MEMS & MICRO SYSTEMS (15A04506)

LECTURE NOTES

B.TECH

(III-YEAR & I-SEM)

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B. Tech III-I Sem. (ECE) **L T P C**
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15A04506 MEMS & MICRO SYSTEMS

C316_1: Explain the operation of MEMS & micro systems.
C316_2: Explain fabrication processes for producing micro sensors and actuators.
C316_3: Explain micro sensors, micro-actuators, their types and applications.
C316_4: Explain micro accelerometer sensor with types and applications in avionics.
C316_5: Apply the concept of MEMS & micro system for different applications

UNIT I : Introduction: Introduction to MEMS & Microsystems, Introduction to Microsensors, Evaluation of MEMS, Microsensors, Market Survey, Application of MEMS, MEMS Materials, MEMS Materials Properties, MEMS Materials Properties.

UNIT II: Microelectronic Technology for MEMS: Microelectronic Technology for MEMS, Micromachining Technology for MEMS, Micromachining Process, Etch Stop Techniques and Microstructure, Surface and Quartz Micromachining, Fabrication of Micromachined Microstructure, Microstereolithography,

UNIT III: Micro Sensors: MEMS Microsensors, Thermal Microsensors, Mechanical Micromachined Microsensors, MEMS Pressure Sensor, MEMS Flow Sensor, Micromachined Flow Sensors, MEMS Inertial Sensors, MEMS Gyro Sensor.

UNIT IV: MEMS Accelerometers: Micromachined Micro accelerometers for MEMS, MEMS Accelerometers for Avionics, Temperature Drift and Damping Analysis, Piezoresistive Accelerometer Technology, MEMS Capacitive Accelerometer, MEMS Capacitive Accelerometer Process, MEMS for Space Application.

UNIT V : MEMS Applications: Polymer MEMS & Carbon Nano Tubes CNT, Wafer Bonding & Packaging of MEMS, Interface Electronics for MEMS, Introduction to BioMEMS and Micro Fluidics, Introduction to Bio Nano Technology, Bio Sensors, Fluidics, MEMS for Biomedical Applications (Bio-MEMS)

Text Books:

1. Nadim Maluf Kirt Williams "An Introduction to Micro electro mechanical Systems Engineering", Second Edition, Artech House, Inc. Boston London, International Standard Book Number: 1-58053-590-9.
2. Varadan, V KandVaradan "Microsensors, actuators, MEMS, and electronics for smart structures" Rai-Choudhury P (ed.) Handbook of Microlithography, Micromachining, and Microfabrication, SPIE Optical Engineering Press.

UNIT-1

Syllabus

Introduction: Introduction to MEMS & Microsystems, Introduction to Microsensors, Evaluation of MEMS, Microsensors, Market Survey, Application of MEMS, MEMS Materials, MEMS Materials Properties.

Introduction to MEMS & MICROSYSTEMS:

MEMS = Micro Electro Mechanical System

Electronic and mechanical components constructed on one chip or device. Milli, micro and nanosize components.

or

Any engineering system that performs *electrical* and *mechanical* functions with *components* in *micrometers* is a MEMS. (1 µm = 1/10 of human hair)

They can be of the size of a rice grain, or smaller!

Examples:

– Digital Mirror Devices used for digital light processing.

- Inertia sensors for air bag deployment systems in automobiles

- Microcars

- ✓ A micro-electromechanical system (MEMS) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components.
- ✓ They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometers to millimeters.
- ✓ These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.

Some benefits of Micro fabricated Components:

• Smaller!

– Much Lighter!

– Energy Efficient!

– Less Materials!

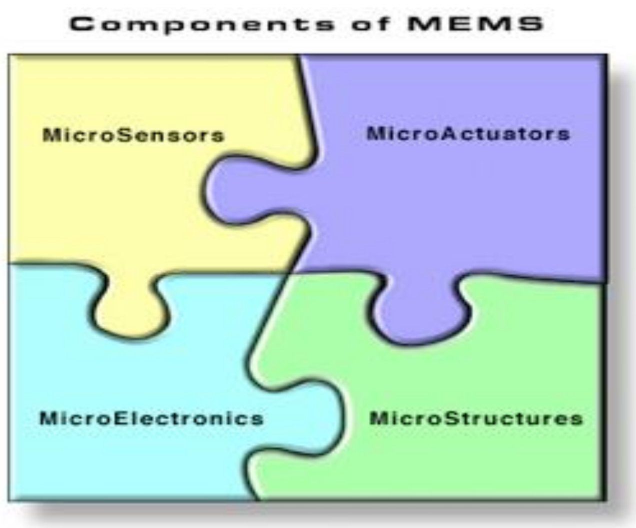
– Greener!

– More Reliable!

– Cheaper? (Maybe and there's the rub) and Economy of Scale

Micro-Electro-Mechanical Systems (MEMS) are the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology.

While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the microsensors and microactuators. Microsensors and microactuators are appropriately categorized as “transducers”, which are defined as devices that convert energy from one form to another. In the case of microsensors, the device typically converts a measured mechanical signal into an electrical signal.



MINIATURIAZATION – The Principal Driving Force for the 21st Century Industrial Technology

There has been increasing strong market demand for:

“Intelligent,”

“Robust,”

“Multi-functional,” and

“Low-cost” industrial products.

Miniaturization is the only viable solution to satisfy such market demand

Microsystems

These are miniature devices or array of devices that usually have parts with electrical and mechanical operational principles

- Sensors and actuators
- Energy conversion (electromechanical)

• **Micro-Systems that integrate both sensors and actuators to provide some useful function**

They are…

smaller

more functional

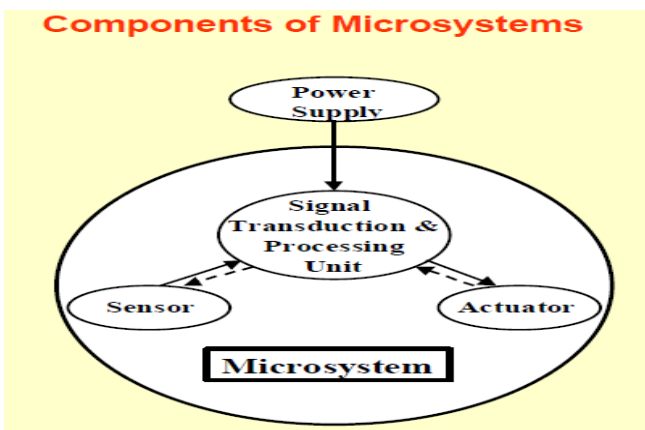
faster

less power-consuming

and cheaper!

Microsystems = sensors + actuators + signal transduction:

- **Microfluidics, e.g. Capillary Electrophoresis (CE)**
- **Microaccelerometers (inertia sensors)**



Transducers

A transducer is a device that transforms one form of signal or energy into another form. The term transducer can therefore be used to include both sensors and actuators and is the most generic and widely used term in MEMS.

Sensors *which Convert Measured Quantities into Electrical Signal*

Actuators *(reciprocal of the sensors), Convert different types of energy into Mechanical Energy*

Sensor

- ✓ A sensor is a device that measures information from a surrounding environment and provides an electrical output signal in response to the parameter it measured. Over the years, this information (or phenomenon) has been categorized in terms of the type of energy domains but MEMS devices generally overlap several domains or do not even belong in any one category. These energy domains include:

• **Mechanical** -force, pressure, velocity, acceleration, position

• **Thermal**- temperature, entropy, heat, heat flow

• **Chemical**- concentration, composition, reaction rate

• **Radiant** - electromagnetic wave intensity, phase, wavelength, polarization, reflectance, refractive index, transmittance

• **Magnetic** - field intensity, flux density, magnetic moment, permeability

• **Electrical** - voltage, current, charge, resistance, capacitance, polarization

Actuator

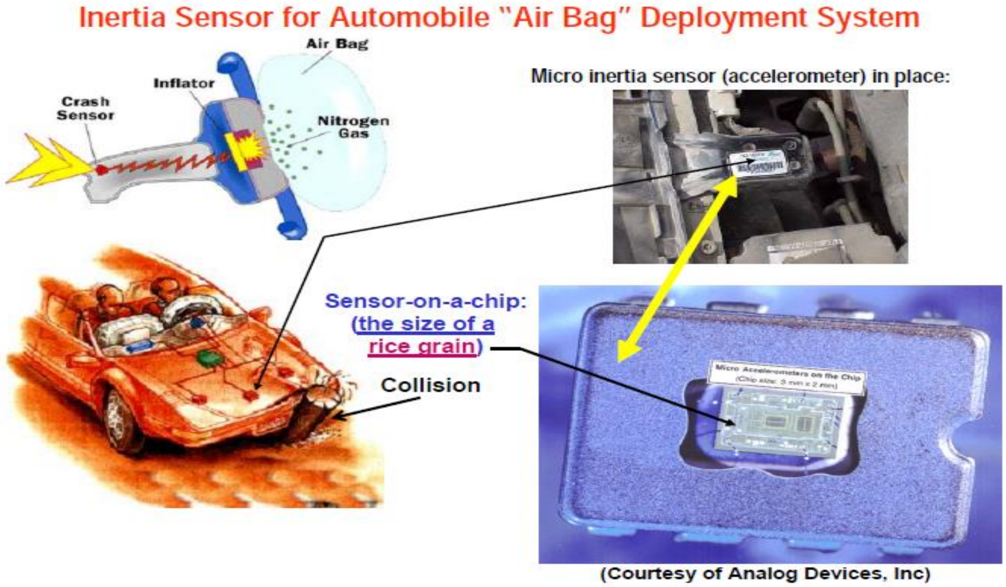
- ✓ An actuator is a device that converts an electrical signal into an action . It can create a forceto manipulate itself, other mechanical devices, or the surrounding environment to perform some useful function.

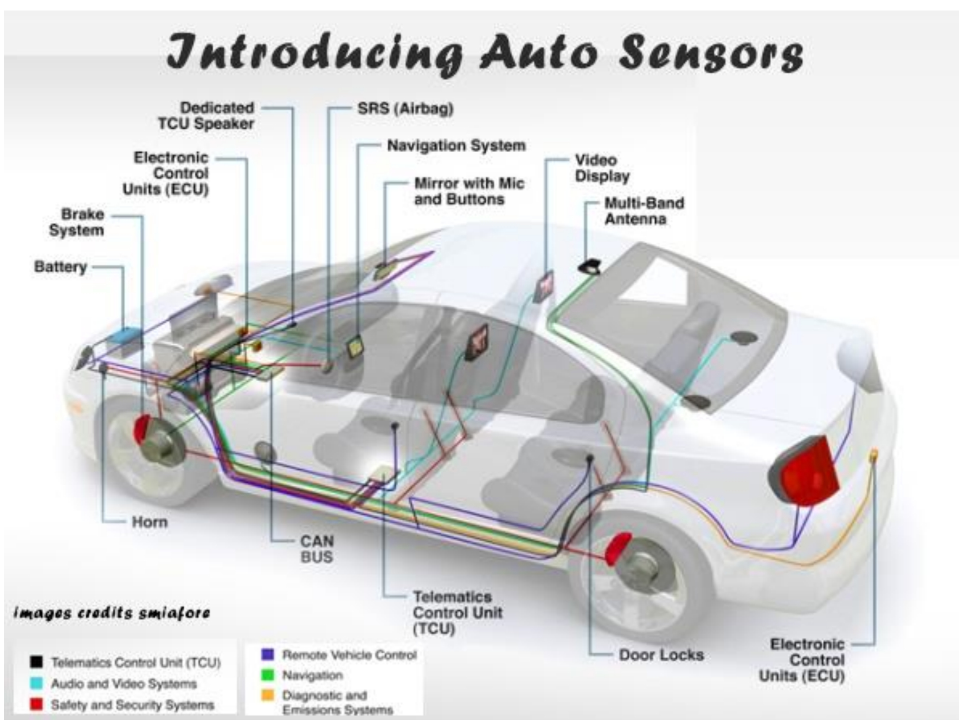
-Micro-pump – used to pump small amounts of fluid (all the way down to pico-liters)

-Micro-gear – this is a SEM (Scanning Electron Micrograph) of a Sandia Gear, each tooth is about 8um or the size of a human red blood cell

-Micro-mirror – used in telecommunications and also displays,

-Heads Up display – the reason this is a MEMs device is because it utilizes micro- mirrors


Inertia Sensor for Automobile "Air Bag" Deployment System
Air Bag
Inflator
Crash Sensor
Nitrogen Gas
Micro inertia sensor (accelerometer) in place:
Sensor-on-a-chip: (the size of a rice grain)
Collision
(Courtesy of Analog Devices, Inc)


Introducing Auto Sensors
Dedicated TCU Speaker
SRS (Airbag)
Electronic Control Units (ECU)
Navigation System
Brake System
Mirror with Mic and Buttons
Video Display
Multi-Band Antenna
Battery
Horn
CAN BUS
Telematics Control Unit (TCU)
Door Locks
Electronic Control Units (ECU)
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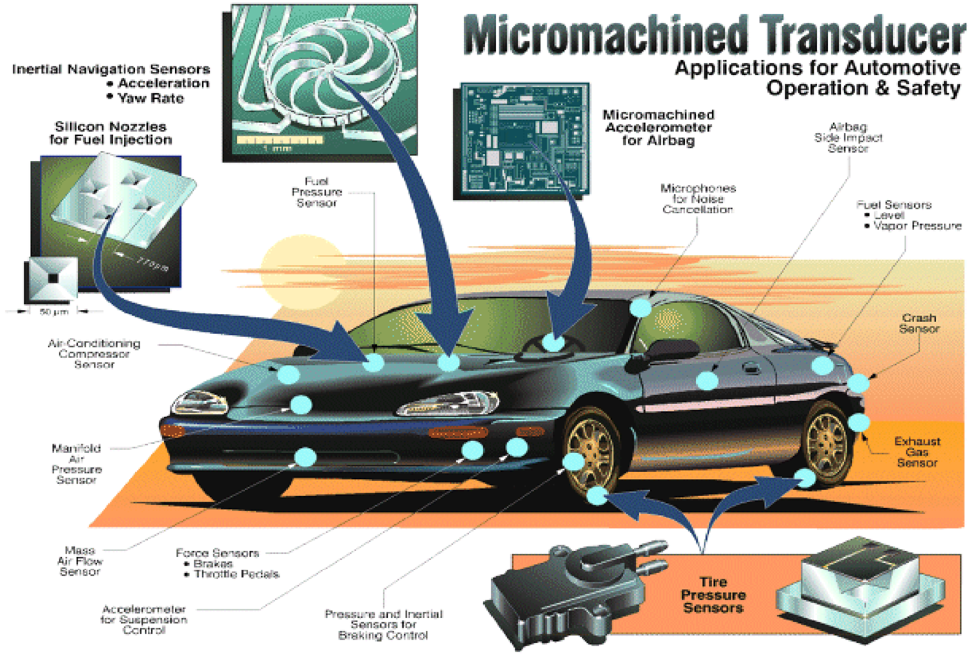
Audio and Video Systems
Safety and Security Systems
Remote Vehicle Control
Navigation
Diagnostic and Emissions Systems



History of MEMS

The history of MEMS is useful to illustrate its diversity, challenges and applications. The following list summarizes some of the key MEMS milestones.

1950's

- ✓ 1958 Silicon strain gauges commercially available.
- ✓ 1959 "There's Plenty of Room at the Bottom" – Richard Feynman gives a milestone presentation at California Institute of Technology. He issues a public challenge by offering $1000 to the first person to create an electrical motor smaller than 1/64th of an inch.

1960's

- ✓ 1961 First silicon pressure sensor demonstrated
- ✓ 1967 Invention of surface micromachining. Westinghouse creates the Resonant Gate Field Effect Transistor, (RGT). Description of use of sacrificial material to free micromechanical devices from the silicon substrate.

1970's

- ✓ 1970 First silicon accelerometer demonstrated 1979 First micromachined inkjet nozzle.

1980's

- ✓ 1982 Disposable blood pressure transducer
- ✓ 1982 "Silicon as a Mechanical Material" [9]. Instrumental paper to entice the scientific community – reference for material properties and etching data for silicon.
- ✓ 1982 LIGA Process

1988 First MEMS conference

1990's

Methods of micromachining aimed towards improving sensors.

- ✓ 1992 MCNC starts the Multi-User MEMS Process (MUMPS) sponsored by Defense

Advanced Research Projects Agency (DARPA)

- ✓ 1992 First micromachined hinge
- ✓ 1993 First surface micromachined accelerometer sold (Analog Devices, ADXL50)
- ✓ 1994 Deep Reactive Ion Etching is patented
- ✓ 1995 BioMEMS rapidly develops

2000 MEMS optical-networking components become big business

Early 1980's: first experiments in surface micromachined silicon. Late 1980's: micromachining leverages microelectronics industry and widespread experimentation and documentation increases public interes

<u>MEMS Applications</u>

• Accelerometers– (Inertial Sensors – "Crash Bags", Navigation, Safety)

Ink Jet Print Heads

Micro Fluidic Pumps– Insulin Pump (drug delivery)

Pressure Sensor – Auto and Bio applications

Spatial Light Modulators (SLM's)

– MOEM – Micro Optical Electro Mechanical Systems

– DMD – Digital Mirror Device

– DM – Deformable Mirror

Chem Lab on a Chip – Homeland security

• RF (Radio Frequency) MEMS– Low insertion loss switches (High Frequency)

• Mass Storage Devices

i) Automotive airbag sensor

- ✓ Automotive airbag sensors were one of the first commercial devices using MEMS. They are in widespread use today in the form of a single chip containing a smart sensor, or accelerometer, which measures the rapid deceleration of a vehicle on hitting an object.
- ✓ The deceleration is sensed by a change in voltage. An electronic control unit subsequently sends a signal to trigger and explosively fill the airbag.
- ✓ Initial air bag technology used conventional mechanical 'ball and tube' type devices which were relatively complex, weighed several pounds and cost several hundred dollars. They were usually mounted in the front of the vehicle with separate electronics near the airbag.
- ✓ MEMS has enabled the same function to be accomplished by integrating an accelerometer and the electronics into a single silicon chip, resulting in a tiny device that can be housed within the steering wheel column.
- ✓ The accelerometer is essentially a capacitive or piezoresistive device consisting of a suspended pendulum proof mass/plate assembly. As acceleration acts on the proof mass, micromachined capacitive or piezoresistive plates sense a change in acceleration from deflection of the plates.
- ✓ Accelerometers are not just limited to automotive applications. Earthquake detection, virtual reality video games and joysticks, pacemakers, high performance disk drives and weapon systems arming are some of the many potential uses for accelerometers.

ii) Medical pressure sensor

- ✓ Another example of an extremely successful MEMS application is the miniature disposable pressure sensor used to monitor blood pressure in hospitals. These sensors connect to a patients intravenous (IV) line and monitor the blood pressure through the IV solution.
- ✓ These expensive devices measure blood pressure with a saline-filled tube and diaphragm arrangement that has to be connected to an artery with a needle.
- ✓ The disposable sensor consists of a silicon substrate which is etched to produce a membrane and is bonded to a substrate.
- ✓ A piezoresistive layer is applied on the membrane surface near the edges to convert the mechanical stress into an electrical voltage. Pressure corresponds to deflection of the membrane.

- ✓ The sensing element is mounted on a plastic or ceramic base with a plastic cap over it designed to fit into a manufacturer's housing. A gel is used to separate the saline solution from the sensing element.
- ✓ As in the case of the MEMS airbag sensor, the disposable blood pressure sensor has been one of the strongest MEMS success stories to date. The principal manufacturers being Lucas Nova sensor, EG & G IC Sensors and Motorola with over 17 millions units per year.
- ✓ More recently, the technology from the blood pressure sensor has been taken a step further in the development of the catheter-tip pressure sensor. This considerably smaller MEMS device is designed to fit on the tip of a catheter and measure intravascular pressure (its size being only 0.15 mm x 0.40 mm x 0.90 mm).
- ✓ Pressure sensors are the biggest medical MEMS application to date with the accelerometer MEMS a distant second. Although the majority of these accelerometer applications remain under development, advanced pacemaker designs include a MEMS accelerometer device that measures the patient's activity.
- ✓ The technology, similar to that found in the airbag sensor, enables the patient's motion and activity to be monitored and signals the pacemaker to adjust its rate accordingly.

iii) Inkjet printer head

- ✓ One of the most successful MEMS applications is the inkjet printer head, superseding even automotive and medical pressure sensors. Inkjet printers use a series of nozzles to spray drops of ink directly on to a printing medium.
- ✓ Depending on the type of inkjet printer the droplets of ink are formed in different ways; thermally or piezoelectrically.
- ✓ Invented in 1979 by Hewlett-Packard, MEMS thermal inkjet printer head technology uses thermal expansion of ink vapour. Within the printer head there is an array of tiny resistors known as heaters. These resistors can be fired under microprocessor control with electronicpulses of a few milliseconds (usually less than 3 microseconds).
- ✓ Ink flows over each resistor, which when fired, heat up at 100 million oC per second, vaporizing the ink to form a bubble. As the bubble expands, some of the ink is pushed out of a nozzle within a nozzle plate, landing on the paper and solidifying almost instantaneously.

