Lecture 1

Introduction of MEMS and Microsystem

• What are they?
  - Several Common Features
• How are they made?
  - Integrated Circuit Fabrication
  - Deposition and Etching
  - Surface Modification and Patterning
• What are they made of?
  - Materials for Microfabrication
• How are they designed?
• Markets for Microsystems and MEMS
• Case Studies

What are they?

MEMS: Microelectromechanical systems in US
Microsystems in Europe

MEMS or Microsystems are “very small systems” or “systems made of very small components.”

Vibrating Micro Gyroscope

Thick PR mold for Electroplating
Several Common Features

1. MEMS involve both electronic and non-electronic elements, and perform functions that can include signal acquisition, signal processing, actuation, display, and control. They can also serve as vehicles for performing chemical and biochemical reactions and assays.

2. MEMS are "systems", which means that important system issues such as packaging, system partitioning into components, calibration, signal-to-noise ratio, stability, and reliability must be confronted.

(continued)

Several Common Features

3. The most successful MEMS have been those which involve paradigm shifts from the "macro" way of doing things, more than simply reducing the size scale. Examples: ink-jet print head, thin-film magnetic disk heads, silicon pressure sensors and silicon and quartz sensors for the measurement of acceleration and rotation. Microfluidic devices are beginning to enable astonishing improvements in the speed of biochemical analysis.

4. Some MEMS involve large arrays of microfabricated elements. Examples: uncooled infrared imaging devices and both reflective and refractive projection devices.
How are they made?

- The batch fabrication offers the potential for great cost reduction when manufacturing in high volume.
- Silicon is often used even when there are no electronic components in the device because the tools and instruments needed for microfabrication are designed to match the characteristics of silicon wafers.
- Lithography offers in-plane sub-micron precision on dimensional scales from micron to millimeter. Thin-sub-micron precision on etching techniques in combination with wafer-bonding techniques allow patterning of the third dimension, making possible the creation of movable parts.

(continued)

Integrated Circuit Fabrication

1. Ingots of crystalline silicon are two feet long by six inches in diameter.
2. Wafers sliced from the ingot by diamond saw and 1–2 μm thick.
3. Wafers are cleaned and coated in preparation for lithographic process.
4. Stoppers lay chip onto silicon.
5. Mask layers are repeated.
6. Silicon is dipped with phosphorus (p-type) and boron (n-type) to enable it to carry current.

(continued)
Integrated Circuit Fabrication

Ultraviolet light is used to imprint each mask's pattern onto the chip.

Steps:
1. Photolithography
2. Etching
3. Passivation
4. Metal deposition
5. Wiring
6. Inspection

Wafer fabrication involves multiple steps to create a multilayer chip.

(continued)

Integrated Circuit Fabrication

Chips are tested by using test probes connected to automatic test equipment (ATE). Defective chips are marked.

WFAs are elided into chips, and defective ICs are discarded.

Chips are encased into protective package with connecting pins.
Deposition and Etching

- Deposition and Bonding (Evaporation, Sputtering, CVD, Bonding)

Substrate | Deposited film
---|---
Substrate | Wafer bonding

- Etching (Dry etching, Wet etching)

Surface Modification and Patterning

- Surface modification (Annealing, Phase change, Hydrophobic or Hydrophilic)

Surface | Film
---|---

- Patterning (Photolithography, Laser machining, Electrodischarge, Mechanical machining)

Film | Substrate
---|---
Overview
How are they made?

- New fabrication methods provide additional freedom to sculpt more general three-dimensional structures, but these have not yet entered high-volume manufacturing.
- There is an almost reflexive urge to make fully integrated microsystems, i.e., integrated circuits that include mechanical or other non-electronic elements on the silicon chip along with the electronic part of system.
- An alternate strategy is to partition the microsystem into subsystems that are fabricated separately, then assembled into a compact system during the packaging operation.
- It is clear that the system architecture and its partitioning into components have an enormous impact on the details of how the system is built.

Fully Integrated Microsystem

Schematic drawing of fully integrated microsystem
**Partitioning into Components**

- Fabricated microgyroscope
- Sensor die with needle’s eye
- CDIP packaged microgyroscope chip

---

**What are they made of?**

- The choice of materials in a microsystem is determined by microfabrication constraints.
- Most IC are inorganic materials (silicon, silicon dioxide, silicon nitride, aluminum, and tungsten), although certain polymers are used well.
- Microfabrication opens up a much broader range of materials and a corresponding set of additional techniques such as electroplating of metals, and molding and embossing of plastics.

