MEMS) resonant sensors, known for their excellent mass resolution, have been studied for many applications, including DNA hybridization, protein–legend interactions, and immunosensor development. They have also been explored for detecting antigens, organic gas, toxic ions, and explosives.

VII. APPLICATIONS

There is a wide range of applications of MEMS sensors:

A. *Medicine*

MEMS technology is emerging as a boon in the field of medicine. The most successful application of MEMS in medicine (at least in terms of number of devices and market size) are MEMS pressure sensors, which actively in use for several decades. The applications of MEMS pressure sensors include:

1. MEMS pressure sensors are used to measure intrauterine pressure during birth. The device is housed in a catheter that is placed between the baby's head and the uterine wall. During delivery, the baby's blood pressure is monitored for problems during the mother's contractions.
2. MEMS pressure sensors are used in hospitals and ambulances as monitors of a patient's vital signs, specifically the patient's blood pressure and respiration.
3. The MEMS pressure sensors in respiratory monitoring are used in ventilators to monitor the patient's breathing.
4. MEMS pressure sensors are used for eye surgery to measure and control the vacuum level used to remove fluid from the eye, which is cleaned of debris and replaced back into the eye during surgery.[5]

B. *Communication*

If electrical components such as inductors and tunable capacitors are made by using MEMS technology, there performance can be improved significantly compared to their integrated counterpart, while the total circuit area, power consumption and cost will be reduced. In addition, the mechanical switches, as developed by several research groups, are a key component in various RF and microwave circuits with huge potentials.

C. *Inertial Sensing*

The need of MEMS inertial sensors, specifically accelerometers and gyroscopes is increasing day by day. For example, MEMS accelerometers have displaced conventional accelerometers for crash air-bag deployment systems in automobiles. Earlier, several bulky accelerometers made of discrete components were mounted in the front of the car with separate electronics near the air-bag and there cost was about □ 2000 per sensor. But today, MEMS technology has made it possible to integrate the accelerometer and electronics onto a single silicon chip at a cost of only a few rupees. These MEMS accelerometers are much smaller, more functional, lighter, more reliable, and are produced at low cost. MEMS inertial sensors are now being used in every car sold as well as notable customer electronic handhelds such as Apple iPhones.

D. *Automation*

MEMS sensors have wide range of applications in field of automation:

1. Airbag Systems
2. Vehicle Security Systems
3. Inertial Brake Lights
4. Headlight Leveling
5. Rollover Detection
6. Automatic Door Lock
7. Active Suspension

E. *Marine Science*

Recently, the achievements in MEMS technology helps in the invention of new sensors that are used underwater. It helps to get more information about temperature, pressure, tidal & current velocity. The MEMS devices, in marine sensing may be attached to: Ships, AUVs (Autonomous underwater vehicle), fixed sea structure, sea bed. These are also used to finding oil & gas reserves.

F. Military Operation

1. An array of MEMS sensors spread on the ocean floor could detect the presence of enemy submarines.
2. MEMS sensors (pressure sensors, accelerometers etc.) are being used in anti-torpedo weapons on submarines and ships.
3. Hitting the target in a crowded environment.
4. Prevent any premature explosion.[10]

VIII. CONCLUSION AND FUTURE SCOPE

This is only a very brief overview of the Micro Electromechanical System and MEMS. MEMS and Micro-Electromechanical System are still the subject of broad and diverse research efforts, and the field is constantly changing. Micro-Electromechanical System and MEMS enabled fuel cells will have optimum characteristics and will have tremendous advantages which can take them toward commercialization. MEMS technology has the potential to change our daily lives as much as the computer has. However, the material needs of the MEMS field are at a preliminary stage. A thorough understanding of the properties of existing MEMS materials is just as important as the development of new MEMS materials. Future MEMS applications will be driven by processes enabling greater functionality through higher levels of electronic-mechanical integration and greater numbers of mechanical components working alone or together to enable a complex action. Future MEMS products will demand higher levels of electrical-mechanical integration and more intimate interaction with the physical world. The high up-front investment costs for large-volume commercialization of MEMS will likely limit the initial involvement to larger companies in the IC industry. Advancing from their success as sensors, MEMS products will be embedded in larger non-MEMS systems, such as printers, automobiles, and biomedical diagnostic equipment, and will enable new and improved systems.

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