- ✓ When the bubble collapses, a vacuum is created which pulls more ink into the print head from the reservoir in the cartridge. It is worth noting there are no moving parts in this system (apart from the ink itself) illustrating that not all MEMS devices are mechanical.

iv) Overhead projection display

- ✓ One of the early MEMS devices used for a variety of display applications is the Digital Micromirror Device (DMD) from Texas Instruments. The device contains over a million tiny pixel-mirrors each measuring 16 μm by 16 μm and capable of rotating by 10^{o}, over 1000 times a second.
- ✓ Light from a projection source impinges on the pupil of the lens (or mirror) and is reflected brightly onto a projection screen.
- ✓ DMD's are used for displays for PC projectors, high definition televisions (HDTV's) and for large venues such as digital cinemas where traditional liquid crystal technology cannot compete.
- ✓ MEMS has enabled the micromirrors to be only 1 μm apart, resulting in an image taking up a larger percentage (89 percent) of space on the DMD chip's reflective surface, as compared to a typical LCD (12 to 50 percent). This reduces the pixelation and produces an overall sharper and brighter image.
- ✓ Today over 30 manufacturers use the DMD (Kodak being the largest) and over 500,000 systems have been shipped.

The fabrication technologies used to create MEMS devices is very broad based. The three most used fabrication technologies include Bulk Micro Machining, Surface Micro Machining and LIGA. There are a wide variety of materials and processes which are part of the MEMS industry.

<u>Typical Applications:</u>

There are plenty of applications for MEMS. As a breakthrough technology, MEMS is building synergy between previously unrelated fields such as biology and microelectronics, many new MEMS and Nanotechnology applications will emerge, expanding beyond that which is currently identified or known.

MEMS technology finds applications in the below general domains

Automotive domain:

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

Consumer domain:

1. Appliances
2. Sports Training Devices
3. Computer Peripherals
4. Car and Personal Navigation Devices
5. Active Subwoofers

Industrial domain:

1. Earthquake Detection and Gas Shutoff
2. Machine Health
3. Shock and Tilt Sensing

Military:

1. Tanks
2. Planes
3. Equipment for Soldiers

Biotechnology:

1. Polymerase Chain Reaction (PCR) microsystems for DNA amplification and identification
2. Micromachined Scanning Tunneling Microscopes (STMs)
3. Biochips for detection of hazardous chemical and biological agents

4. Microsystems for high-throughput drug screening and selection
5. Bio-MEMS in medical and health related technologies from Lab-On-Chip to biosensor & chemosensor.

The commercial applications include:

1. Inkjet printers, which use piezo-electrics or thermal bubble ejection to deposit ink on paper.
2. Accelerometers in modern cars for a large number of purposes including airbag deployment in collisions.
3. Accelerometers in consumer electronics devices such as game controllers, personal media players / cell phones and a number of Digital Cameras.
4. In PCs to park the hard disk head when free-fall is detected, to prevent damage and data loss.
5. MEMS gyroscopes used in modern cars and other applications to detect yaw; e.g. to deploy a roll over bar or trigger dynamic stability control.
6. Silicon pressure sensors e.g. car tire pressure sensors, and disposable blood pressure sensors.
7. Displays e.g. the DMD chip in a projector based on DLP technology has on its surface several hundred thousand micromirrors.
8. Optical switching technology, which is, used for switching technology and alignment for data communications.
9. Interferometric modulator display (IMOD) applications in consumer electronics (primarily displays for mobile devices).
10. Improved performance from inductors and capacitors due the advent of the RF-MEMS technology

MEMS devices:

Few examples of real MEMS products are,

1. Adaptive Optics for Ophthalmic Applications
2. Optical Cross Connects
3. Air Bag Accelerometers
4. Pressure Sensors

5. Mirror Arrays for Televisions and Displays
6. High Performance Steerable Micromirrors
7. RF MEMS Devices
8. Disposable Medical Devices
9. High Force, High Displacement Electrostatic Actuators
10. MEMS Devices for Secure Communications

MEMS devices used in Space exploration field include:

1. Accelerometers and gyroscopes for inertial navigation
2. Pressure sensors
3. RF switches and tunable filters for communication
4. Tunable mirror arrays for adaptive optics
5. Micro-power sources and turbines
6. Propulsion and attitude control
7. Bio-reactors and Bio-sensors, Microfluidics
8. Thermal control
9. Atomic clocks.

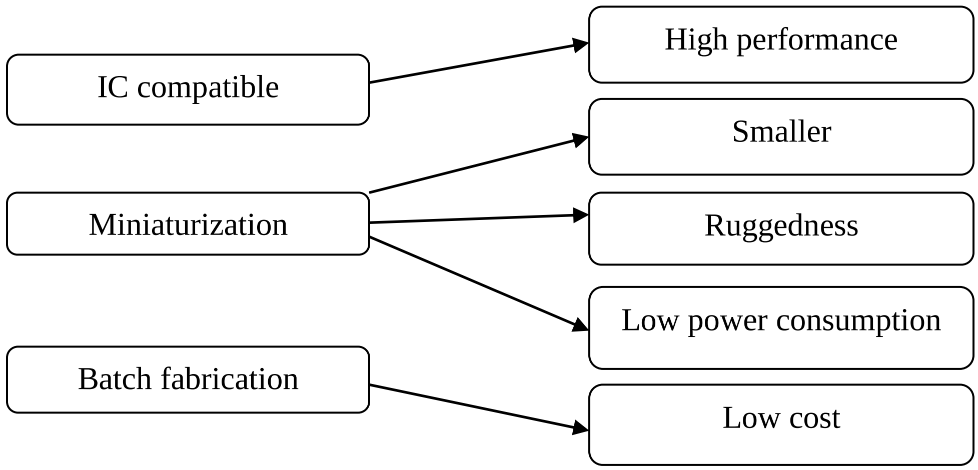
Advantages of the MEMS

1. MEMS devices now days which are coming are IC compatible. If it is IC compatible its performance is very good.

2. Miniaturization has three advantages. Not only size is small, it is a rugged and at the same time if you reduce the size, then power consumption are also low. That is another demand of the day so whatever the system or chip you made it, power consumption should be low as minimum as possible. Because everybody wants the system should be battery driven. And battery driven means, the voltage level if the whole system should 1 volt, 2 volts or 1.5 volts in that range. So for that we need that the power consumption should be less so that the life of the battery will be higher. So we have to make innovation in circuits so that low voltage, low power circuits are added into the feature at the same time you have to have the miniature device whose power consumption will be extremely small.

3. Batch fabrication. Batch fabrication means the low cost. So automatically it is obvious if the same batch you can fabricate millions of devices, so cost parts will be reduced drastically. So these are the three major advantages.

MEMS-Advantages



MEMS Market

The three most well known market studies are the Network of Excellence in Multifunctional Microsystems (NEXUS) study (1998), the System Planning Corporation (SPC) study (1999) and the Battelle study (1990) and there is discrepancy between each study [23, 24, 25 respectively]. The size of the MEMS market (M3) is contingent on how MEMS is defined (M3 is shorthand for MEMS, Microsystems and Micromachining and although it is not yet common, it is used as a reference for the entire MEMS market. Smaller M3 figures are obtained if MEMS is considered as just micromachining, which is more elemental and at the device level. Alternatively, much larger M3 figures arise if MEMS is examined at the system or subsystem level (as in the case of NEXUS). Depending on the study under review, the M3 market today ranges from $4.2 billion to $14.2 billion. Much of the current market centres on read/write heads for computer disk drives, pressure sensors, inkjet printer heads and accelerometers. Table 3 provides the NEXUS worldwide M3 market size in 1996 and forecasts for 2002 for existing MEMS product types.

Table 3. Worldwide M3 market size in 1996 and 2002 for existing MEMS product types in $US millions

Product Types	1996 Units (millions)	$ (millions)	2002 Units (millions)	$ (millions)
HDD heads	530	4500	1500	12000
Inkjet print heads	100	4400	500	10000
Heart pacemakers	0.5	1000	0.8	3700
In vitro diagnostics	700	450	4000	2800
Hearing aids	4	1150	7	2000
Pressure sensors	115	600	309	1300
Chemical sensors	100	300	400	800
Infrared imagers	0.01	220	0.4	800
Accelerometers	24	240	90	430
Gyroscopes	6	150	30	360
Magnetoresistive sensors	15	20	60	60
Microspectrometers	0.006	3	0.15	40
TOTAL	**1595**	**$13,033**	**6807**	**$34,290**

In the area of emerging MEMS products, Table 4 provides the NEXUS worldwide M3 market size in 1996 and forecasts for 2002. Drug delivery systems (microfluidic microdosing systems), lab-on-a-chip devices and MEMS-based optical switches are predicted to reach billion dollar market segments by 2002.

Table 4. Worldwide M_3 market size in 1996 and 2002 for emerging MEMS product types in $US millions

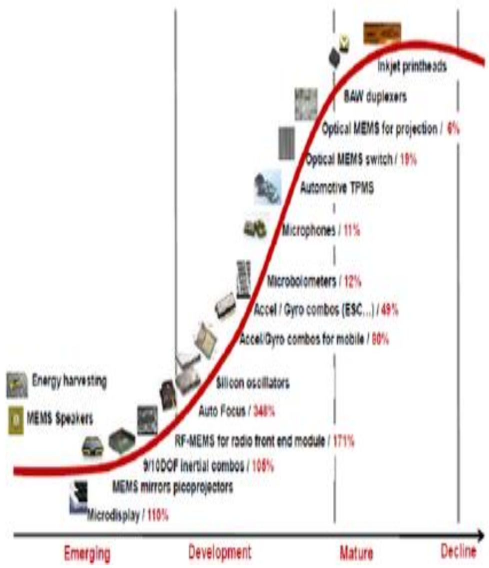
Product Types	1996 Units (millions)	$ (millions)	2002 Units (millions)	$ (millions)
Drug delivery systems	1	10	100	1000
Optical switches	1	50	40	1000
Lab on ship	0	0	100	1000
Magneto optical heads	0.01	1	100	500
Projection valves	0.1	10	1	300
Coil on chip	20	10	600	100
Micro relays		0.1	50	100
Micromotors	0.1	5	2	80
Inclinometers	1	10	20	70
Injection nozzles	10	10	30	30
Anti-collision sensors	0.01	0.5	2	20
Electronic noses	0.001	0.1	0.05	5
TOTAL	**33**	**$107**	**1045**	**$4,205**

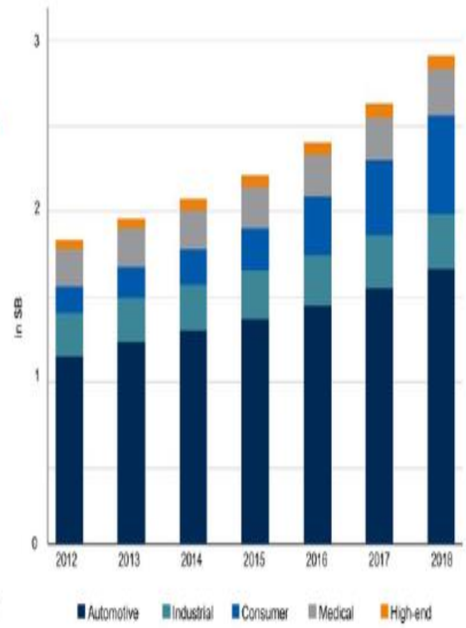
A more recent market study by NEXUS/Roger Grace Associates, shown in Table 5, estimated the M_3 market to be $14.2 billion in 2000, increasing to $30.4 billion by 2004. This corresponds to a compounded annual growth rate (CAGR) of 21%. Telecommunications is forecast to be the major growth area, comprised of both optical MEMS and RF MEMS-based devices.

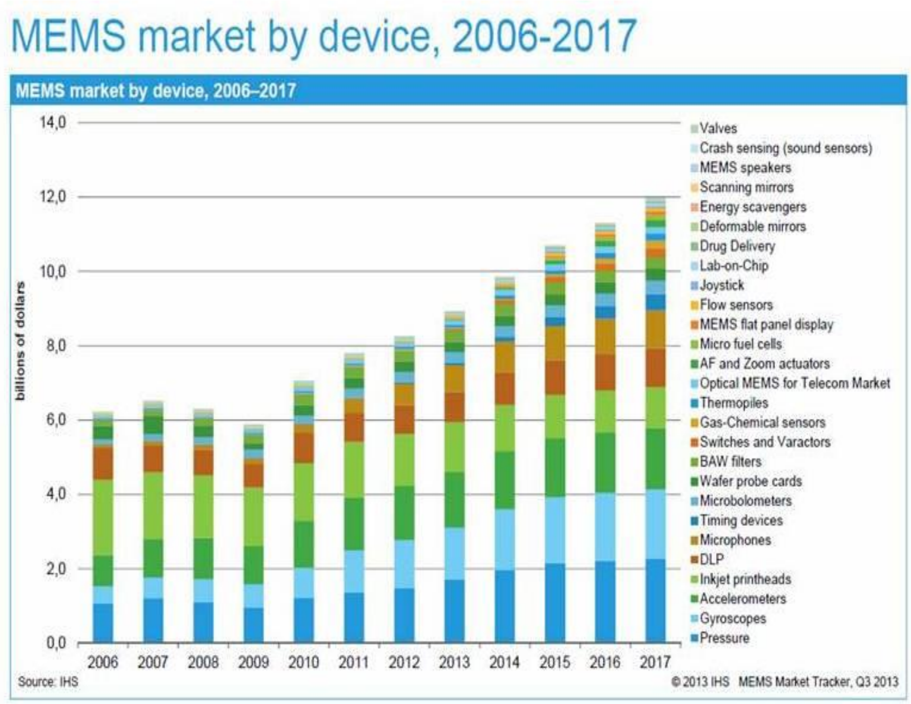
Table 5. Worldwide shipment of M_3 products by application sector for 2000-2004 in $US millions

Application Sector	2000	2004	CAGR(%)
IT/Peripheral	$ 8,700	$13,400	11.5
Medical/Biochemical	2,400	7,400	32.5
Industrial/Automation	1,190	1,850	11.6
Telecommunications	130	3,650	128.1
Automotive	1,260	2,350	16.9
Environmental Monitoring	520	1,750	35.4
TOTAL	**$14,200**	**$30,400**	**21.0%**

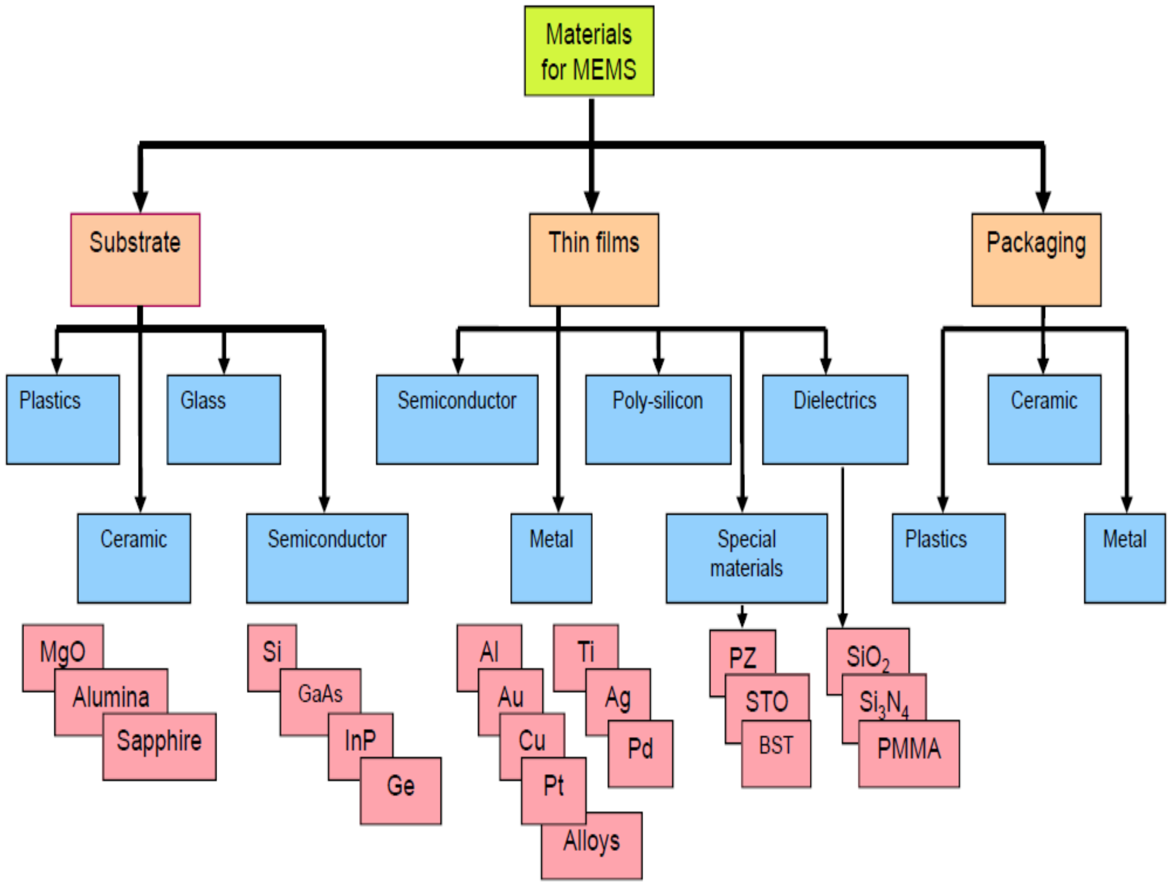
Market For MEMs







Materials for EMS



Materials for MEMS and Microsystems

Many Microsystems use microelectronics materials such as silicon, and gallium arsenide (GaAs) for the sensing and actuating elements.

- Reasons: (1) dimensionally stable;

(2) well-established fabricating and packaging techniques.

- However, there are other materials used for MEMS and Microsystems products:

  - Such as quartz and Pyrex , polymers and plastics, and ceramics. (not common in microelectronics)

Substrates and Wafers

➢ **Substrate :**

- In microelectronics, substrate is a flat macroscopic object on which microfabrication processes take place.
- In microsystems, a substrate serves an additional purpose:
  - Act as signal transducer besides supporting other transducers that convert mechanical actions to electrical outputs or vice versa.

➢ **Wafer:**

- In semiconductors, the substrate is a single crystal cut in slices from a larger piece call a wafer (which can be of silicon or other single crystalline materials such as quartz or gallium arsenide).
- In microsystems, there are two types of substrate materials:
  1. Active substrate material.
  2. Passive substrate material.
- Material classifications:
  - ➢ Insulators: electric resistivity $\rho > 10^{8}$ Ω-cm
  - ➢ Semiconductors: $10^{-3} < \rho < 10^{8}$ Ω-cm
  - ➢ Conductors: $\rho < 10^{-3}$ Ω-cm

Table 7.1 | Typical electrical resistivity of insulators, semiconductors, and conductors

Materials	Approximate electrical resistivity ρ, Ω-cm	Classification
Silver (Ag)	10^{-6}	Conductors
Copper (Cu)	$10^{-5.8}$	
Aluminum (Al)	$10^{-5.5}$	
Platinum (Pt)	10^{-5}	
Germanium (GE)	10^{-3}–$10^{1.5}$	Semiconductors
Silicon (Si)	10^{-3}–$10^{4.5}$	
Gallium arsenide (GaAs)	10^{-3}–10^{8}	
Gallium phosphide (GaP)	10^{-2}–$10^{6.5}$	
Oxide	10^{9}	Insulators
Glass	$10^{10.5}$	
Nickel (pure)	10^{13}	
Diamond	10^{14}	
Quartz (fused)	10^{18}	

- In MEMS, common substrate materials (silicon Si, germanium Ge, gallium arsenide GaAs) all fall in the category of semiconductors. Why?
  - They are at the borderline between conductors and insulators, so they can be made either a conductor or an insulator as needed. → can be converted to a conducting material by doping (p- or n-type).
  - The fabrication processes (e.g., etching) and the required equipment have already been developed for these materials.