(continued)
### Materials for Microfabrication

<table>
<thead>
<tr>
<th>Name</th>
<th>UDM</th>
<th>Fabrication Method</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>Structure</td>
<td>Photolithography, LIGA</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>Glass</td>
<td>Structure</td>
<td>Photolithography</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>PSG (Phospho Silicate Glass)</td>
<td>Exposed Coating</td>
<td>Photolithography</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>Tungsten</td>
<td>Structure</td>
<td>HF resistant, Malleable</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Structure</td>
<td>HF resistant</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>Al</td>
<td>Structure, Sacrificial Layer, Vacuum Deposition</td>
<td>Suitable for high-speed and high-precision cutting</td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>Structure</td>
<td>Spin Coating</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>ZnO</td>
<td>Conductive</td>
<td>Photolithography, LIGA</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>PZT</td>
<td>Conductive</td>
<td>Photolithography</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
<tr>
<td>TiNi</td>
<td>Conductive</td>
<td>Photolithography</td>
<td>Suitable for high-speed and high-precision cutting</td>
</tr>
</tbody>
</table>

(continued)
What are they made of?

- Since the performance of MEMS devices depends on the constitutive properties of the materials from which they are made, the increased diversity of material choices carries with it a requirement for measurement and documentation of their properties.
- Many of these materials are used in thin-film form, and it is well known that thin-film properties can differ from bulk properties.
- The elastic modulus or residual stress of a suspended beam, must be monitored in manufacturing to ensure repeatability from device to device.
- This demands new methods of material property measurement, a subject of increasing importance in the microsystems field.

How are they designed?

- The design of microsystem requires several different levels of description and detail.
- On one level, the designer must document the need and specifications for a proposed microsystem, evaluate different methods by which it might be fabricated, and if the device is to become a commercial product, further evaluate the anticipated manufactured cost.
- At another level, for each proposed approach, one must deal with details of partitioning the system into components, materials selection and the corresponding fabrication sequence for each component, methods for packaging and assembly, and means to assure adequate calibration and device uniformity during manufacture.

(continued)
How are they designed?

- Quantitative models play a key role in the design process by permitting prediction of performance prior to building a device, supporting the troubleshooting of device designs during development, and enabling critical evaluations of failure mechanisms after a device has entered the form of numerical simulations carried out on high-speed workstations.
- Experience suggests that there is a natural progression from approximate analytical models early in the design cycle to more detailed and comprehensive numerical simulations later in the design cycle, continuing into device development and manufacture.

Markets for Microsystems and MEMS


<table>
<thead>
<tr>
<th>Devices</th>
<th>Applications</th>
<th>1996</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial Measurement</td>
<td>Accelerometers and rate gyros</td>
<td>350 - 540</td>
<td>700 - 1,400</td>
</tr>
<tr>
<td>Microfluidics</td>
<td>Ink-jet printers, mass-flow sensors, biolab chips</td>
<td>400 - 500</td>
<td>3,000 - 4,450</td>
</tr>
<tr>
<td>Optics</td>
<td>Optical switches, displays</td>
<td>25 -40</td>
<td>440 - 950</td>
</tr>
<tr>
<td>Pressure Measurement</td>
<td>Automotive, medical, industrial</td>
<td>390 - 760</td>
<td>1,100 - 2,150</td>
</tr>
<tr>
<td>RF Devices</td>
<td>Cell phone components, devices for radar</td>
<td>none</td>
<td>40 - 120</td>
</tr>
<tr>
<td>Other Devices</td>
<td>Microrelays, sensors, disk heads</td>
<td>510 - 1,050</td>
<td>1,230 - 2,470</td>
</tr>
</tbody>
</table>
## Case Studies

