Cyber-physical Systems
Structures and Functions

Student Research Project

Research in MEMS sensors

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INTRODUCTION

HISTORY OF MEMS

The process of miniaturization began in the early 13th century with watchmakers and was accelerated in the 17th century with the introduction of microscopes. In 1947, transistors were invented, ushering in a new era of man-made miniaturization. Integrated Circuits (ICs) changed the computing industry today. According to Moore's law, the number of transistors in a single integrated circuit is expanding exponentially and will continue to do so in the future. Microprocessors are currently being integrated with actuators and sensors, allowing for more advanced data processing.

MEMS AND MICROMACHINING:

MEMS stands for microelectromechanical system and was originally proposed in the 1980s in the United States. The term MEMS stands for the collection of actuators and microsensors that is sensitive to its environment achieved by a microcircuit control. Microelectromechanical systems are defined by its size in anywhere between one millimeter and one micron which utilizes procedures starting from incorporated circuit (IC) with focus on silicon-based structures and microelectronic circuitry. MEMS relate to mechanical systems and other wider areas such as micro optical systems, microanalysis systems or chemical sensors. The application of MEMS varies from the industrial to the medical field. Accelerometers in airbags, micro-heat exchanges micro-mirrors in high definition display, blood analyzers, catheter tip pressure sensing are some of the applications of MEMS.

Micromachining is the foundation and toolbox of MEMS. Micromachining is a set of tools for design and fabrication that accurately form and machine elements at micro-scale. In other words, micro-engineering can be described as techniques as well as technologies involved in the creation of systems and elements with the dimension or size-scale of a few millimeters. Micromachining is mostly done on silicon substrate and has been done on more materials recently. It can be used to make features such as membranes, cantilever, grooves, orifices, springs, gears, suspensions etc. Micromachining can be classified into mostly two technology types.

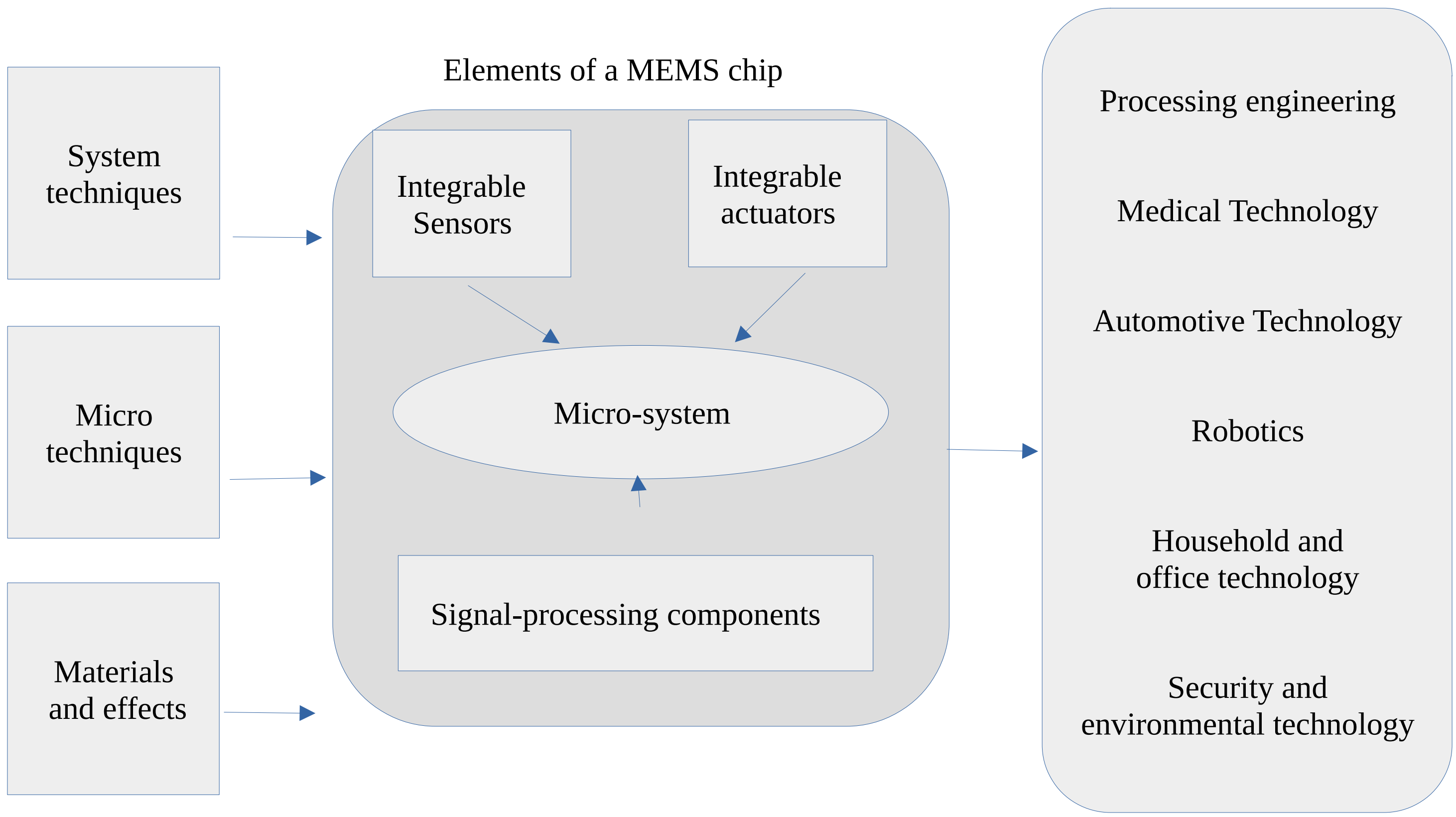
1. **Bulk Micromachining** which structures are etched into silicon substrate.