Active Substrate Materials

- Active substrate materials are primarily used for sensors and actuators in Microsystems.

- Typical materials: Si, GaAs, Ge, and quartz.

  (All except quartz are classified as semiconductors in Table 7.1)

- Have a cubic crystal lattice with tetrahedral atomic bond.
- Reason for active substrate materials: dimensional stability

  → Insensitive to environmental conditions.

  → A critical requirement for sensors and actuators with high precision.

- Each atom carries 4 electrons in the outer orbit, and shares these 4 electrons with its 4 neighbors.

1. Silicon as A substrate Material

The Ideal Substrate for MEMS

- Single-crystal silicon is the most widely used substrate material for MEMS and microsystem. The reasons are:

1. (a) Mechanically stable; (b) can be integrated with electronics for signal transduction on the same substrate.
2. An ideal structural material because of high Young's modulus (which can better maintain a linear relationship between applied load and the induced deformation) and light weight.
   - About the same as steel (about 2×10^{5} MPa)
   - As light as aluminum with a mass density of about 2.3 g/cm^{3}.
3. High melting point at 1400℃
   - About twice as high as that of aluminum.
   - Dimensionally stable.

4. Low thermal expansion coefficient
   - About 8 times smaller than that of steel.
   - More than 10 times smaller than that of aluminum.
5. (a) Show virtually no mechanical hysteresis.
   → An ideal candidate material for sensors and actuators.

   (b) Extremely flat and accept coatings and additional thin-film layers for building microstructures and conducting electricity.
6. Treatment and fabrication processes for silicon substrate are well established and documented.

2 Single Crystal Silicon and Wafer

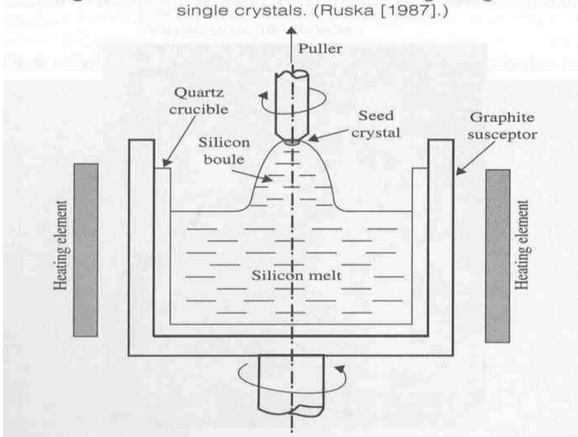
- The Czochralski (CZ) method: is the most popular one to produce pure silicon crystal. (Fig. 7.1)

  - The raw silicon in the form of quartzite are melted in a quartz crucible with carbon (coal, coke, wood chips, etc.), which is placed in a furnace.

  $$SiC+SiO_2 \rightarrow Si+CO+SiO$$

- A "seed" crystal is brought into contact with the molten silicon to form a larger crystal (a large bologna-shaped boule.
- The silicon boule is then ground to a perfect circle, then sliced to form thin disks, which are then chemically-lap polished for finishing.

Figure 7.1 I The Czochralski method for growing single crystals. (Ruska [1987].)



Wafer sizes:

- 100 mm (4 in) diameter × 500μm thick
- 150 mm (6 in) diameter × 750μm thick
- 200 mm (8 in) diameter × 1mm thick
- 300 mm (12 in) diameter × 750μm thick (tentative)

Silicon substrates often are expected to carry electric charges.

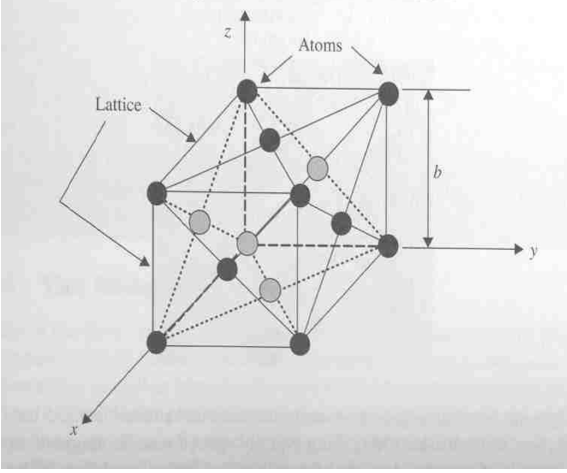
- Require p or n doping of the wafers either by ion implantation or by diffusion
- n-type dopants: phosphorus [P], arsenic [As], and antimony[Sb]
- p-type dopants: boron [B]

3 Crystal Structural

- Silicon: has basically a face-centered cubic (FCC) unit cell, called a *lattice* (as shown in Fig. 7.4).

- Lattice constant b=0.543 nm.
- Crystal structure of silicon: more complex
  → two penetrating face-centered cubic crystals, as shown in Fig. 4.4.
  → 4 additional atoms in the interior of the FCC.
  → 18 atoms in a unit cell.
  → spacing between adjacent atoms in the diamond subcell: 0.235 nm.
- Asymmetrical and nonuniform lattice distance: exhibits anisotropic thermophysical and mechanical characteristics.

Figure 7.4 | A typical face-center-cubic unit cell.



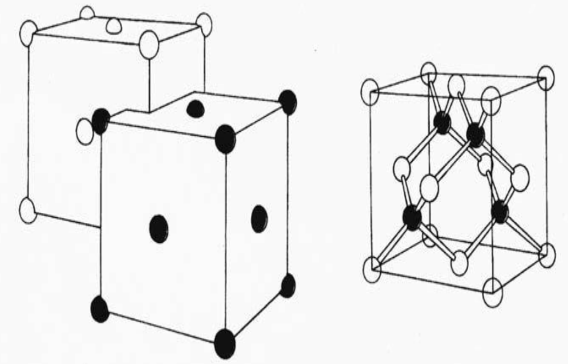
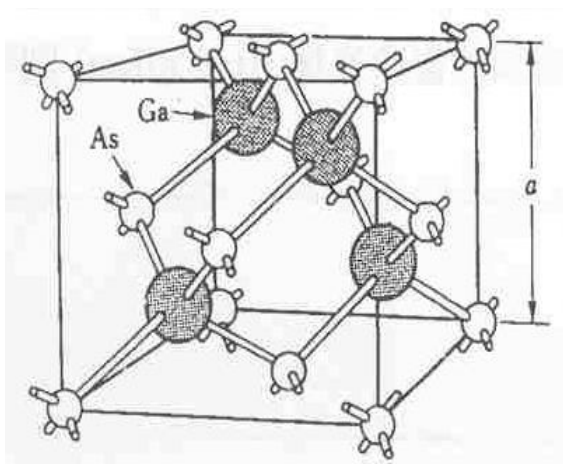


Figure 4.4 The diamond-type lattice can be constructed from two interpenetrating face-centered cubic unit cells. Si forms four covalent bonds, making tetrahedrons.

- Crystal structure of GaAs:



The Miller Indices

- Because of the skew distribution of atoms in a silicon crystal, it is important to designate the principal orientations as well as planes in the crystal.
- **Miller Indices:**
  - ✓ A plane that intercepts x, y, and z axes at a, b, and c, can be expressed as:

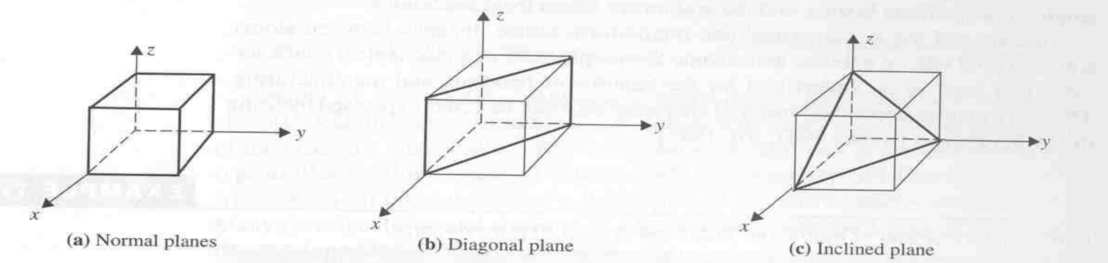
    1=++*czbyax* (7.1)
  - ✓ Equation (7.1) can be rewritten as:

    1=++*mzkyhx*

    Where h=1/a, k=1/b, and m=1/c.
  - ✓ (hkm): designate the plane, and <hkm>: designate the direction normal to the plane.

✓ Examples:

Figure 7.8 | Designation of the planes of a cubic crystal.



We can designate various planes in Figure 7.8 by using Equations (7.1) and (7.2) as follows:

Top face in Figure 7.8a:	(001)
Right face in Figure 7.8a:	(010)
Front face in Figure 7.8a:	(100)
Diagonal face in Figure 7.8b:	(110)
Inclined face in Figure 7.8c:	(111)

Figure 7.9 | Silicon crystal structure and planes and orientations.

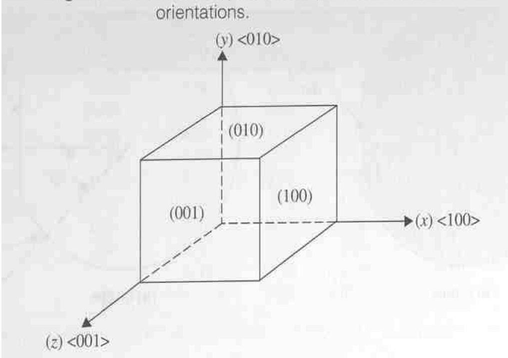
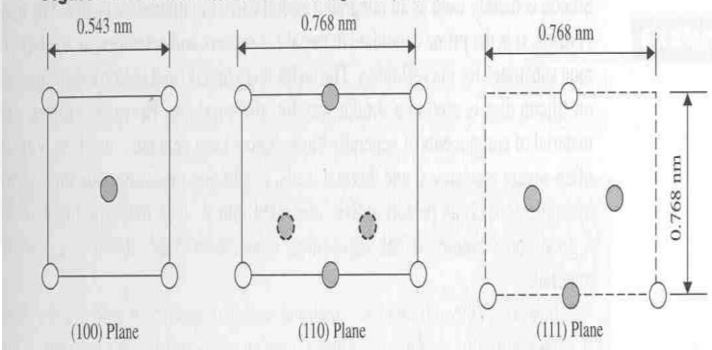


Figure 7.10 | Silicon atoms on three designated planes.



In Fig. 7.10,

- The lattice distances between adjacent atoms are shortest on (111) plane.
- These shortest lattice distance makes the attractive forces between atoms stronger on (111) than those on the (100) and (110) planes.
- On the (111) plane, the growth of crystal is the slowest, and the fabrication processes will proceed slowest.

4. Mechanical Properties of Silicon

- Silicon, as the material of 3-D structures, needs to withstand often-severe mechanical and thermal loads, in addition to accommodating electrical instruments.
- Silicon is an ideal sensing and actuating material because

1. It is an elastic material with no plasticity or creep below 800^0C.
2. Show virtually no fatigue failure.

- Disadvantages:

1. brittle
2. weak resistance to impact loads
3. anisotropic which makes stress analysis of the structures tedious.

Young's moduli and shear moduli in three directions:

Table 7.2 | The diverse Young's moduli and shear moduli of elasticity of silicon crystals

Miller index for orientation	Young's modulus E, GPa	Shear modulus G, GPa
<100>	129.5	79.0
<110>	168.0	61.7
<111>	186.5	57.5

- Bulk material properties of silicon, silicon compounds, and other active substrate materials:

Table 7.3 | Mechanical and thermophysical properties of MEMS materials*

Material	σ_y, 10^9 N/m^2	E, 10^{11} N/m^2	ρ, g/cm^3	c, J/g-°C	k, W/cm-°C	α, 10^{-6}/°C	T_M, °C
Si	7.00	1.90	2.30	0.70	1.57	2.33	1400
SiC	21.00	7.00	3.20	0.67	3.50	3.30	2300
Si_3N_4	14.00	3.85	3.10	0.69	0.19	0.80	1930
SiO_2	8.40	0.73	2.27	1.00	0.014	0.50	1700
Aluminum	0.17	0.70	2.70	0.942	2.36	25	660
Stainless steel	2.10	2.00	7.90	0.47	0.329	17.30	1500
Copper	0.07	0.11	8.9	0.386	3.93	16.56	1080
GaAs	2.70	0.75	5.30	0.35	0.50	6.86	1238
Ge		1.03	5.32	0.31	0.60	5.80	937
Quartz	0.5-0.7	0.76-0.97	2.66	0.82-1.20	0.067.0.12	7.10	1710

*Principal source for semiconductor material properties: *Fundamentals of Microfabrication*, Marc Madou, CRC Press, 1997

Legend: σ_y = yield strength, E = Young's modulus, ρ = mass density, c = specific heat, k = thermal conductivity, α = coefficient of thermal expansion, T_M = melting point.

5 Silicon Compounds

✓ 3 often-used silicon compounds:

1. Silicon dioxide (SiO_2)
2. Silicon Carbide (SiC)
3. Silicon Nitride (Si_3N_4)

5.1 Silicon Dioxide (SiO_2)

✓ Three principal uses of SiO_2:

1. as a thermal and electric insulator (see Table 7.1);
2. as a mask in the etching of silicon substrates;

   (SiO_2 has much stronger resistance to most etchants than silicon)
3. as a sacrificial layer in the surface micromachining.

Properties:

Table 7.5 | Properties of silicon dioxide

Properties	Values
Density, g/cm^3	2.27
Resistivity, Ω-cm	$\geq 10^{16}$
Relative permittivity	3.9
Melting point, °C	~1700
Specific heat, J/g-°C	1.0
Thermal conductivity, W/cm-°C	0.014
Coefficient of thermal expansion, ppm/°C	0.5

Source: Ruska [1987].

- Oxidation: by heating silicon in an oxidant (e.g., O_2) with or without steam.

  (a) Dry oxidation: $Si + O_2 \rightarrow SiO_2$

  (b) Wet oxidation in steam:

  $$Si + 2H_2O \rightarrow SiO_2 + 2H_2$$

- Oxidation is effectively a diffusion process (see Chapter 3). Diffusivity of SiO_2 at 900^0C in dry oxidation:

  (a) 4×10^{-19} cm^2/s for arsenic (As)-doped silicon (n-type);

(b) 3×10^{-19} cm^2/s for boron (B)-doped silicon (p-type);

Note: Steam would accelerate the oxidation process.

5.2 Silicon Carbide (SC)

- Properties and usages:

1. dimensional and chemical stability at high temperature
   (a) strong resistance to oxidation at very high temperature
   (b) deposited over MEMS components to protect them from extreme temperature
2. The thin SiC film can be patterned by dry etching with aluminum masks, and can be further used as passivation layer (protective layer) in micromachining for the underlying silicon layer. (∵ SiC can resist common etchants such as KOH and HF.)

- SiC: a by-product in producing single crystal silicon boule.
- Intense heating of the carbon raw materials (coal, wood chips, etc.) would results in SiC sinking to the bottom of the crucible.
- The SiC film: produced by various deposition techniques.
- Table 7.3 lists some thermophysical properties.

5.3 Silicon

Superior properties attractive for MEMS:

✓ An excellent barrier to diffusion of water and ions (e.g., sodium)

- Ultrastrong resistance to oxidation and many etchants → Suitable for masks for deep etching.

➢ Applications:

- Optical waveguides
- Encapsulants to prevent diffusion of water and other toxic fluid into the substrate.
- High-strength electric insulators and ion implantation masks.

➢ Production Processes:

➢ Produced from silicon containing gases and NH_3:

$$3SiCl_2H_2 + 4NH_3 \rightarrow Si_3N_4 + 6HCl + 6H_2 \quad (7.5)$$

- Can be produced by both LPCVD (low pressure chemical vapor deposition) and PECVD (plasma-enhanced chemical vapor deposition) processes.

Note: plasma

- Properties: listed in Tables 7.3 and 7.6.

Table 7.6 | Selected properties of silicon nitride

Properties	LPCVD	PECVD
Deposition temperature, °C	700–800	250–350
Density, g/cm^3	2.9–3.2	2.4–2.8
Film quality	Excellent	Poor
Relative permittivity	6–7	6–9
Resistivity, Ω-cm	10^{16}	10^{6}–10^{15}
Refractive index	2.01	1.8–2.5
Atom % H	4–8	20–25
Etch rate in concentrated HF	200 Å/min	
Etch rate in boiling HF	5–10 Å/min	
Poisson's ratio	0.27	
Young's modulus, GPa	385	
Coefficient of thermal expansion, ppm/°C	1.6	

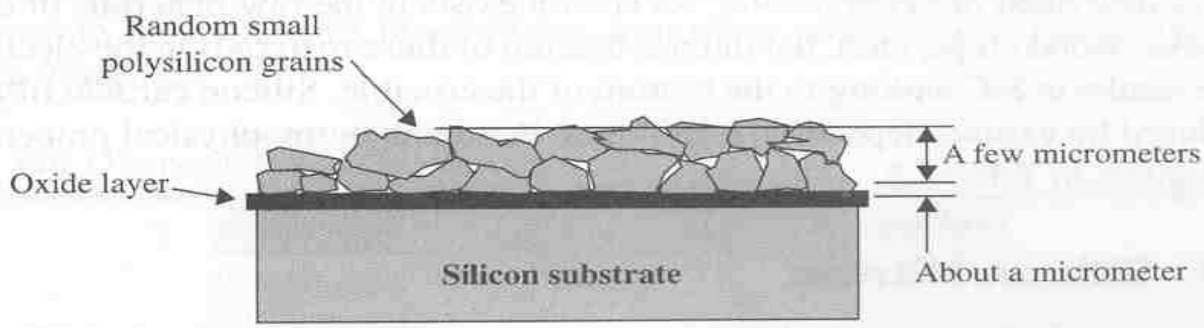
Source: Madou [1997].

5.4 Polycrystalline Silicon

- Polysilicon is a principal material in surface micromachining

- Production

Figure 7.12 | Polysilicon deposits on a silicon substrate.



Production process:

- LPCVD is frequently used for depositing polycrystalline silicon onto silicon. → Temperature: 600 to 650^{0}C

- **Applications and properties:**

- In IC industry: resistors, gates for transistors, thin-film transistors, etc.

- Highly doped polysilicon can reduce the resistivity of polysilicon to produce conductors and control switches.

→ Ideal material for microresistors as well as easy ohmic contacts.

- Polysilicon can be treated as isotropic material in structural and thermal analyses (due to its crystals in random sizes and orientations).

- Table 7.7: list some key properties of polysilicon and other materials.

Table 7.7 | Comparison of mechanical properties of polysilicon and other materials

Materials	Young's modulus, GPa	Poisson's ratio	Coefficient of thermal expansion, ppm/°C
As substrates:			
Silicon	190	0.23	2.6
Alumina	415		8.7
Silica	73	0.17	0.4
As thin films:			
Polysilicon	160	0.23	2.8
Thermal SiO_2	70	0.2	0.35
LPCVD SiO_2	270	0.27	1.6
PECVD SiO_2			2.3
Aluminum	70	0.35	25
Tungsten	410	0.28	4.3
Polymide	3.2	0.42	20–70

Source: Madou [1997].

Gallium Arsenide (GaAs**)**

- GaAs

- A compound semiconductor

- Advantages

  - A prime candidate material for photonic device due to its high mobility of electrons (7 times higher than silicon, see Table 7.11)

    → easier for electric current to flow in the material

  - Superior thermal insulator with excellent dimensional stability at high temperature

Table 7.11 | Electron mobility of selected materials at 300 K

Materials	Electron mobility, $m^2/V\text{-}s$
Aluminum	0.00435
Copper	0.00136
Silicon	0.145
Gallium arsenide	0.850
Silicon oxide	~0
Silicon nitride	~0

Source: Kwok [1997].

-Disadvantages

1. More difficult to process than silicon
2. Low yield strength (one-third of that of silicon)
3. More expensive than silicon due to its low use

- Comparison of GaAs and silicon

Table 7.12 | A comparison of GaAs and silicon in micromachining

Properties	GaAs	Silicon
Optoelectronics	Very good	Not good
Piezoelectric effect	Yes	No
Piezoelectric coefficient, pN/°C	2.6	Nil
Thermal conductivity	Relatively low	Relatively high
Cost	High	Low
Bonding to other substrates	Difficult	Relatively easy
Fracture	Brittle, fragile	Brittle, strong
Operating temperature	High	Low
Optimum operating temp., °C	460	300
Physical stability	Fair	Very good
Hardness, GPa	7	10
Fracture strength, GPa	2.7	6

Source: Madou [1997].