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Partitioning</th>
<th>Technology</th>
<th>Transduction</th>
<th>Packaing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure sensor</td>
<td>Monolithic</td>
<td>Bulk micromachining with bipolar circuitry plus glass frit wafer bonding</td>
<td>Piezoresistive sensing of diaphragm deflection</td>
<td>Plastic</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>Monolithic</td>
<td>Surface micromachining with CMOS circuitry</td>
<td>Capacitive detection of proof-mass motion</td>
<td>Metal can</td>
</tr>
<tr>
<td>Resonant rate gyroscope</td>
<td>Hybrid</td>
<td>Bulk micromachined quartz</td>
<td>Piezoelectric sensing of rotation-induced excitation of resonant mode</td>
<td>Metal can</td>
</tr>
<tr>
<td>Electrostatically driven display</td>
<td>Hybrid</td>
<td>Surface micromachining using XeF2 release</td>
<td>Electrostatic actuation of suspended tensile ribbons</td>
<td>Bonded glass device cap plus direct wire bond to ASIC</td>
</tr>
<tr>
<td>DNA amplification with PCR</td>
<td>Hybrid</td>
<td>Bonded etched</td>
<td>Pressure-driven flow across temperature-controlled zones</td>
<td>Microcapillaries attached with adhesive</td>
</tr>
<tr>
<td>Catalytic combustible gas sensor</td>
<td>Hybrid</td>
<td>Surface micromachined with selective deposition of catalyst</td>
<td>Resistance change due to heat of reaction of combustible gas</td>
<td>Custom mounting for research use</td>
</tr>
</tbody>
</table>

---

## Pressure Sensor

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Partitioning</th>
<th>Technology</th>
<th>Transduction</th>
<th>Packaing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure sensor</td>
<td>Monolithic</td>
<td>Bulk micromachining with bipolar circuitry plus glass frit wafer bonding</td>
<td>Piezoresistive sensing of diaphragm deflection</td>
<td>Plastic</td>
</tr>
</tbody>
</table>

Illustrating lateral and transverse piezoresistor placements using an accelerometer flexure as an example. Illustrating the placement of piezoresistors on a micromachined diaphragm pressure sensor. A Wheatstone-bridge circuit constructed from resistors.
### Accelerometer

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Partitioning</th>
<th>Technology</th>
<th>Transduction</th>
<th>Packaing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>Monolithic</td>
<td>Surface micromachining with CMOS circuitry</td>
<td>Capacitive detection of proof-mass motion</td>
<td>Metal can</td>
</tr>
</tbody>
</table>

Schematic illustration of the design of the sensor portion of the ADXL 150 accelerometer.  
Enlarged view of electrodes on an Analog Devices accelerometer.

### Resonant Rate Gyroscope

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Partitioning</th>
<th>Technology</th>
<th>Transduction</th>
<th>Packaing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant rate gyroscope</td>
<td>Hybrid</td>
<td>Bulk micromachined quartz</td>
<td>Piezoelectric sensing of rotation-induced excitation of resonant mode</td>
<td>Metal can</td>
</tr>
</tbody>
</table>

Schematic illustration of the QRS(Quartz Rotation Sensors)/rate sensor.  
One of commercially available QRS Gyro Chip™
**Electrostatically Driven Display**

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Partitioning</th>
<th>Technology</th>
<th>Transduction</th>
<th>Packaing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrostatically driven display</td>
<td>Hybrid</td>
<td>Surface micromachining using XeF₂ release</td>
<td>Electrostatic actuation of suspended tensile ribbons</td>
<td>Bonded glass device cap plus direct wire bond to ASIC</td>
</tr>
</tbody>
</table>

Schematic illustration of the pixel design for a grating-light-valve (GLV) display.

Illustrating how the diffractive projection from a single pixel is achieved.

**DNA Amplification with PCR**

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Partitioning</th>
<th>Technology</th>
<th>Transduction</th>
<th>Packaing</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNA amplification with PCR</td>
<td>Hybrid</td>
<td>Bonded etched</td>
<td>Pressure-driven flow across temperature-controlled zones</td>
<td>Microcapillaries attached with adhesive</td>
</tr>
</tbody>
</table>

A continuous-flow PCR (Polymerase Chain Reaction) system. A two-layer glass sample with flow channels etched into it is clamped to a support containing three copper heat sinks, each one controlled to a fixed temperature. As fluid flows through the channel, it encounters a typical PCR temperature cycle.

Photo of the continuous-flow PCR cell of Kopp et al.
**Catalytic Combustible Gas Sensor**

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Partitioning</th>
<th>Technology</th>
<th>Transduction</th>
<th>Packaing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalytic combustible gas sensor</td>
<td>Hybrid</td>
<td>Surface micromachined with selective deposition of catalyst</td>
<td>Resistance change due to heat of reaction of combustible gas</td>
<td>Custom mounting for research use</td>
</tr>
</tbody>
</table>

System architecture for the combustible-gas sensor.

A pair of wire-bonded filaments, in this case, without the high-temperature metallurgy. The lower of the two filaments has been platinum coated using selective CVD.