2. **Surface Micromachining** in which films are deposited on the surface of silicon substrate to form micromechanical layers.

Bulk Micromachining is the most mature out of the two methods provided and has been the most popular since its emergence in the 1960s. The bulk micromachining techniques can be divided into wet etching and dry etching based on the state of the etchants. Surface micromachining on the other hand is used to build structures on the surface of the silicon called sacrificial layers. The sacrificial layer is then removed to reveal the mechanical structures. Surface micromachining also provides better integration with IC elements.

MICROSYSTEMS:

A microsystem is made up of many microengineered components. Microsensors detect changes in system parameters, and microactuators which are controlled by a control unit uses data from the microsensors.



1. **Sensors**: Devices that change one physical quantity into another are known as sensors. Sensors come in a variety of shapes and sizes.

- **Thermal Sensors**
  Thermocouples are one of the most prevalent types of thermal sensors, consisting of two dissimilar metals connected in a circuit with junctions held at different temperatures. This produces a low voltage, which is then measured with a high resistance voltmeter. This voltage is related to the temperature difference `(Ta-Tb).`

  $$v = (Pa - Pb)(Ta - Tb)$$

  Another popular thermal sensor is **Thermoresistors** and its working principle is based on linear relationship between resistivity (r) and temperature (T) of metals above -200°C.

  $$r = R(1 + aT + bT^2)$$

- **Radiation Sensors**
  Radiation sensors can measure radiations varying from visible light, infrared to UV. Some of the most used ones are **Photodiodes** which are basically a reverse biased p-n Junction whose current flowing varies based on the amount of light falling on it. Another type is a **Phototransistors** which can be described as a transistor whose base current is provided by the

illumination of base-collector junction. **Charged-Couple Devices** (CCD) are mainly used in cameras and consists of two dimensional large linear arrays. Another popular radiation sensor is **Pyroelectric Sensors** whose working principle is based on pyroelectric effects on polarized crystals.

- **Magnetic Sensors**
  The different ways of sensing magnetic field ranges from **optical sensors** that are based on specially doped optical fibers or crystals who exhibit magneto-optic effect. Current developments in high temperature superconductors also open doors for sensors based on **superconducting quantum interface devices** (SQUIDS)

- **Chemical sensors and Biosensors**
  A large number of chemicals are made from metal-oxide-semiconductor field effect transistor devices. One such popular sensor is **ISFET Sensors** which senses the concentration level of a particular ion in a solution. Meanwhile, biosensors employ active biological components in a transduction process. This can be a sensory cell from a organism or an enzyme that helps to catalyze a reaction to antibodies.