6 Quartz

- A compound of SiO_2
- Unit cell in the shape of tetrahedron
- Orientation: (Senturia, 2001)
    1. Not based on miller indices
    2. Some basic orientations, such as *X*-cut and *Z*-cut quartz, refer to the crystalline axes normal to the plane of the wafer.

3. However, some others, such as *AT*-cut quartz, refer to off-axis orientations that are selected for specific temperature insensitivities of their piezoelectric or mechanical properties.

- An ideal material for sensor because of its near absolute thermal dimensional **stability**
- A desirable material in microfluidics applications in biomedical analyses
    1. Inexpensive
    2. Work well in electrophoretic fluid transportation due to its excellent electric insulation properties
    3. Transparent to ultraviolet light which is good for the purpose of species detection
- Hard to machine
    1. Could use "diamond cutting" or "ultrasonic cutting"
    2. Can be etched chemically by HF/NH_4F into the desired shape
- More dimensionally stable than silicon
- More flexibility in geometry than silicon

Table 7.13 | Some properties of quartz

Properties	Value ∥ Z	Value ⊥ Z	Temperature dependency
Thermal conductivity, cal/cm-s°/C	29×10^{-3}	16×10^{-3}	↓ with T
Relative permittivity	4.6	4.5	↓ with T
Density, kg/m³	2.66×10^3	2.66×10^3	
Coefficient of thermal expansion, ppm/°C	7.1	13.2	↑ with T
Electrical resistivity, Ω/cm	0.1×10^{15}	20×10^{15}	↓ with T
Fracture strength, GPa	1.7	1.7	↓ with T
Hardness, GPa	12	12	

Source: Madou [1997].

Polymers

- Polymers
    - Include diverse materials such as plastics, adhesives, Plexiglas and Lucite
    - Become increasingly popular materials for MEMS and Microsystems
    - Examples in MEMS and microsystems:
        1. Plastic cards approximately 150 mm wide containing 1000 microchannels for microfluidic electrophoretic systems by the biomedical industry (Lipman, 1999)

2. Epoxy resins and adhesives such as silicone rubber used in packing

- Made up of long chains of organic (mainly hydrocarbon) molecules
- Characteristics:
    1. Low mechanical strength
    2. Low melting point
    3. Poor electric conductivity
- Thermoplastics and thermosets: 2 groups of common polymers
    1. Thermoplastics: easily formed to the desired shape
    2. Thermosets: have better mechanical strength and temperature resistance up to 350℃

Polymer as Industrial Materials

➢ Applications:

- Used as Insulators,

    Sheathing capacitor films in electric devices, and

    Die pads in integrated circuits.

- Advantages
    1. Light weight
    2. Ease in processing
    3. Low cost of raw materials and processes for producing polymers
    4. High corrosion resistance
    5. High electrical resistance
    6. High flexibility in structures
    7. High dimensional stability
    8. Great variety

Polymers for MEMS and Microsystems

Applications:

1. Photoresist polymers: used as masks for creating desired patterns on substrates by photolithography.
2. Photoresist polymers: used to produce the prime mold in the LIGA process.
3. Conductive polymers: used as organic substrates.

4. Ferroelectric polymers (which behave like piezoelectric crystals): used as a source of actuation in microdevices such as those for micropumping
5. Thin Langmuir-Blodgett (LB) film: used for miltilayer microstructures
6. Used as a coating substances for capillary tubes to facilitate electro-osmotic flow in microfluidics.
7. Thin polymer films: used as electric insulators in microdevices and as a dielectric substances in microcapacitors.
8. Used for electromagnetic interference (EMI) and radio-frequency interference (RFI) shielding in Microsystems.
9. Used for the encapsulation of microsensors and packaging of other microsystems.

Conductive Polymers

- For some application, polymers have to be made electrically conductive.
  - By nature, polymers: poor electric conductors (Table 7.15).
  - Polymers can be made electrically conductive by the following 3 methods:

1. Pyrolysis:
   - A pyropolymer based on phthalonitrile resin: by adding an amine heated above 600^0C

Table 7.15 | Electric conductivity of selected materials

Materials	Electric conductivity, S/m*
Conductors:	
Copper	10^6–10^8
Carbon	10^4
Semiconductors:	
Germanium	10^0
Silicon	10^{-4}–10^{-2}
Insulators:	
Glass	10^{-10}–10^{-8}
Nylon	10^{-14}–10^{-12}
SiO_2	10^{-16}–10^{-14}
Polyethylene	10^{-16}–10^{-14}

*S/m = siemens per meter. Siemens = Ω^{-1}= A^2-s^3/kg-m^2

2. Doping Examples:
   - For polyacetylenes (PA): Dopants such as Br_2, I_2, AsF_5, $HClO_4$, and H_2SO_4 to produce p-type polymers, and sodium naphthalide in tetrahydrofuran (THF,〔1071〕) for the n-type polymer.

3. Insertion of Conductive Fibers

A. Incorporate conductive fillers (e.g., carbon, aluminum flakes, stainless steel, gold, and silver fibers) into both thermosetting and thermoplastic polymer structures.

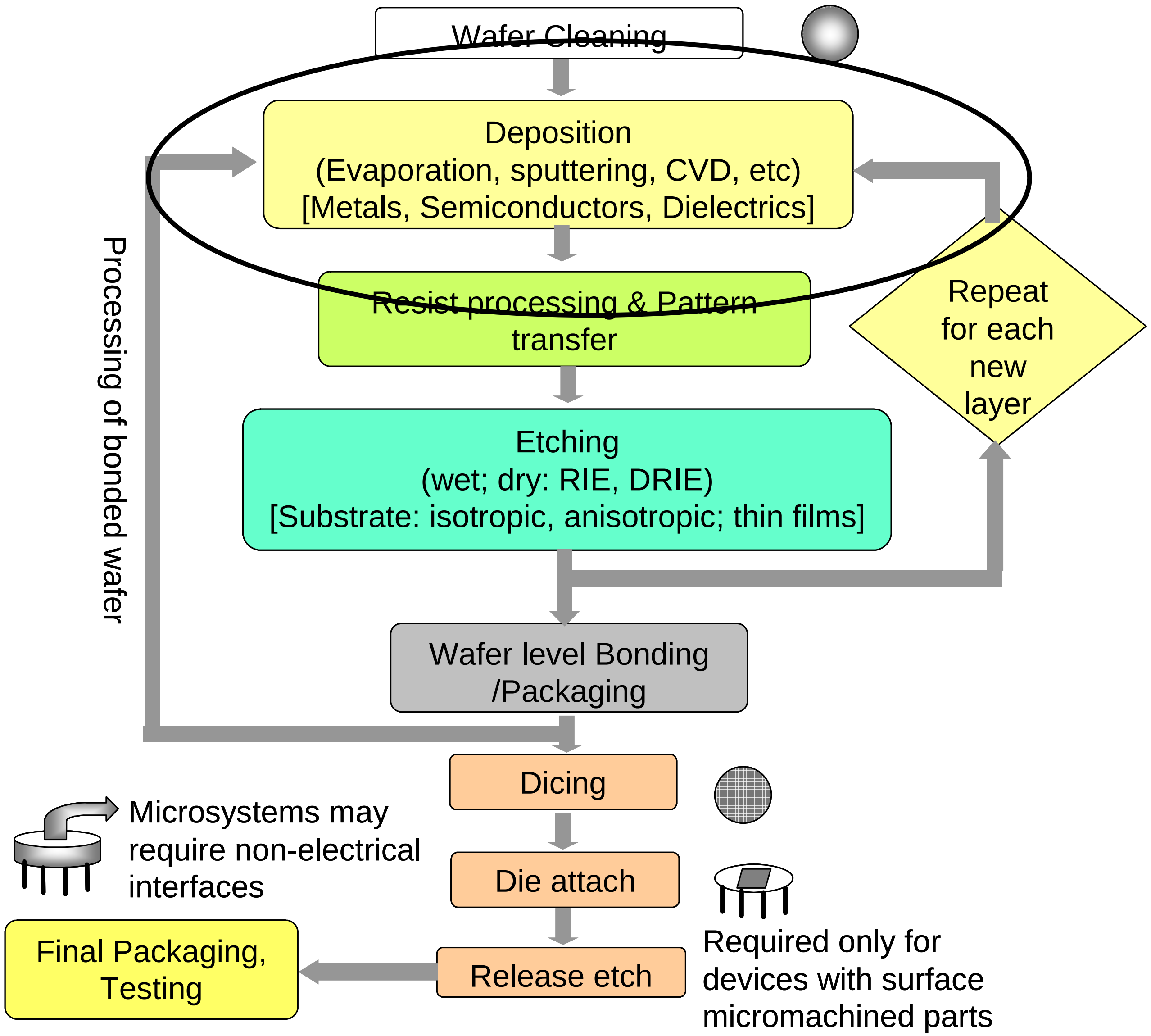
B. Other inserts include semiconducting fibers (nanometers in length), e.g., silicon and germanium.

Packaging Materials

- Distinction between the IC packaging and the microsystems packaging:
  - For IC: to protect from the hostile operating environment.
  - For microsystems: in addition to protection, it is required to be in contact with the media that are sources of action.
- Materials for microsystem packaging:
  - Include those for IC packaging:
    (a) wires made of noble metals at silicon die level,
    (b) metal layers for lead wires,
    (c) solders for die/constraint base attachments, etc.
  - Also include metal and plastics.
- Consider the microsystem packaging in Fig. 7.21:
  (a) Use aluminum or gold metal films as ohmic contacts to the piezoresistors that are diffused in the silicon diaphragm.
  (b) Similar materials: used for the lead wires to the interconnects outside the casing.
  (c) Casing: made of plastic or stainless steel
  (d) Constrain base: made of glass (e.g., Pyrex or ceramics (e.g., alumina)
  (e) Adhesives that attach the silicon die to the constraint base: can be
    i) tin-lead solder alloys (thin metal layers needs to be sputtered at the joints to facilitate the solderingP;
    ii) epoxy resins
    iii) or Room-temperature vulcanizing (RTV) silicone rubber.

Thin Film Materials & their Deposition

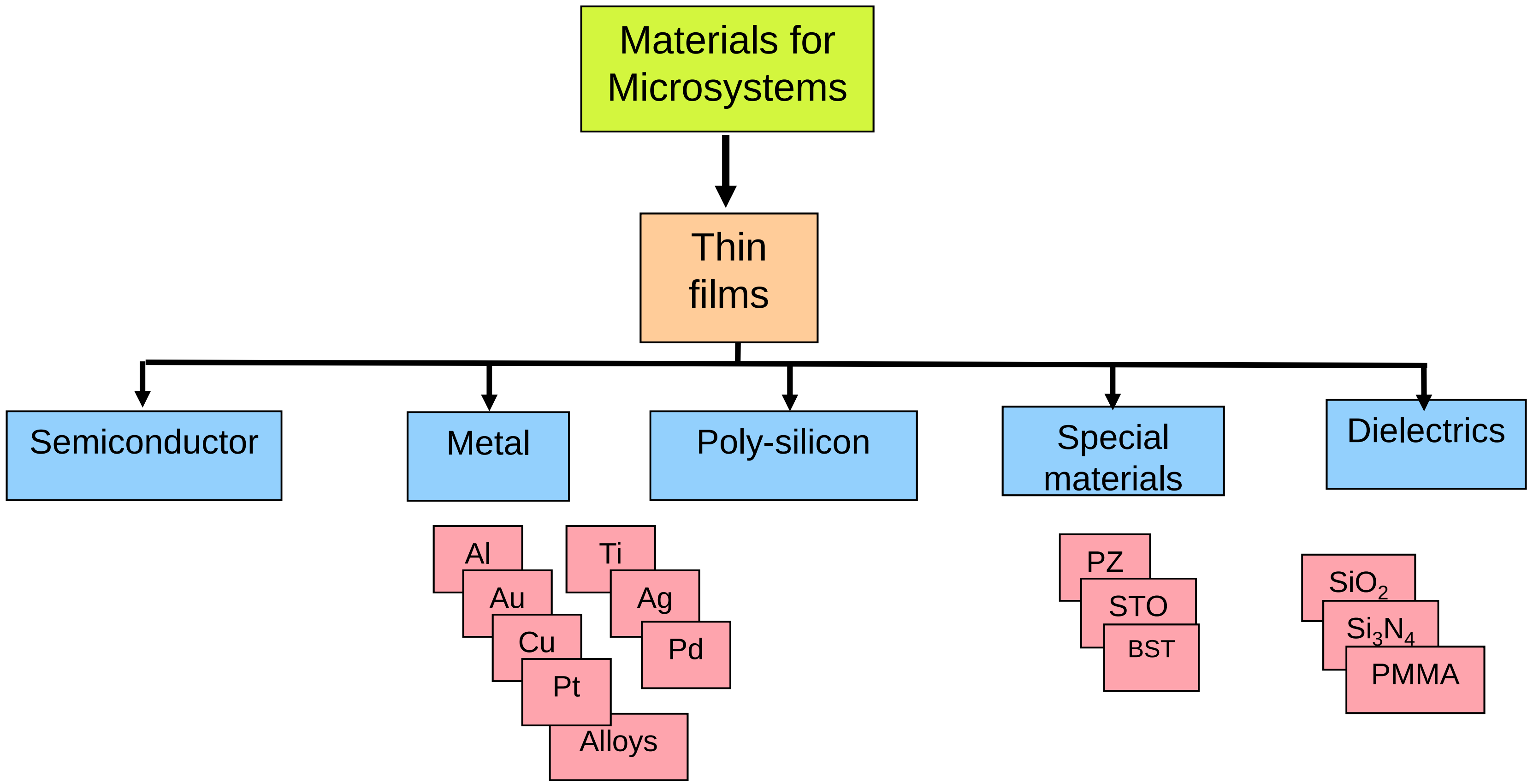
Fabrication of Microsystems



Thin films

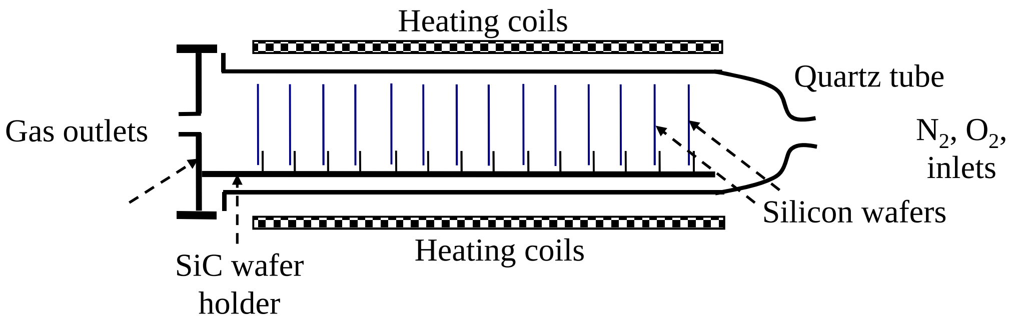
- **Most engineering materials (usually called bulk materials) have fixed properties like electrical resistivity, optical opacity, etc.**
  - Bulk materials have fixed properties and hence their applications are limited
  - When the thickness is reduced, beyond certain limits these properties show a drastic change
  - This is called size effect and this adds flexibility in designing devices for a particular application
- **Thin film possess attractive properties and therefore can have versatile applications.**
  - Devices with thin films occupy less space
  - Their fabrication requires less materials, hence inexpensive.

Materials for MEMS



Thermal oxidation of Silicon

- **Oxidation involves heating of Si in wet/or dry oxygen/nitrogen mixture**
  - Wet oxidation
    - $Si + 2H_2O \rightarrow SiO_2 + H_2$ (temperature: 600 to 12500C)
  - Dry oxidation
    - $Si + O_2 \rightarrow SiO_2$ (temperature: 600 to 12500C)
- **Wet oxidation process results in faster oxide growth.**
- **However, SiO2 films grown by this process are less dense and porous.**
- **Dry oxidation process results in much slower oxide growth (typically one tenth the growth rate of wet oxidation) resulting in films that are compact, dense and nonporous.**



- **Amount of silicon consumed is 44-46% of final oxide thickness**

  $$Si + O_2 \rightarrow SiO_2$$

  Molecular weight: Si →28; Oxide → 60 (1g Si →2.142g oxide)
  Density: Si → 2.33; Oxide →2.24
  Volumes: (0.429cm^3 Si → 0.956cm^3 oxide)
  Thickness: 0.44μm → 1 μm oxide

- **Oxidation rates depends on;**
  - Crystallographic orientation of Si
    - (1 0 0) surface oxidizes 1.7 times more slowly than a (1 1 1) surface
  - Doping
  - Presence of impurities in the oxidizing gas,
  - Pressure of oxidizing gas
  - Use of plasma or photon flux

- **Oxide thickness can be measured by Ellipsometer or color table**

Deposition process

- **Source**
- **Transport**
- **Condensation on substrate**

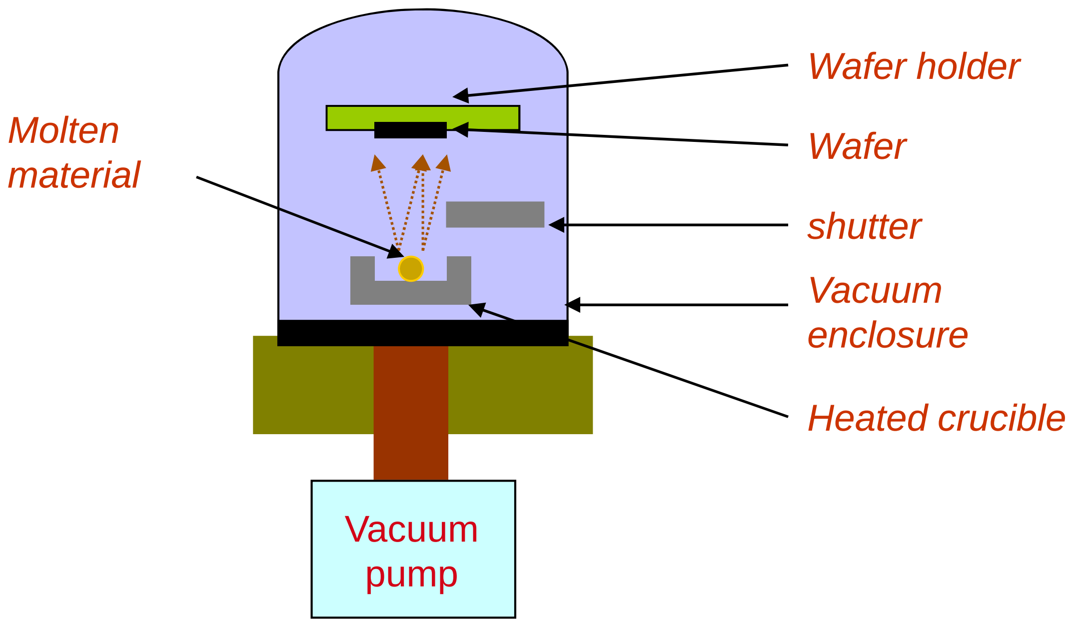
- **The nature of the film deposited depends on process parameters like substrate, deposition temperature, gaseous environment, rate of deposition etc.**

- **Favorable conditions are created to transfer the material from the source (*target*) to the destination (*substrate*).**
  - In PVD process, this transfer takes place by a physical means such as evaporation or impact
  - In CVD process films are deposited through a chemical reaction.

Major deposition schemes

- **Physical vapor deposition (PVD)**
  - Evaporation
    - High temperature
  - Sputtering
    - DC sputtering/ RF Sputtering
- **Chemical vapor deposition (CVD)**
  - Source contains the material
  - High quality films
- **Others**
  - Electroplating (for very high thickness films, fast process, less control on thickness)
  - Spin-cast
  - epitaxial

Thermal Evaporation



Schematic diagram for a thermal evaporation system

- **Procedure**
  - metal to be deposited is placed in an inert crucible
  - chamber is evacuated to a pressure of 10^{-6} – 10^{-7} Torr
  - crucible is heated using a tungsten filament or an electron beam to flash-evaporate the metal from the crucible and condense onto the cold substrate
- **The evaporation rate is a function of the vapor pressure of the metal**

Deposition by Evaporation

- **Deposition rate for Al, 0.5µm/min i.e fast process,**
  - no damage on substrate.