- **Mechanical Sensors**
  Mechanical sensors can be divided mainly into two types based on how they sense parameters, one which uses physical mechanism and other using microstructures. Some popular mechanical sensors which belong to first kind are **piezoelectric sensors** which utilizes piezoelectric effect, **piezo resistors** which depend on piezoresistive effect, **optical sensors**, **resonant sensors** etc. Mechanical sensors which belong to the second type are accelerometers which consists of mass suspended on thin beams, pressure sensors which have thin films with one side exposed to pressure to be measured and other side to evacuated cavity.

2. Microactuators

Microactuators produce the mechanical output that are needed for the microsystem. Some of the popular types of microstructures are discussed below.

- **Electrostatic Actuators**
  One most popular electrostatic actuator is **comb drives** which consists of several interdigitated fingers. An attractive force is generated between the fingers with an application of a voltage which is proportional to the number of fingers. Another popular electrostatic actuator is **Wobble motors** which consists of a circular disk as a rotor. While in operation the electrodes are switched on and switched off which are beneath the rotor. The force generated (Fx) when plates in a capacitor move towards each other can be given with respect to capacitance (C), voltage (V) and distance (x).

$$Fx = \frac{V^2}{2} \frac{\partial C}{\partial x}$$

- **Magnetic Actuators**
  Nickel is widely used in magnetic actuators because of its weak ferromagnetic properties. **Linear motor** is a magnetic actuator that consists of a magnetic resting which is controlled by switching current into various coils.

- **Piezoelectric Actuators and Hydraulic Actuators**
  Piezoelectric effect is applied to silicon membranes which deforms on application of a voltage. Fluids are pumped through microvalves which applies the force. Hydraulic Actuators even with its problems like leakage in seals and valves can deliver large power in small areas.

METHODS AND MATERIALS

Materials for MEMS Sensors

The fabrication of MEMS sensors is not done from any one material but a number of materials which all serves different purposes. The usage of materials in MEMS sensors can vary from structural, sacrificial to masking materials.

- **Single-Crystal Silicon**
  The use of Silicon in Micro-sensors can be traced back to 1954. Within a few decades the mechanical and chemical techniques for micromachining has matured a lot. Silicon has a electronic band gap of 1.1eV with a cubic crystal structure which makes it a very suitable material in micromachining. The addition of impurities such as Phosphorous and Boron can be used to alter its conductivity. Silicon is the most suitable material in bulk micromachining. Wet and dry etching in conjugation with etch masks and etch stops are used in micromachining of single-crystal silicon.

- **Polysilicon**
  In the surface micromachining of the sensors, **polysilicon** is used as the material for the primary structure and the SiO_2 as the sacrificial material. Polysilicon is made from several single-crystal domains called grains. Similar Mechanical properties of polysilicon with that of singe crystal silicon and its resistance to SiO_2 etchants make Polysilicon a suitable material in the MEMS industry. As silicon is a widely used material in the IC industry, the silicon micromachining can take advantage of the already established capital investments in film deposition and material characterization. The most common deposition process for thin polysilicon layers is low-pressure chemical vapor deposition (LPCVD) based on a hot-wall resistance-heated horizontal fused silica tube design. The ideal temperature and pressure for the deposition process are 580-650 °C and 1000-400mtorr with SiH_4 as the source gas.

- **Silicon Dioxide**
  As already discussed, SiO_2 is mainly used in sacrificial layer and rarely also used in dry etching as an etch mask. SiO_2 is grown on silicon substrates thermally. **LPCVD** and **thermal oxidation** are the methods that is normally used in deposition of thick films of SiO_2. LPCVD requires much lower temperature than thermal oxidation. LPCVD deposition is done low pressure, hot walls and in fused silica layers whereas thermal oxidation can be done at temperate ranging from 900 to 1100 °C and oxidation is done by passing oxygen in the presence or absence of water-vapor.