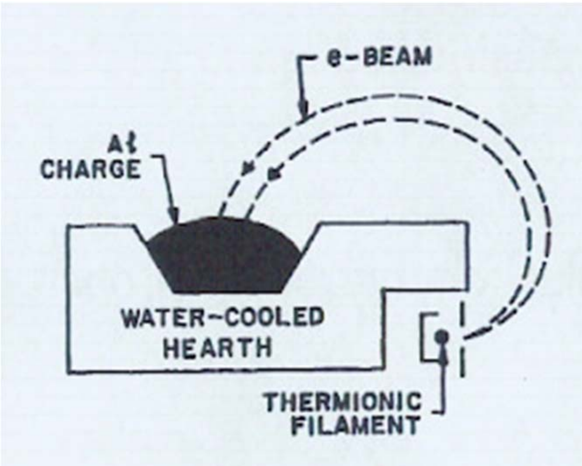
Al is the most popular interconnect material.
Resistivity: 2.65µΩcm.
Good adherance to Si/SiO_2.
Corrosion resistant, compared to Cu.
Easy to deposit / etch.
Ohmic contact is formed with Si at 450-500°C

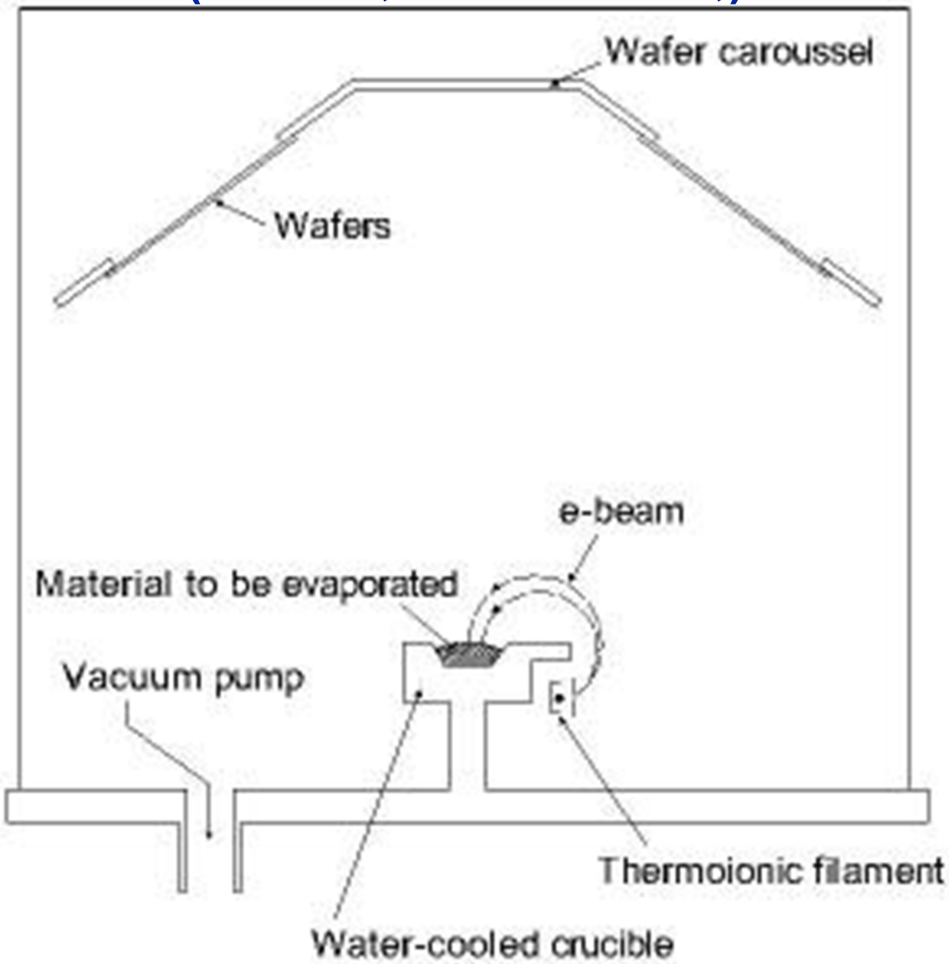
- **Source material shaped depending on the heating approach**

- **Methods for heating:**
  - Resistive heating
    - eg in lab set ups.
    - Tungsten boat/ filament as containment structure.
    - Filament life limits thickness.(for industrial use)

E-beam Evaporation

- **Focused beam of electrons are used to locally heat the Source**
- **Can be used to heat / evaporate even high melting point materials**
- **Alloys could be deposited without dissociation of constituent elements**
- **Ideally suited for reactive evaporation (Oxides, Nitrides etc.,)**

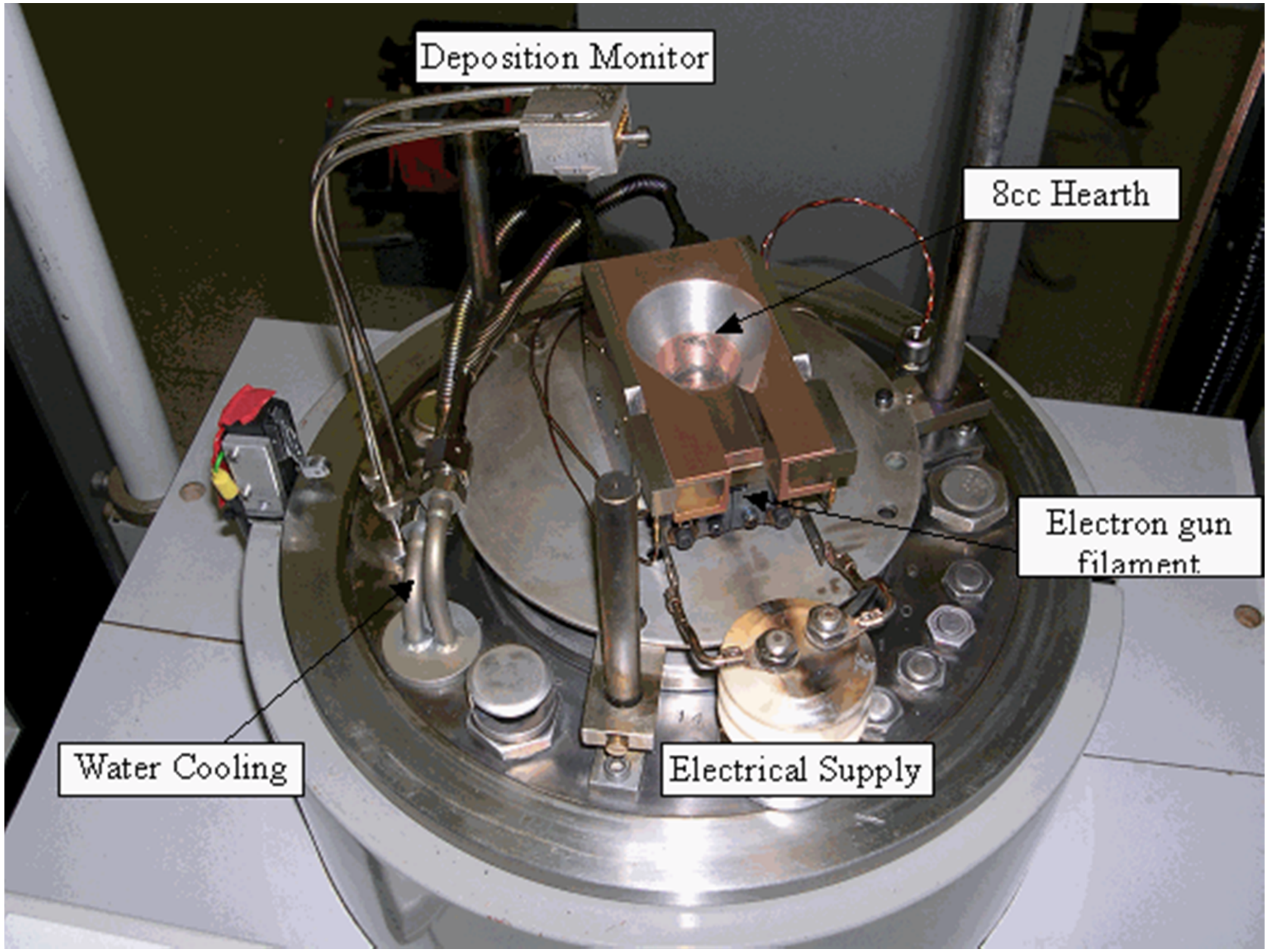




Evaporation by Ebeam/RF induction:

- **High intensity electron beam gun (3 to 20 kev) is focused on the target material that is placed in a copper hearth (water cooled)**
- **The electron beam is magnetically directed onto the evaporant, which melts locally.**
- **No contamination from crucible.**
- **High quality films.**
- **High deposition rate 50 to 500nm/min.**
- **Disadvantages:**
  - Process might induce x-ray damage and ion damage at the substrate.
  - At high energy(> 10kev), the incident electron beam causes x-ray emission.
  - Deposition equipment is more costly.

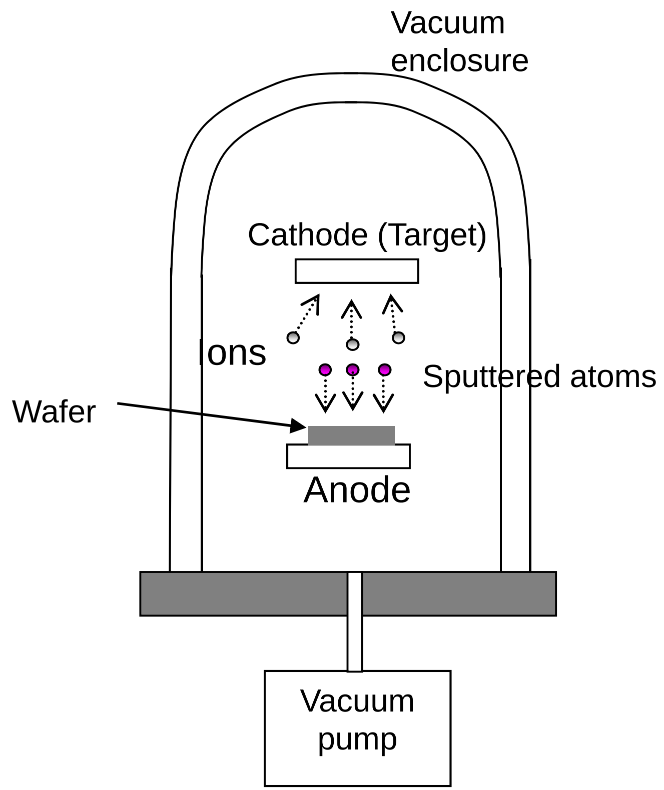
E-Beam Gun



Deposition Monitor
8cc Hearth
Electron gun filament
Water Cooling
Electrical Supply

Sputtering

- **A physical phenomenon involving**
  - The creation of plasma by discharge of neutral gas such as helium
  - Acceleration of ions via a potential gradient and the bombardment of a ‘target’ or cathode
  - Through momentum transfer atoms near the surface of the target metal become volatile and are transported as vapors to a substrate
  - Film grows at the surface of the substrate via deposition



- **For ion sputtering, the source material is put on the cathode (target); for sputter deposition, the substrates to be coated on the anode.**
- **The target, at a high negative potential is bombarded with positive argon ions created in a (high density) plasma. Condensed on to substrate placed at the anode.**

Features

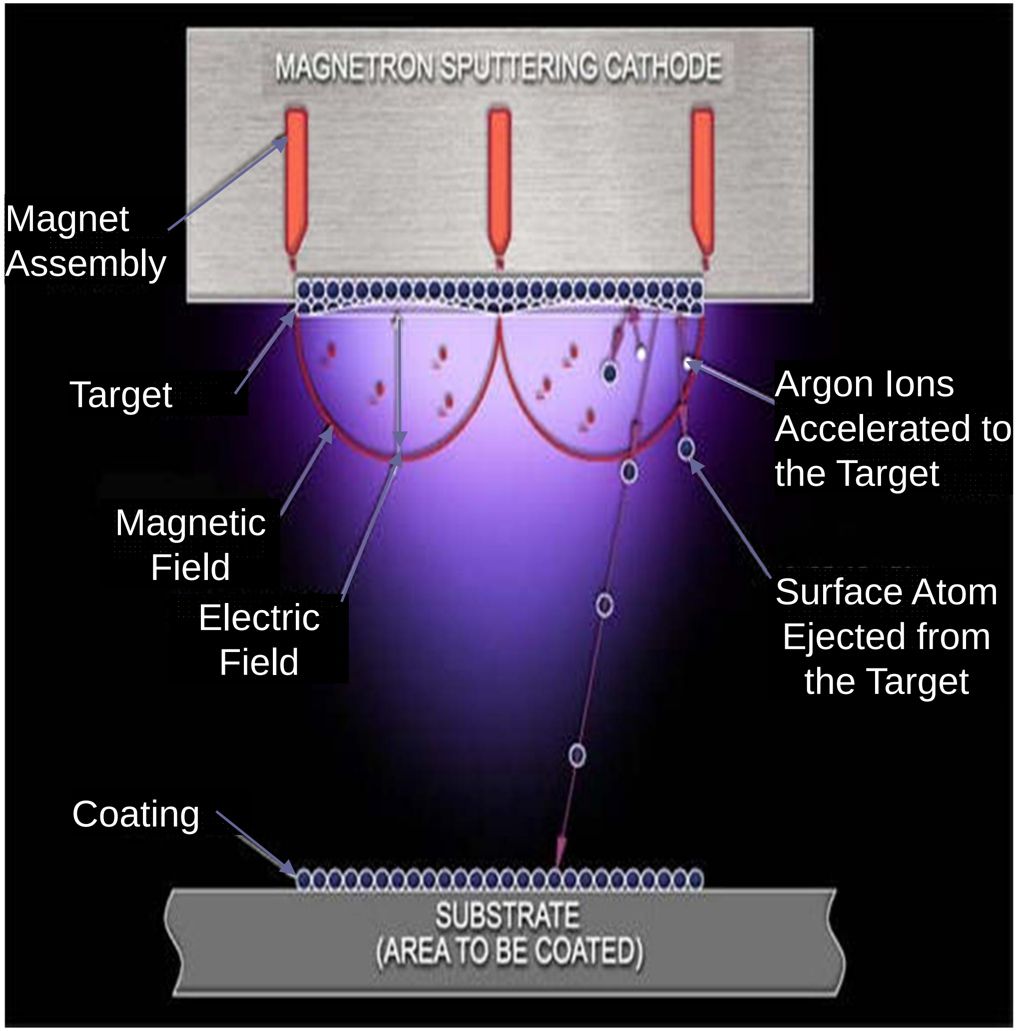
- **Sputtering yield is the average number of atoms ejected from the target per incident ion. Depends on**
  - Ion incident angle
  - Energy of the ion
  - Masses of the ion and target atoms
  - Surface binding energy of atoms in the target.
- **Sputter yields for various materials at 500ev Argon**
  - Al 1.05 Cr 1.18
  - Au 2.4 Ni 1.33
  - Pt 1.4 Ti 0.51

Key features of Sputtering

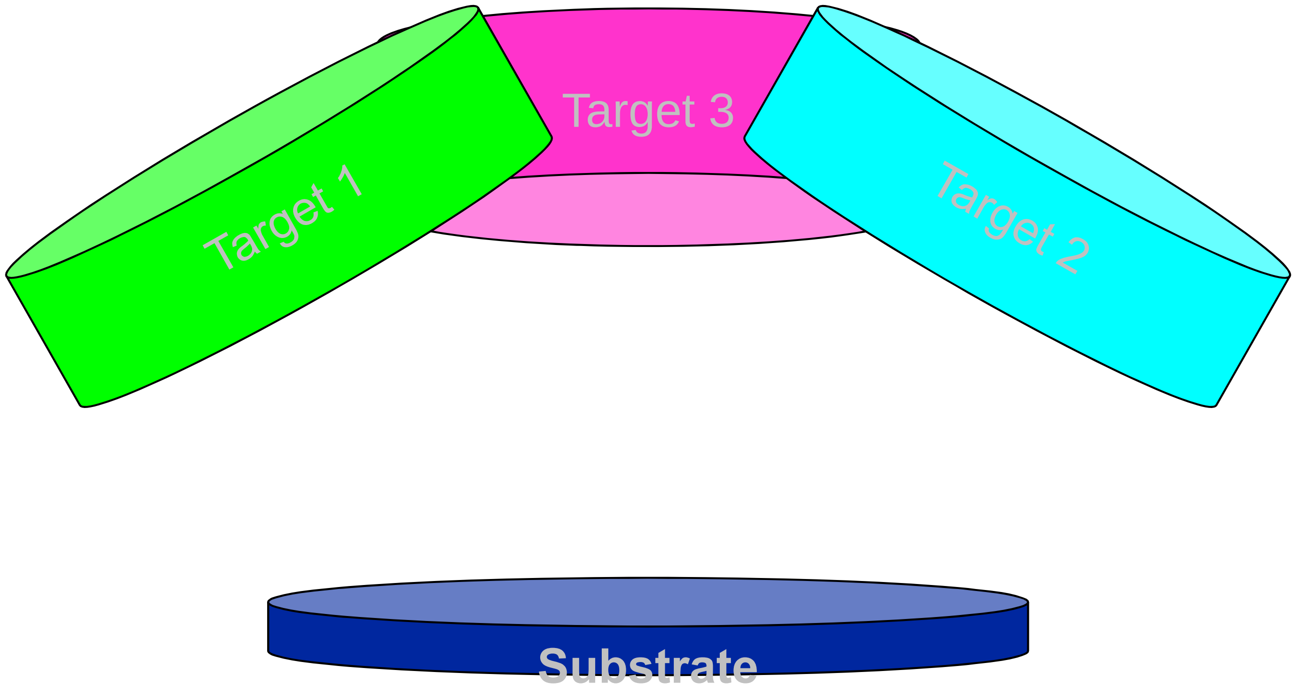
- **Advantages of sputtering over evaporation:**
  - Wider choice of materials.
  - Better adhesion to substrate.
  - Complex stoichiometries possible.
  - Films can be deposited over large wafer (process can be scaled)
  - Sputter yield= #of atoms removed per incident ion
  - Deposition rate is proportional to yield for a given plasma energy
- **Disadvantages:**
  - High cost of equipment.
  - Substrate heating due to electron (secondary) bombardment.
  - Slow deposition rate. (1 atomic layer/sec).

RF Magnetron Sputtering

- **For Dielectrics/insulators**
- **Advantages**
  - Electron Confinement
  - High ionization
  - Low pressure sputtering
  - High purity of the films
- **Disadvantages**
  - Non uniform erosion
  - Thickness uniformity
  - Less target utilization



Co-sputtering



- More than one magnetron target
- Composition controlled by the power to individual targets
- Substrate rotation is required for composition uniformity.

Comparison: Evaporation & Sputtering

	Evaporation	Sputtering
Rate	1000 atomic layer/sec (thickness control is difficult)	1 atomic layer/sec (thickness control possible)
Choice of material	Limited (to those with low melting point)	Almost unlimited
Purity	Better	Possibility of incorporating impurity
Alloy composition	Little or no control	Can be tightly controlled
Changes in source material	Easy	Expensive
Decomposition of material	High	Low
Adhesion	Often poor	Very good

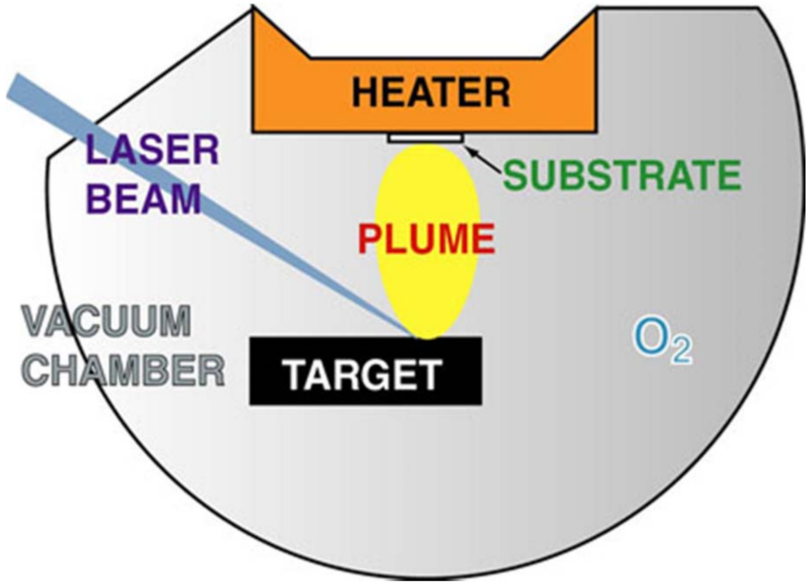
Deposition Methods for some metals

Metal	Melting point (°C)	Methods of deposition
Aluminium	659	Thermal evaporation
Silver	957	Thermal evaporation
Gold	1067	Thermal evaporation/sputtering
Copper	1083	Thermal evaporation/sputtering
Palladium	1552	Electron beam/sputtering
Platinum	1769	Electron beam/sputtering
Titanium	1677	Electron beam/sputtering
Nickel	1453	Electron beam/evaporation
Chromium	1887	Electron beam/sputtering
Tungsten	3377	Electron beam/sputtering

Deposition Systems at CEN/IISc

Laser Ablation

- **Uses LASER radiation to erode a target, and deposit the eroded material onto a substrate.**
  - The energy of the laser is absorbed by the upper surface of the target resulting in an extreme temperature flash, evaporating a small amount of material.
  - Usually pulsed laser is used.
- **Material displaced is deposited onto the substrate without decomposition.**
- **The method is highly preferred when complex stoichiometries are required.**
  - Thin film keeps the same atomic ratio as the target material.