- **Silicon Nitride**
  Si_3N_4 are mainly used in passivation of surfaces, etch masking, electrical isolation and as a mechanical material. **LPCVD** and **PECVD** are the most commonly used in deposition of Si_3N_4. The use of PECVD in micromachining is often considered undesirable because of its

high etch rate. LPCVD are done in temperature ranging between 700 and 900 °C and pressure ranging between 200 and 500 mtorr with source gases dichlorosilane and ammonia.

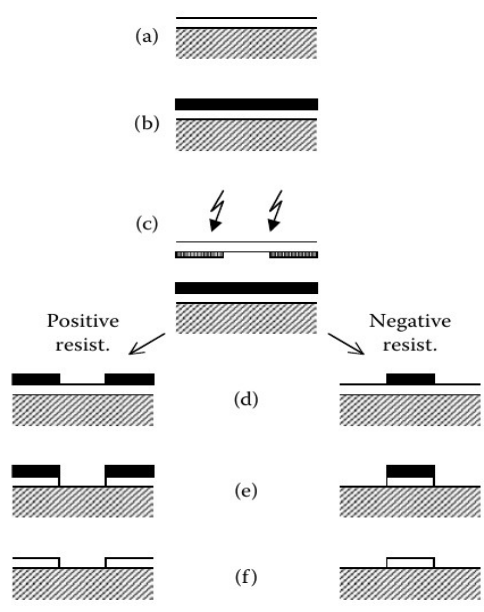
- **Metals**
  Metals are deposited by making use of several processes ranging from **evaporation, sputtering, electroplating** and **CVD**. The use cases can vary from interconnecting thin film conductors to hard etch masks. The wide range of available deposition techniques make metals very versatile. **Aluminum** in conjugation with polymers such as Polymide is widely used because of its easiness in deposition at relatively lower temperatures and is mostly used as sacrificial/ structural materials. The Polymide/Aluminium combination is very efficient for micromachining and in most cases, acid-based etchants are used to dissolve AI sacrificial layer. Other materials such as **Tungsten** in combination with Silicon dioxide (sacrificial material) is used in micromachining. Similarly, **polymides, chromium** and other metals with **nickel** and **copper** as sacrificial layer are also used in micromachining.

- **Silicon Carbide**
  The use of silicon is largely limited because of its physical, chemical and mechanical properties. Therefore, alternate materials which can withstand high temperature, radiation, wear and acidic conditions needs to be considered. Silicon Carbide (SIC) can withstand many of these harsh conditions and with the recent developments such as **APCVD** and **LPCVD**, high quality SiC single crystal films can be made. SiH_4 and C_3H_8 are mainly used as sources for silicon and carbide in the fabrication process with dual precursors. The two major steps involved are carbonization that involves passing propane/hydrogen at a temperature around 1300°C that converts Si substrate near surface region into 3C-SiC .Second step is the subsequent epitaxial growth. Wet etching is not possible in the case of Silicon Carbide, instead conventional dry etching can be used.

- **Diamond**
  Diamond is the natures hardest material and its high electronic band gap makes it suitable in high temperature application. This combined with good insulation properties, chemical inertness, high young's modulus makes it ideal for micromachining applications. Similiar to SiC, the bulk micromachining of diamond is done from Si molds over which polycrystalline diamond is deposited with methane as carbon source and hydrogen as a carrier gas.

<u>**Fabrication Techniques**</u>

1. **Photolithography:** Photolithography normally utilizes optical techniques or light to etch and deposit the pattern on a structural material. Some very popular Photolithography techniques are.



- **UV Lithography**

  A thin film of Silicon dioxide is deposited on a silicon wafer surface from the following steps.
  (a) silicon substrate with oxide coating
  (b) photoresist is spun on: photoresist can be of two types

- negative resist: the chemical bonds strengthen when exposed to UV
- positive resist: the chemical bonds weaken when exposed to UV

(c) exposed to UV light through mask,
(d) developed
(e) etching of underlying film mostly done by immersing in HF-acid
(f) photoresist stripped, leaving the pattern.

- **X-Ray Lithography**
  The UV lithography is mostly limited by its penetration capacity into the resist. X-ray lithography is suitable for structures that demands high ratio of height to width (high aspect-ratio). The low wavelength and high energy ensure little diffraction through the mask and high penetration. A mask must be chosen that has enough contrast. Silicon nitride with gold deposited on it is the most common attenuating material. The major disadvantage of this type of lithography is x-rays can heat up the mask and can limit the resolution and performance.

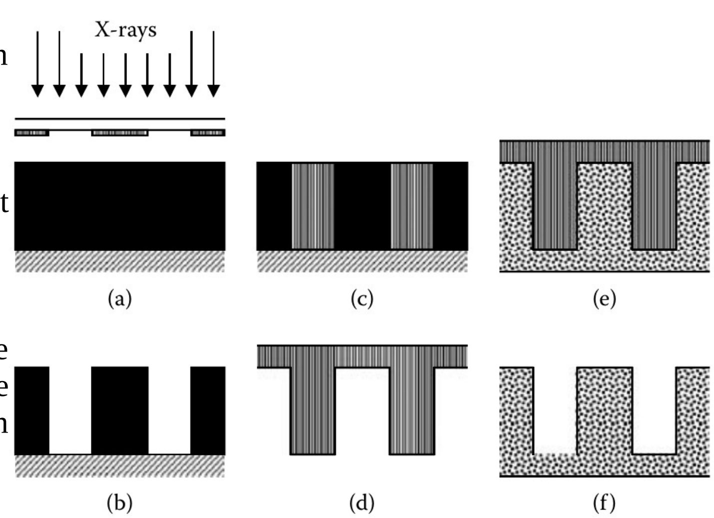
- **E-beam lithography**
  The use of e-beam direct write systems to write the design directly to the Mask plate avoids the requirement for intermediate masks that can only be used once. E-beam systems typically use a heated tungsten as an electron source with acceleration voltages ranging from 10 to 50 kV. Scanning coils and blanking plates control the focus and acceleration of the electrons to a bright area on the substrate. The high energy of electrons causes them to scatter as they reach the material, which is one of this method's biggest limitations (proximity effects).

Non-Silicon Micromachining

- **Chemical-Mechanical Polishing**
  Also used in Silicon micromachining, this method can be extended to micromachine several materials such as Aluminum, Copper, Titanium. CMP consists of an abrasive powder suspended on a corrosive etching material in which the mechanical components remove the bulk of the material and chemical process does the final polishing. CMP considerably helps in **Planarization** which involves in the deposition of flat surfaces and thick insulating layers.

- **LIGA And Electroplating**
  LIGA consists of molding, electroplating, and lithography to produce microstructures. LIGA process can be used to achieve microstructures with aspect-ratio up to 1000:1. LIGA can produce patterns on thick layers of photoresist.

(a) Photoresistive layer is exposed to X-ray through a mask.
(b) The resist is developed
(c) Pattern is electroplated
(d) A metal mold is developed although not necessary
(e) Mold filled with suitable material
(f) Finished product is made.
The microstructure's form is determined by the current density, and it needs to be consistent for the best results. Pulse electroplating and overplating can bring good results



CONCLUSION AND RECOMMENDATIONS

The earliest advancements in MEMS sensors can be credited to the acknowledgment of silicon as a mechanical material. Over the last decade, the main advancements in MEMS is due to the consideration in unused potential in many materials which have extended the usefulness of micro fabricated materials beyond silicon. The material science in MEMS engineering is not limited to the structural materials but also sacrificial and masking materials. The concept of MEMS originated from IC industry and silicon micromachining still remains one of the most mature and developed micro-engineering technique. A number of silicon and non-silicon micromachining techniques were discussed and each micromachining techniques suit different materials.