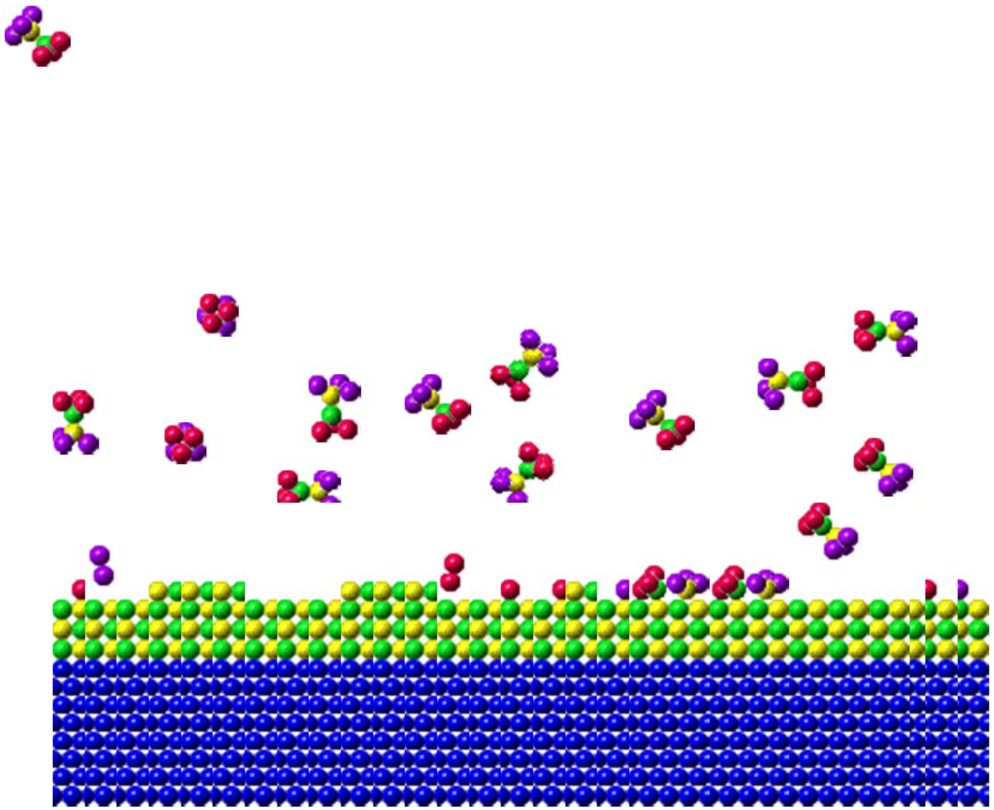
Pulsed Laser Ablation deposition (PLD)

- **Used for high quality thin films,**
  - e.g., superconducting materials such as $YBa_2Cu_3O_{7-y}$
  - short-wavelength lasers such as the KrF or XeCl excimer laser in a non-equilibrium process.
- **Ease of operation and reproducibility.**
- **Films do not require post-deposition annealing**

- **Processing variables**
  - laser energy,
  - laser pulse repetition rate,
  - substrate temperature
  - oxygen background pressure.

Chemical vapor deposition

- **Chemical Vapor Deposition is chemical reactions which transform gaseous molecules, called precursor, into a solid material, in the form of thin film or powder, on the surface of a substrate**



Constituents of a vapor phase, often diluted with an inert carrier gas, react at the hot surface to deposit a solid film.

Film-forming by

Heterogeneous reactions

Occurring at or close to heated surface.

Homogenous reactions

Occurring in gas phase

Result in stoichiometric-correct film

Used for

very thin Si deposition,

copper,

low dielectric insulators

- **Common thin films deposited by CVD are**
  - Polysilicon
  - Silicon Nitride
  - Titanium
  - Nitrides of W & Ti & Ta
  - Silicon oxide
  - Tungsten
  - Tantalum
  - Copper
  - Low permittivity dielectric insulators

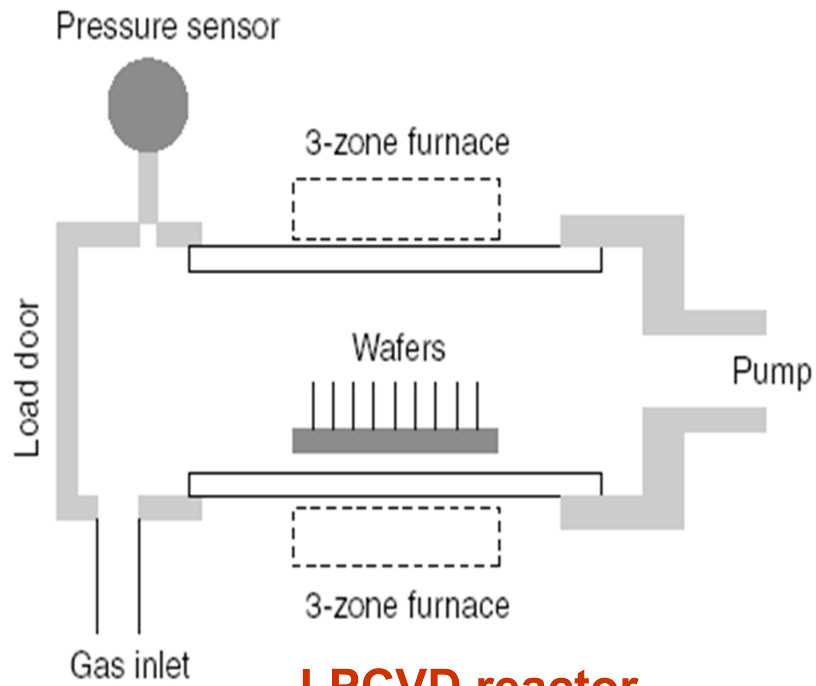
- **Parameters that significantly influence the rate of chemical vapour deposition are:**
  - temperature
  - pressure of carrier gas
  - velocity of gas flow
  - distance along the direction of gas flow

Process in CVD

- Mass transport of reactant (and diluent gases) in the bulk gases flow region from the reactor inlet to the deposition zone.
- Gas phase reactions leading to film precursors and by-products.
- Mass transport of film pre-cursors and reactants to the growth surface.
- Adsorption of film precursors and reactants on the growth surface.
- Surface reactions of adatoms occurring selectively on the heated surface.
- Surface migration of film formers to the growth sites.
- Incorporation of film constituents into the growing film.
- Desorption of by-products of the surface reaction.
- Mass transport of by-products in the bulk gas flow region away from the deposition zone towards the reactor exit

Types of CVD

- Plasma enhanced (PECVD)
- Atmospheric pressure (APCVD)
- Low pressure (LPCVD)
- Very low pressure (VLCVD)
- Metallographic (MOCVD)



LPCVD reactor

Process key		Temperature	Pressure	Typical materials
Atmospheric pressure	APCVD	700-800°C	1 atmos (760 Torr)	Polysilicon
Low pressure	LPCVD	600-620°C	0.25 to 2 Torr	Polysilicon, Silicon nitride
Plasma enhanced	PECVD	250-300°C	100 -200 mTorr	Silicon nitride, Amorphous silicon, Silicon dioxide

LPCVD of Si Compounds

CVD is used to form SiO_2 layers that are much thicker in relatively very short times than thermal oxides.

SiO_2 can be deposited from reacting silane and oxygen in LPCVD reactor at 300 to 500°C where

$$SiH_4 + O_2 \xrightarrow{500°C} SiO_2 + 2H_2$$

SiO_2 can also be LPCVD deposited by decomposing dichlorosilane

$$SiCl_2H_2 + 2H_2O \xrightarrow{900°C} SiO_2 + 2H_2 + 2HCl$$

SiO_2 can also be LPCVD deposited by from tetraethyl orthosilicate (TEOS or, $Si(OC_2H_5)_4$) by vaporizing this from a liquid source.

Si_3N_4 can be LPCVD or PECVD process.
In the LPCVD process, dichlorosilane and ammonia react according to the reaction

$$3SiCl_2H_2 + 4NH_3 \xrightarrow{\sim 800°C} Si_3N_4 + 6HCl + 6H_2$$

LPCVD for Polysilicon

- **Carried out at low pressure (200mTorr to 1000mTorr) by pyroletic decomposition of silane (SiH_4). in the temperature range 500-625°C**

$$SiH_4 \rightarrow Si + 2H_2$$

- **Most common low-pressure processes used for polysilicon**
- **Pressures between 0.2 and 1.0 Torr using 100% silane.**
- **PolySi deposition rate is approximately 10nm /minute at 620°C Maximum LPCVD Poly Si thickness is generally restricted to 2μm (2000 nm).**
- **Amorphous Si when deposited below 580°C and deposition rate is very low (2nm/min at 550°C)**

- **LPCVD poly Si is compatible with VLSI Technology**
- **Low pressure enables vertical mounting of the silicon Hence permits loading 30 to 50 wafers at a time .**

Polysilicon

- Polysilicon comprises of small crystallites of single crystal silicon, separated by grain boundaries.

- Polysilicon is often used as a **structural material** in MEMS.
- This is also used in MEMS and microelectronics for electrode formation and as a **conductor or high-value resistor**, depending on its doping level (must be highly doped to increase conductivity).

- When doped, resistivity 500-525$\mu\Omega$cm
- Polysilicon is commonly used for MOSFET Gate electrode:
- Poly can form ohmic contact with Si.

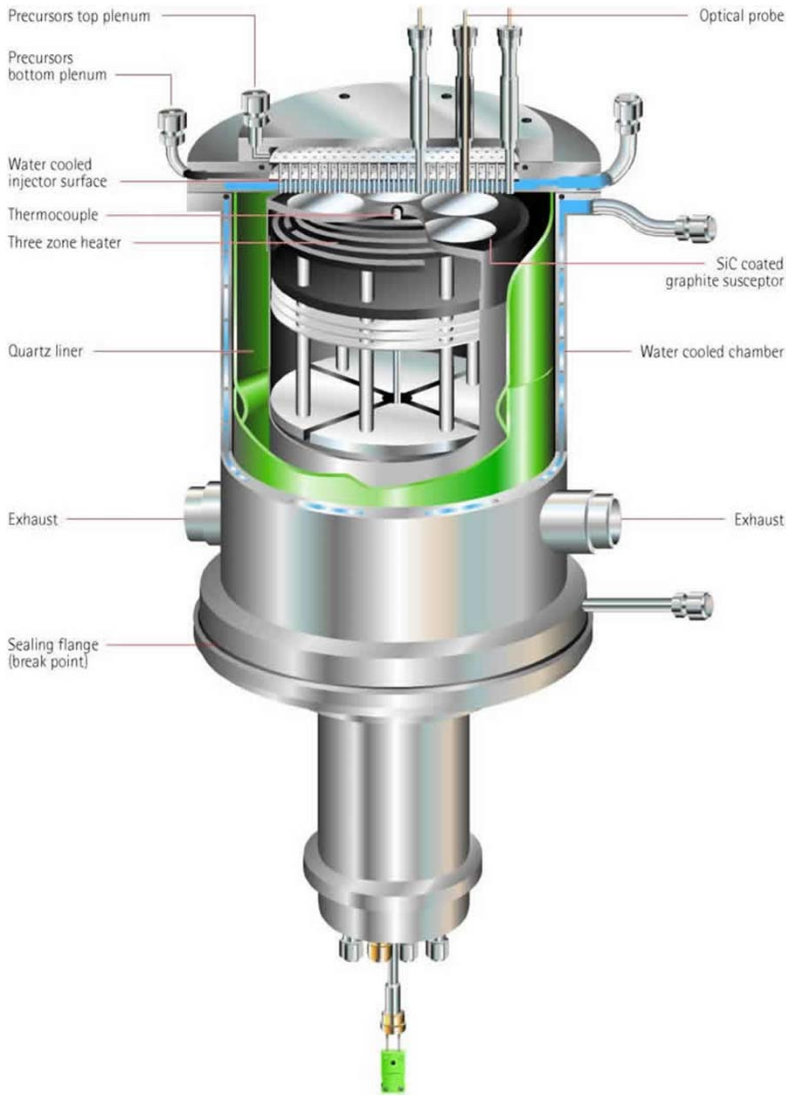
- Easy to pattern

MO-CVD

- **Metallo-organic chemical vapor deposition (MOCVD) is a relatively low temperature (200 – 800°C) process for epitaxial growth of metals on semiconductor substrates.**
- **Metallo-organics are compounds where each atom of the element is bound to one or many carbon atoms of hydrocarbon groups. For precise control of the deposition, high purity materials and most accurate controls are necessary.**
- **Due to the high cost, this approach is used only where high quality metal films are required.**
- **Also called organo-metallic vapour phase epitaxy**
  - Thickness control of ~1 atomic layer.
- **Used for**
  - compound SC devices, opto electronic devices solar cells.

MO-CVD System

- **The reagents are injected into the reactor chamber through separate orifices in a water-cooled showerhead injector, to create a very uniform distribution of reagent gases.**
- **A homogeneous gas phase is achieved at a distance of 5 mm below the showerhead**
- **The very fine mesh of injection tubes (~100 / square inch) ensure ideal growth conditions and growth thickness uniformity right across the susceptor.**
  - Uniformity of layer thickness
  - Uniformity of alloy composition
  - Abruptness of Interface
  - Reproducibility of product
  - New processes can be quickly optimised
- **Substrates are placed on top of a rotating susceptor, which is resistively heated.**



http://www.thomasswan.co.uk/ccs_reactor.html

Deposition of Metals by CVD

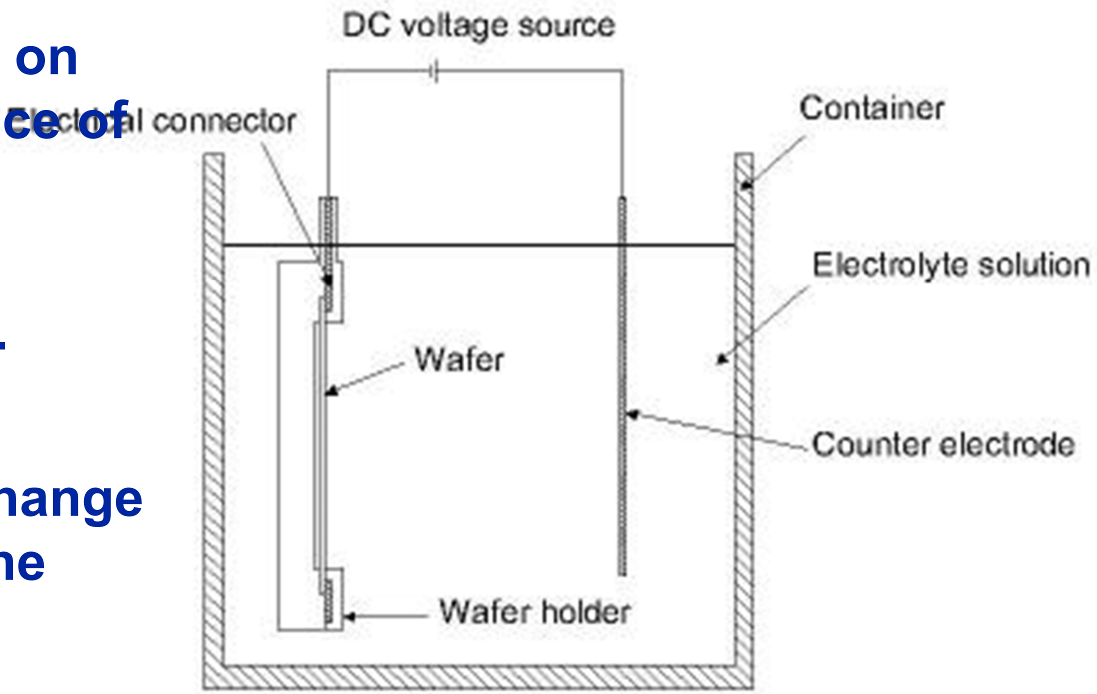
Metal	Reactants	Conditions
Al	Trimethyl aluminum Tryethyl aluminum Tri-isobutyl aluminum Demethyl aluminum hydride	200-300°C, 1 atm
Au	Dimethyl 1-2,4 pentadionate gold, Dimethyl-(1,1,1-trifluoro-2-4-pentadionate) gold, Dimethyl-(1,1,1-5,5,5 hexafluoro 2-4 pentadionate) gold	NA
Cd	Dimethyl cadmium	10 Torr,
Cr	Dicumene chromium	320-545°C
Cu	Copper acetylacetonate Copper hexafluoroacetylacetonate	260-340°C 200°C
Ni	Nickel alkyl Nickel chelate	200°C in H_2 250°C
Pt	Platinum hexafluoro-2,4-pentadionate Tetrakis-trifluorophosphine	200-300°C in H_2
Rh	Rhodium acetyl acetonate Rhodium trifluoro-acetyl acetonate	250°C,1 atm 400°C, 1 atm
Sn	Tetramethyl tin Triethyl tin	500-600°C
Ti	Tris-(2,2'bipyridene) titanium	<600°C

Molecular Beam Epitaxy

- **Enable deposition of single crystal films.**
- Also used for the deposition of some types of organic semiconductors. In this case, molecules, rather than atoms, are evaporated and deposited onto the wafer.
- **Key features**
  - Low Deposition Rate
  - Better vacuum
  - Higher substrate temperature
  - Directed atomic beams (Effusion cell)

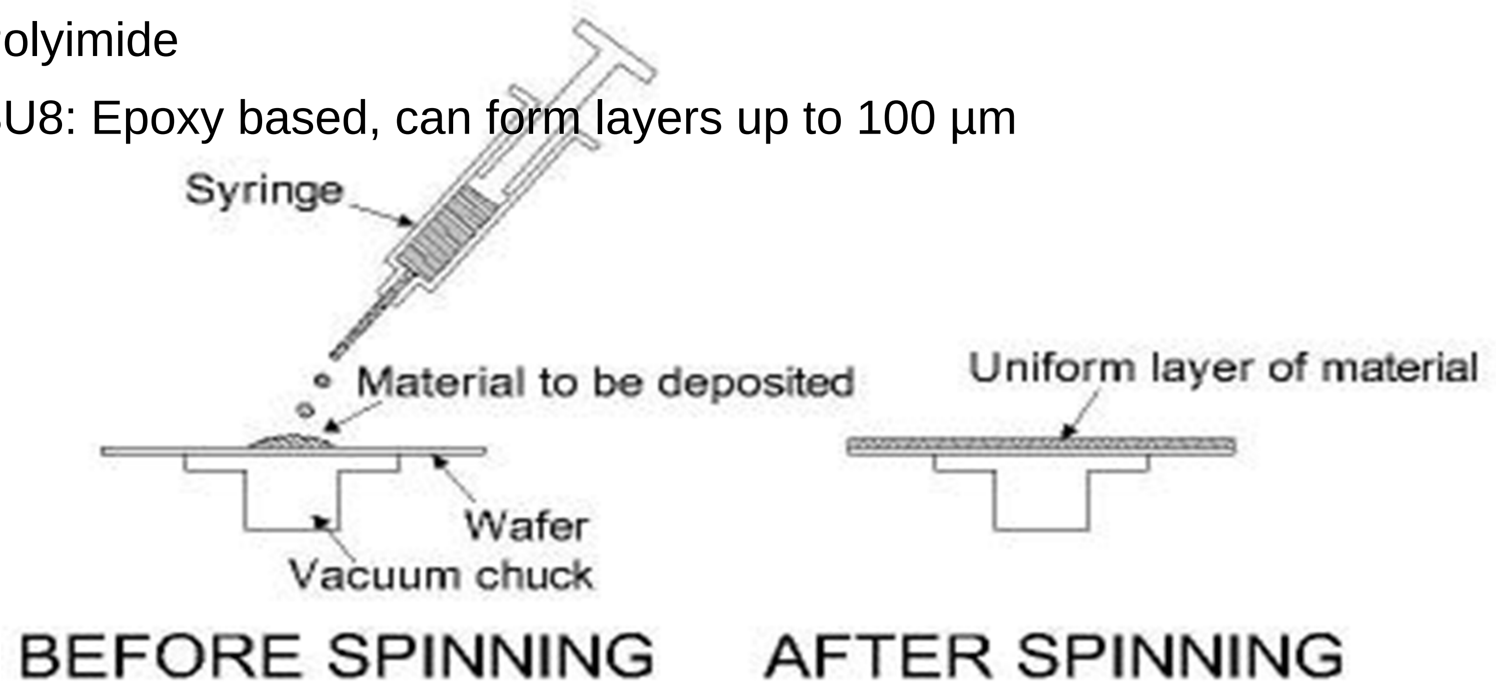
Typical electroplating system

- Chemical changes occur due to the flow of electric current through an electrolyte →Electrolysis.
- Deposition of any substance on an electrode as a consequence of electrolysis is called electro deposition.
- Governed by Faraday's laws.
- Magnitude of the chemical change occuring is proportional to the electricity passed.
- Masses of different species deposited at or dissolved form the electrodes by the same quantity of electricity are proportional to their chemical equivalent weights.



Spin casting

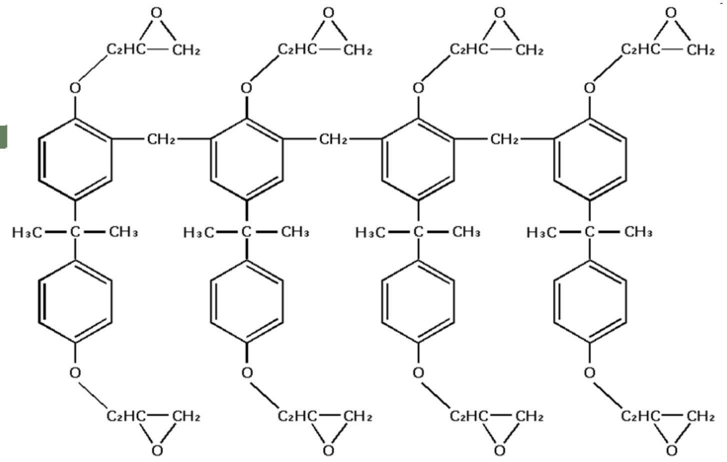
- **Casting is a simple technology which can be used for a variety of materials (mostly polymers).**
- **The control on film thickness depends on exact conditions, but can be sustained within +/-10% in a wide range. While using photolithography, casting is invariably used.**
- **Varying thickness; few nm – hundreds of microns**
- **Used for Photoresists,**
  - Photoresist
  - Polyimide
  - SU8: Epoxy based, can form layers up to 100 µm



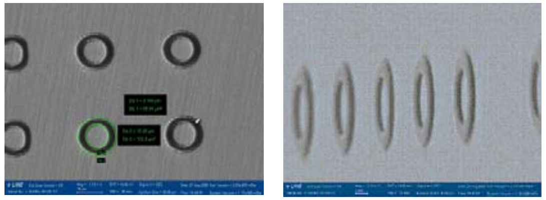
Polymeric Materials

- **Photoresists**
- **Polyimide**
- **PMMA**

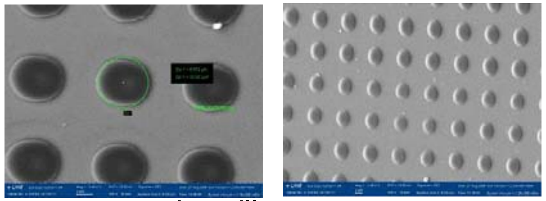
- **SU-8**
  - for wide range of thickness
  - Thick resist
  - Structural material in microsystem



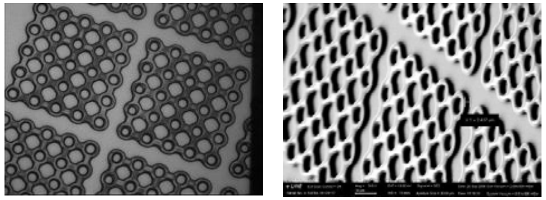
Wide range of applications
Microelectronics - coils, capacitors etc.
Micromechanics - sensors, prototyping etc.
Microfluidics- biochips, micropumps etc.
Packaging - microconnectors, Chip Scale packaging, etc.
Magnetics, Others like Flat panel displays, microoptics etc.



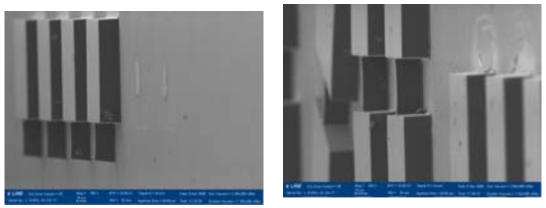
An array of Cylinders



Micropillar Arrays



Mutually Anchored Structures

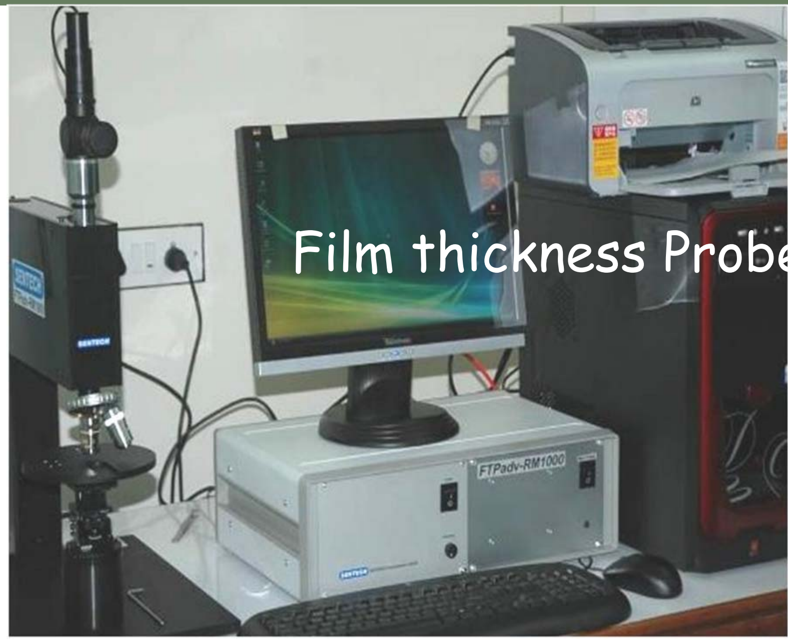


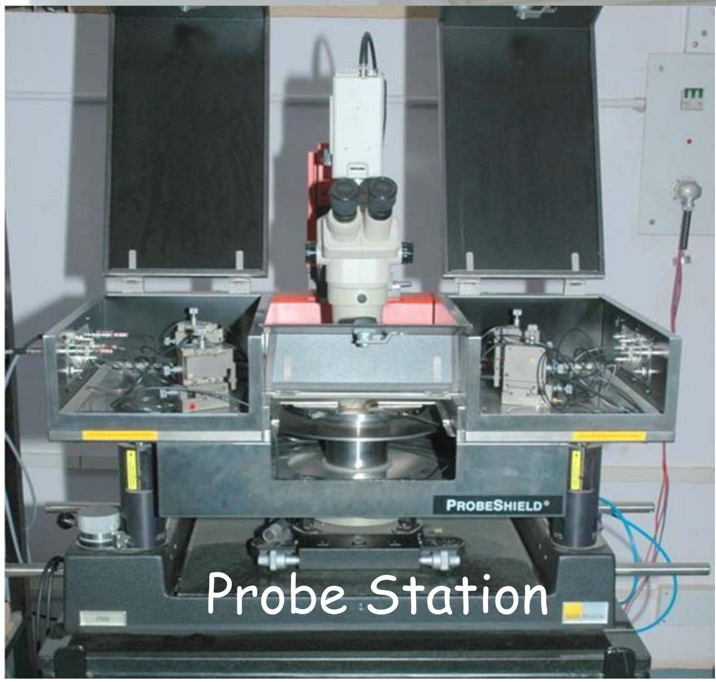
CANTILEVERS AND BEAMS

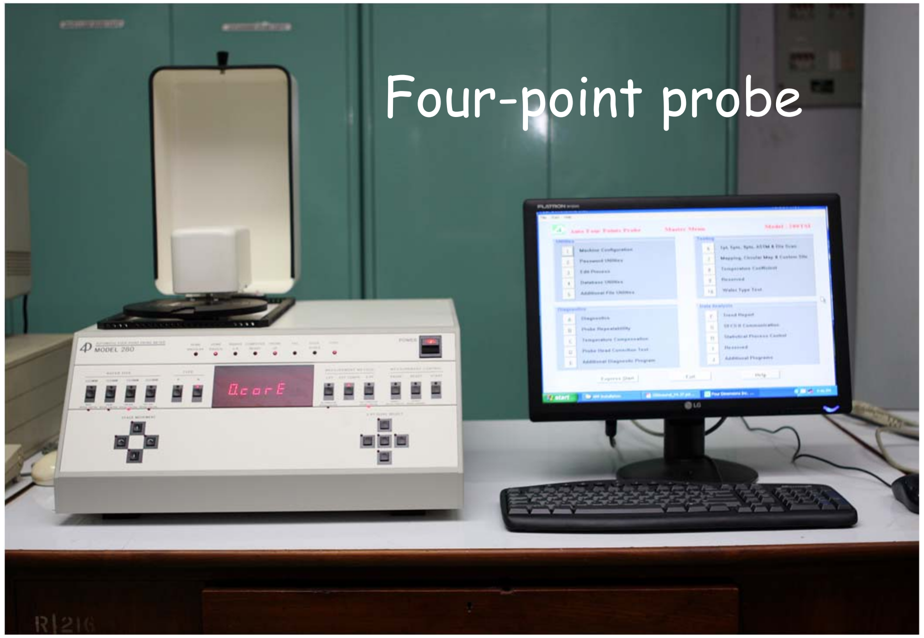
Parameters in Film Quality

- **Film composition**
- **Grain size**
- **Thickness**
- **Uniformity**
- **Step- coverage**
- **Adhesion**
- **Corrosion resistance**

Film surface Characterization at CEN/IISc







Thin films used in MEMS

- **Thermal silicon dioxide**
- **Dielectric layers**
  - polymeric
  - ceramic
  - silicon-compound
- **Polycrystalline silicon**
  - poly-Si
- **Metal films**
  - predominantly aluminum
- **Active Materials**
  - Ferroelectrics
  - Piezoelectrics

Role of Thin films

Structural
Sacrificial
Dielectric
Semiconductor (epi-layers)
Conductor

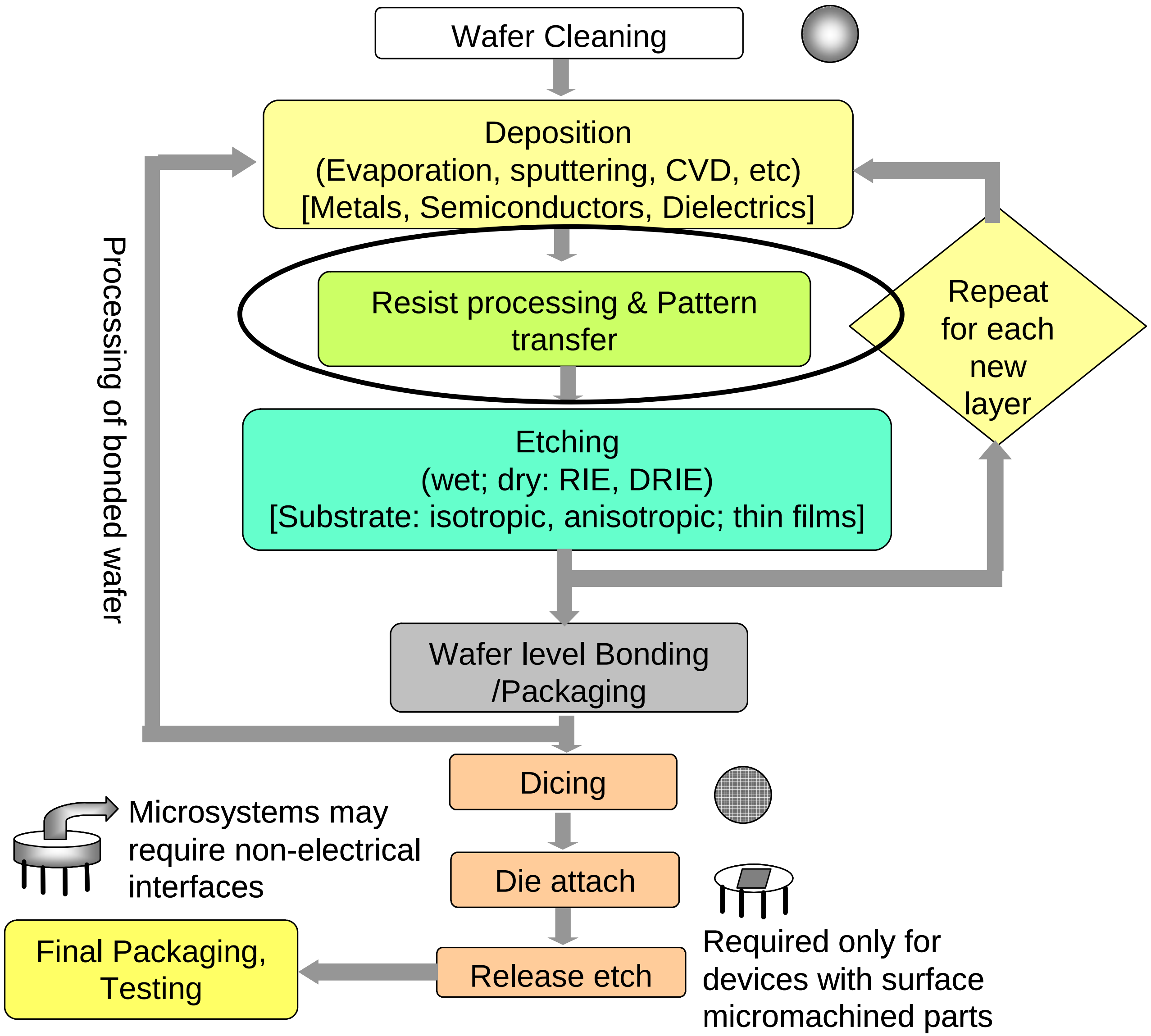
- **Usually thin film materials may have multiple functions**

Selection of Materials for Microsystems

- **Mechanical properties**
  - Elasticity (Young's Modulus)
- **Chemical and electrochemical properties**
- **Bio-compatibility issues**
- **Electrical characteristics**
  - Conductivity
  - Mobility
- **Thermal properties**
  - Heat conductivity,
  - Expansion coeff.
- **Processing issues**
  - feasibility
- **Optical properties**
  - Roughness, crystalline

Approaches for Pattern Transfer

Fabrication of Microsystems



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(epi-layers)
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Objectives of Pattern transfer

- **Selectively remove thin films**
  - Electrodes
  - Dielectrics
  - Microstructures

Pattern transfer followed by etching of thin film

- **Create doped regions**

Diffusion/ Ion implantation
Performed after defining a masking film

Commonly used Metals

- **Aluminum**
  - Basic electrical interconnections (common and easy to deposit)
  - Non-corrosive environment only
  - Good light reflector (visible light)
- **Gold/ titanium/tungsten**
  - Better for higher temperature
  - Harsher environments
  - Gold is good light reflector in the IR
- **Platinum and palladium**
  - Stable for electrochemistry

Various forms of SiO_2

- **SiO_2 – Silica**
  - Fused silica is a purer version of Fused quartz
  - Made from various Silicon gasses.
  - 17 crystalline phases
- **Quartz**
  - single crystal material, low impurity concentration
  - Fused quartz is the amorphous form of quartz.
  - Fused quartz is made from natural crystalline quartz, usually quartz sand that has been mined.
- **Glass**
  - Amorphous solid
  - Usually has impurities,
  - Low melting temperature
- **Borosilicate glass**
  - An "Engineered" glass developed specifically for laboratories and heating applications
  - Some common names are Pyrex™ by Corning, and Duran™ by Schott Glass.
  - Dominant component is SiO2
  - Boron and various other elements added

Silicon-based Films

- **Si_3N_4**
  - Can be LPCVD deposited by an intermediate-temperature process or a low-temperature PECVD process
  - Key Properties
    - low density
    - high temperature strength
    - superior thermal shock resistance
    - excellent wear resistance
    - good fracture toughness
    - mechanical fatigue and creep resistance
    - good oxidation resistance
  - Key Applications
    - Etch mask
    - Gate insulator
    - Thermal insulator
    - Chemical resistant coating etc.
- **Polysilicon**
  - A low-pressure reactor, operated at a temperature of between 600ºC and 650°C, is used to deposit polysilicon by pyrolizing silane

Polymeric Materials

- **Photoresists**
- **Polyimide**
- **PMMA**

- **SU-8**
  - for wide range of thickness
  - Thick resist
  - Structural material in microsystem

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Magnetics, Others like Flat panel displays, microoptics etc.

Patterning Thin films

- **Lithography**
  - Photolithography
    - Litho - stone + graphein – to write

Most common in Microsystems

- **Liftoff**

- **Advanced**
  - x-ray,
  - electron beam

Difficult

Nano-scale

Lithography

- Process steps are similar to that used in PCB fabrication
- Copper-clad PCB
- Coated with Resist
- Exposed with a mask film
- Developed
- Etching of Copper

Mask

- **A stencil used to repeatedly generate a desired pattern and resist coated wafers**

- **Consists of optically flat glass / quartz plate coated with an absorber (opaque to UV) pattern of metal. (eg, 800 Å thick Chromium layer)**

- **Usually the mask is kept in direct contact with the photoresist while exposing to UV.**
  - This results in 1:1 image on the wafer (contact lithography).