Major Challenges And Recommendations

- **Limited access to MEMS foundries:**
  Large initial capital outlay in terms of clean rooms, hazardous chemicals and equipment's makes MEMS sensor industry a very difficult area to enter and the organizations that are meant to be benefited from the MEMS industry doesn’t have the required infrastructure and competency to support MEMS industry. The access to MEMS sensor fabrication techniques are still very limited to the companies. A lot of these issues can be solved by adopting the tried and useful fabrication techniques developed in the research area to the mass markets. For eg; fabrication using both potassium hydroxide (KOH) and Isopropyl alcohol (IPA) These can accelerate the growth of low cost, high efficiency and mass-produced MEMS sensors.

- **Design, Simulation and Modelling:**
  Requirements for MEMS such as its high integration and interdisciplinary nature of components combined with high level fabrication and manufacturing knowledge requirements can lead to complexities and incompatibilities in MEMS systems. In order to minimize such problems and improve innovation and creativity, an interface should be setup to separate design and fabrication. The replacement of old tools that rely on ‘trial and error’ with advanced modelling and simulation tools can make better prediction in MEMS behavior. Integration of related sensors or actuators can bring down the cost, complexity and improve the reliability of the system.

- **Packaging and testing:**
  Packaging and testing of MEMS systems are most often the biggest challenge against the MEMS industry. Packaging area is mostly neglected during the research and development of MEMS industry and can contribute up to 90% of MEMS final cost. Micro engineered needs interfacing well beyond simple electronic connections. Exposure of MEMS devices or sensos to the outside world could bring out unexpected behavior than that of the lab environment. Dust particles, bubbles, water vapor and other contaminants or mechanical interaction with the package, difference in thermal expansion coefficient of devices etc, could contribute to such problems. The individual handling of dies and the high time and labor requirements in packaging are the core reasons for high packaging costs. Automation of such processes as well as minimizing the handling times for individual dies could be a solution to problems in packaging area.

- **Standardization:**
  High quality control and standardization is normally found in well-established industries with billions of dollars in investment. Due to the relatively small number of MEMS devices and the slow pace of development of MEMS industry, the standardization of MEMS industry has been exceptionally troublesome. Since, the 2000s a lot of progress has been made due to the formation of MEMS trade organization in Pittsburgh USA whose main contributions were identifying a road map and acted as a source for objective statistics. The European Union and governments have also started many initiatives which fueled or lead to the creation of organizations such as Micro systems Service for Europe whose main objective is to enhance industrial competency . Others include Netpack whose main role is to promote the use and development of advanced packaging material, NEXUS (Network of Excellence in multi-functional microsystems) whose goal is to improve the competitiveness of industries in global market.

- **Education and Training:**
  High level of knowledge and good training are important qualities for scientists and engineers in the MEMS industry mainly due to the complexity and interdisciplinary nature of MEMS devices. Unfortunately, the number of eligible personnel to work in this field is limited due to only a handful of institutions that offer MEMS based degrees. One way to overcome this issue is for the academic and research institutions to offer study programs that are technology specific with commercial integration and training.

<u>Recommendations for new materials and technologies:</u>

A wide range of materials, including alloys, ceramics, high-temperature materials (SiC, Al_2O_3), nano-materials, and newly created crystalline and non-crystalline materials, can be used in conjunction with silicon/semiconductor materials. As MEMS sensor or packaging materials, these novel materials have enormous potential.

- **MEMS Sensors in IOT applications**
  With the growing demand for sensor innovation to satisfy IoT requirements under 5G infrastructure, traditional MEMS sensors are undergoing a transformation, Starting with MEMS fabrication technology, which is required for all sensors to function.

- **MEMS Component in Future Sensor**
  Future sensors, as part of an integrated sensor system, will likely benefit things such as low power consumption, wireless transmission, and self-power generation under such a structure.

- **MEMS Energy harvesting**
  Mechanical, thermal, radiative, and biological energy are some of the energy sources that can be employed for energy harvesting in the environment. Mechanical energy, out of all of these energy sources, was the most ideal for MEMS energy harvesting for sensor nodes due to its availability.

- **MEMS in AI**
  To deliver enhanced functionality, such as immersive experience and feedback control, future AI will rely heavily on novel MEMS sensors. MEMS have huge potential to be explored in AR and VR areas.

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