- **Pattern on the mask**
  - Use CAD (L-edit) for drawing
  - Use LASER plotter (resolution)

Laser Writer

- **Wave length of the laser is 405nm (GaN solid state laser)**
- **Minimum feature size achievable : 1-2 μm**
- **Various formats for drawings**
  - GDS, DXF & CIF formats can be used
- **High resolution multi layer patterning capability using alignment marks**
- **Variable pixel to pixel exposure available – Gray level patterning**

- **can be used for direct pattern generation on any substrate (including curved substrates) using photolithographic principles without using a conventional mask plate**
- **Can also be used for patterning several materials including SU-8**

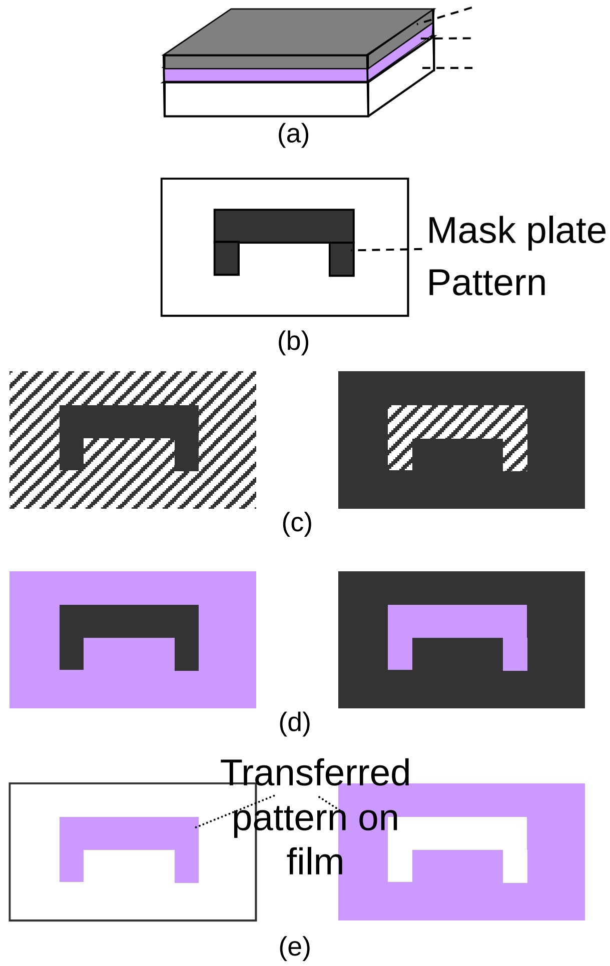
Laser Writer at CEN

Resists used in Lithography

- **Resist**
  - Polymer base resin
  - Changes structure when exposed
- **Resist consists of**
  - Sensitizer
    - controls photochemical reaction
  - Solvent
    - enables spin casting
- **Types (tones) of resists**
  - Positive tone
    - Photochemical reaction weakens polymer
    - *e.g.*, PMMA (poly methyl metacrylate)
  - Negative tone
    - Exposed resists hardens by crosslinkage of polymer main chains

Patterning with positive and negative resists

- **(a) Start wafer with oxide thin film and resist coated on it;**
- **(b) Mask plate with the image.**
- **(c) After exposure,**
- **(d) after developing and**
- **(e) after removal (stripping) of resist. tt**



Comparison of Negative and Positive Resists

Parameter	**Positive Photoresist**	**Negative Photoresist**
Commercial Examples	AZ 1350J, PR120	Kodak 747, SU8
Adhesion to Silicon surface	fair	excellent
Cost	**expensive**	relatively cheap
Developer process tolerance	small	wide
Suitable for lift off process	yes	yes
Minimum feature size with UV	< 0.5 μm	<2 μm
Opaque dirt on clear portion of mask	Not very sensitive	**pinholes**
Resistance to plasma etch	very good	Not so good
Step coverage	better	Not so good

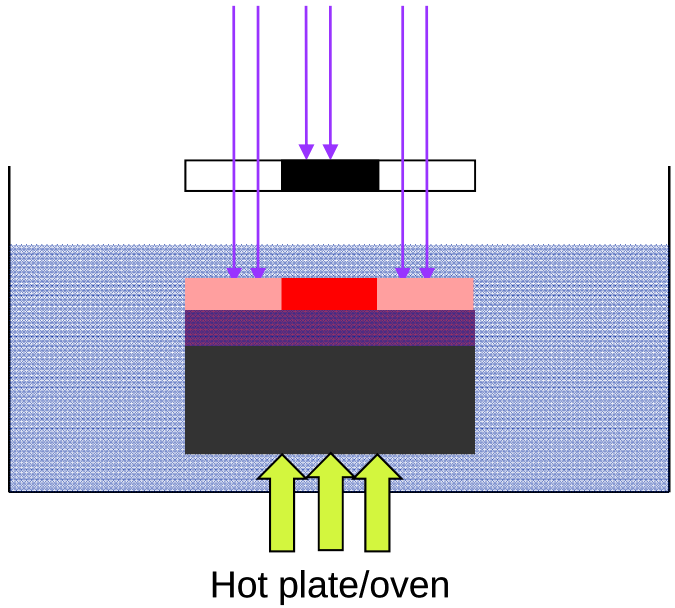
Positive and Negative Resist materials

- **Positive photoresists**
  - poly methyl methacrylate (PMMA).
  - diazpquinone ester + phenolic novolak resin
  - sensitive to UV light in the range 300 to 400nm
  - can be developed in alkaline solvents such as potassium hydroxide, ketones or acetates.
- **Negative photoresists**
  - typically two component bisazide rubber resist or azide sensitized poly isotroprene rubber.
  - less sensitive to optical and x-ray exposure but are more sensitive to electron beam.
  - Xylene is a common developer for negative resists

RESIST	TONE
Kodak 747	Negative
SU 8	Negative
AZ 1350J	Positive
PR 102	Positive

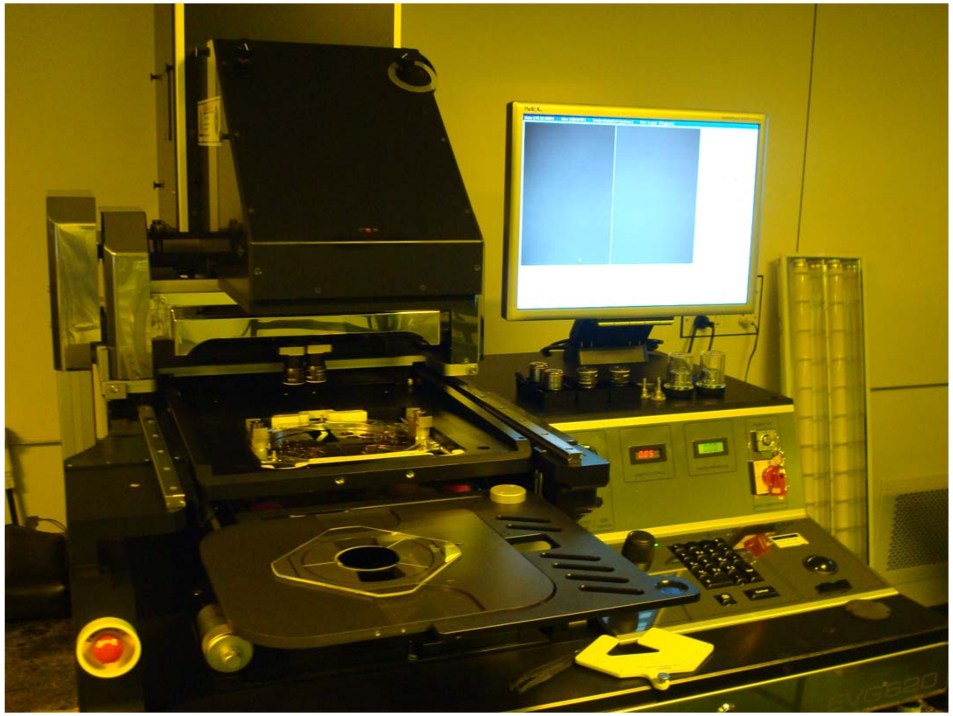
Patterning: Photo Lithography

- **Objective: To pattern SiO_2 layer**
- **Oxide by wet oxidation**
- **Resist coating**
  - Spin coating
- **Soft baking**
  - resist contains up to 15% organic solvent.
  - removed by soft baking at 75-100ºC for ~ 10 minutes
  - Release stress, Improve adhesion of the resist
- **UV exposure**
  - Wafer mask alignment
  - UV lamp used to illuminate the resist should have;
    - Proper intensity
    - Directionality
    - Spectral characteristics
    - Uniformity across the wafer
- **Development**
  - transforms latent resist images joined during exposure into a relief image
- **Post baking**
  - To remove residual solvents
  - Annealing of film to improve adhesion
  - Improves hardness of the film
  - done at 120°C for approximately 20 minutes
- **Etching of SiO_2**
- **Resist striping**



Can be used for patterning metal and dielectric thin films

Mask Aligner (Double sided) at CEN/IISc



Exposure modes Constant Dose, Constant Time, Periodic
Alignment X, Y: +/- 5mm, Theta +/- 3.5°, 0.06μm alignment resolution
Contact modes Soft contact, Hard contact, Vacuum contact, Vacuum+Hard contact, Proximity
Microscopes (Top and bottom) Split field with two objectives (3.6x, 5x, 10x, 20x,)
UV Lamp Standard NUV for 350 – 450nm, 350W to 500W-Power
Printing Resolution Depends on contact modes, contact pressure and process parameters. Best achievable is 1 micron

Etching of thin films

- **Silicon Nitride etching**
  - 1%HF → 60nm/min
  - 10%HF → 500nm/min
  - H_3PO_4 → 10nm/min (180C)

- **Silicon Dioxide Etching**
  - Buffered HF → 100-250nm/min
  - HF (very fast)

- **Etch rates do ary depds on how the film was deposited (film quality)**

- **Copper or Nickel**
  - $FeCl_3$

- **Gold**
  - Aqua regia or Iodine

Chromium

Aquaregia or HCl:Glycerine

Theoretical limits of Lithography

- **Smallest feature size by projection lithography is the same as the λ of the UV source**

- **Factors affecting resolution**
  - Diffraction of light at the edge of an opaque feature in the mask
  - Non uniformity in the wafer flatness
  - Debris between mask and wafer

- **For λ = 400nm Z=1µm resolution is approximately 1µm**

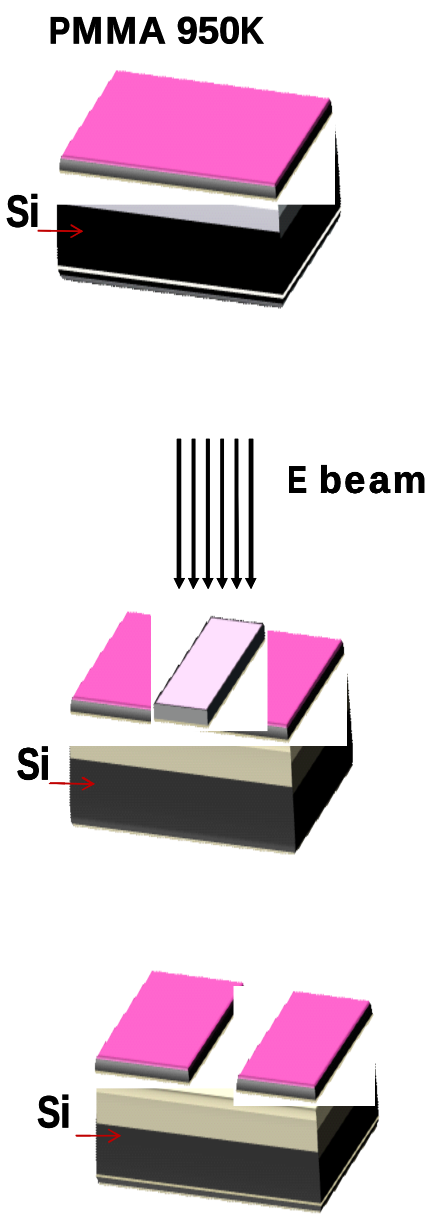
- **Extreme ultraviolet lithography**
  - Requirements
    - Reflective optics for camera.
    - New resists.
    - Imaging should be done in vacuum

New generation lithography techniques

- **X-ray lithography**
  - No need for vacuum.
  - Flood exposure is possible
  - Resolution~0.5μm, registration ~0.2μm
- **Electron beam lithography**
  - An electron source that produces a small diameter spot
  - A blanker for turning the beam on and off
  - Two electrostatic plates for directing the electron beam to the substrate
- **Ion beam lithography**
  - Resist is exposed to energetic ion bombardment in vacuum
  - Point-by-point exposures with a scanning source (liquid gallium) or flood exposure with H^+, He^{2+} or Ar^+.

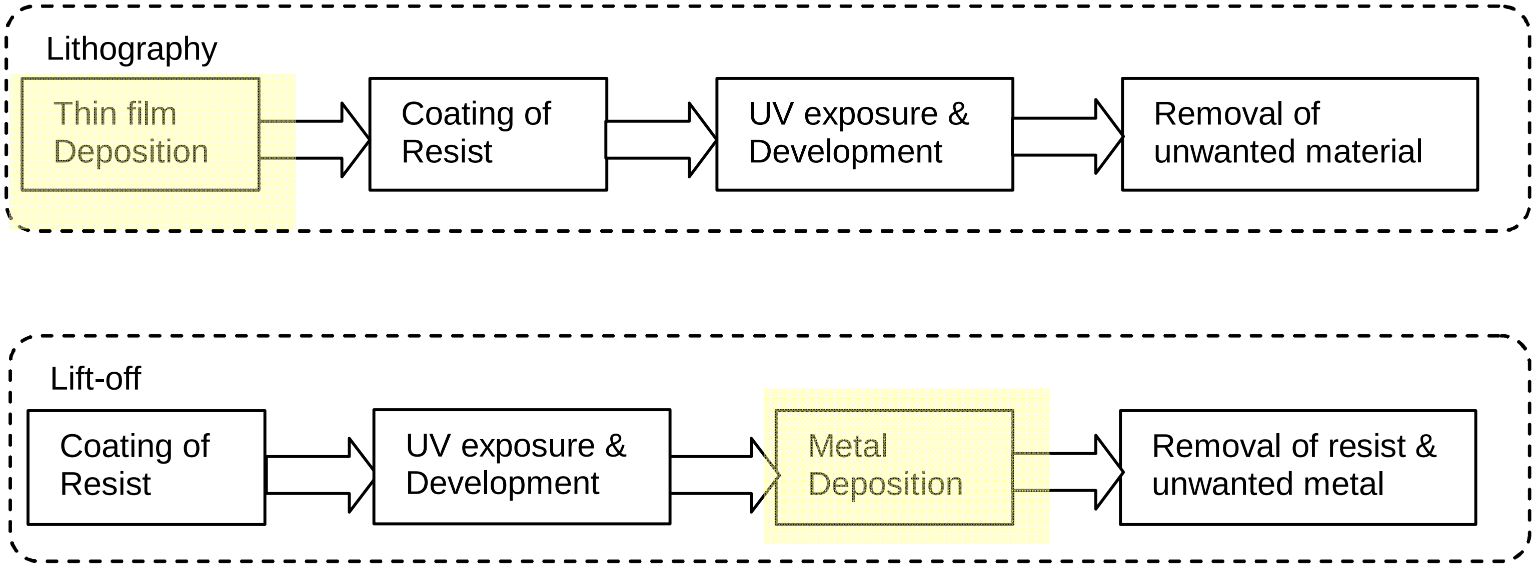
E-beam Lithography

- **Smaller electron wavelengths makes E beam lithography capable of very High resolution. The wavelength of the electrons in a 10 kV SEM is then 12.3 x 10^{-12} m (12.3 pm)**
  - Line of 13nm width achieved
  - Dots of 20 nm Diameter achieved
  - Direct Write
  - Nano manipulation
- **Applications**
  - Nano lithography with sub 20 nm resolution
  - Fabrication of photonic crystals, Gratings
  - Optical devices, holograms, micro lenses
  - Three-dimensional structures
  - CMOS process and device development
  - E-beam induced deposition and etching
  - Nano probing and electrical measurements
  - High resolution SEM inspection



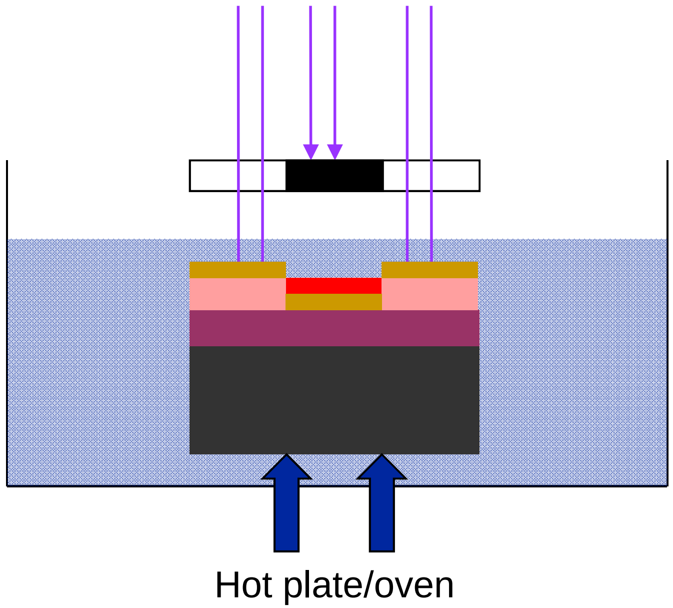
Lift-off for Pattern Transfer

- As compared to conventional lithography, in lift off process a photoresist pattern is generated initially on the substrate instead of etching the unwanted material.
- The basic criterion for the lift off technique is that the thickness of deposited film should be significantly less than that of the photoresist and the developed patterns have vertical side walls.
- Metal layers with high resolution can be patterned using lift off technique. Metals such as gold (which can be etched with aqua regia) can be patterned with simple processes by lift off.Ltt



Detailed Steps involved in Liftoff

- **Objective: To create a pattern of Gold on an oxidised Si wafer**
- **Oxide by dry/ wet oxidation**
- **Resist coating**
- **Soft baking**
- **UV exposure**
- **Development**
- **Gold deposition (sputtering)**
- **Liftoff**



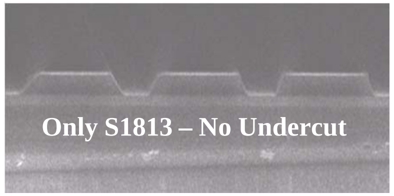
Can be used for patterning metal and dielectric thin films

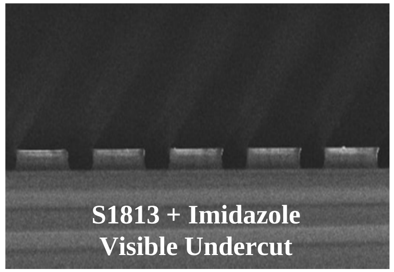
Lift-off

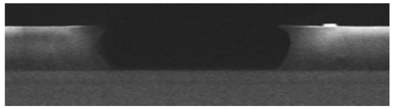
- **For realizing very small metal features not achievable with wet chemical etching**
- **For lift-off, the photoresist should have an undercut profile after development**
- **Conventional Image Reversal Process**
  - Positive photoresist is made to simulate a negative resist
  - This is done either by mixing the resist with a compound such as Imidazole or by using an ammonia bake step after exposure
  - Has been reported for optical lithography
- **Direct Write Laser (DWL) Lithography**
  - A mask less lithography technique where a laser source is used for patterning the photoresist
  - Resist thinning during development
  - Long exposure times

Lift-off by surface Modification

- **Difference**
  - For every 2ml of positive photoresist, 27mg of Imidazole is added
  - Imidazole acts as a catalyst in the decarboxylation reaction of the exposed photoresist regions
- **During post exposure bake, the rate of decarboxylation speeds up, thereby forming Indene, a salt, which is insoluble in photoresist developers.**
  - This salt formation is limited only to the top surface of the resist because of the short duration of UV flood exposure.
  - The remaining bulk resist is still photoactive and behaves like a positive photoresist.
- **The formation of the salt creates a difference in the solubility of the top surface and bulk of the resist in the developer, leading to an undercut profile upon development.**



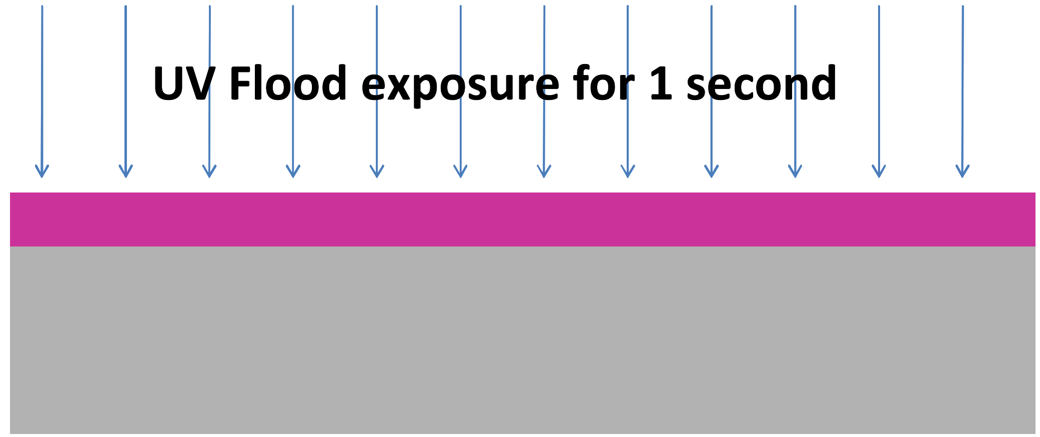




Process Steps

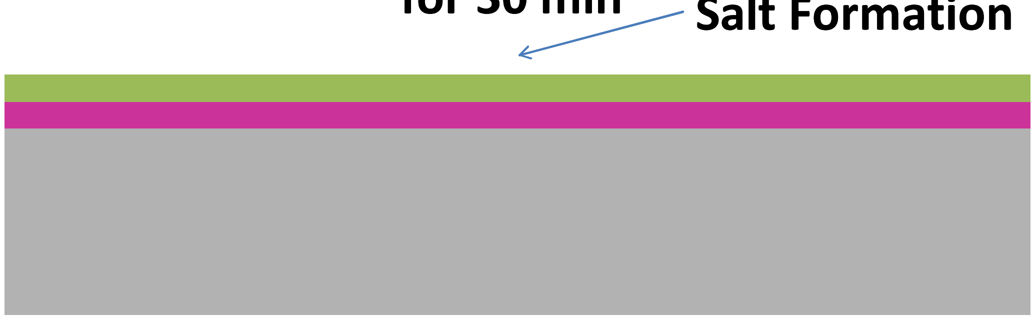
**Spin coat S1813 + Imidazole mixture
and soft bake in an oven at 100°C for 20 min**

UV Flood exposure for 1 second

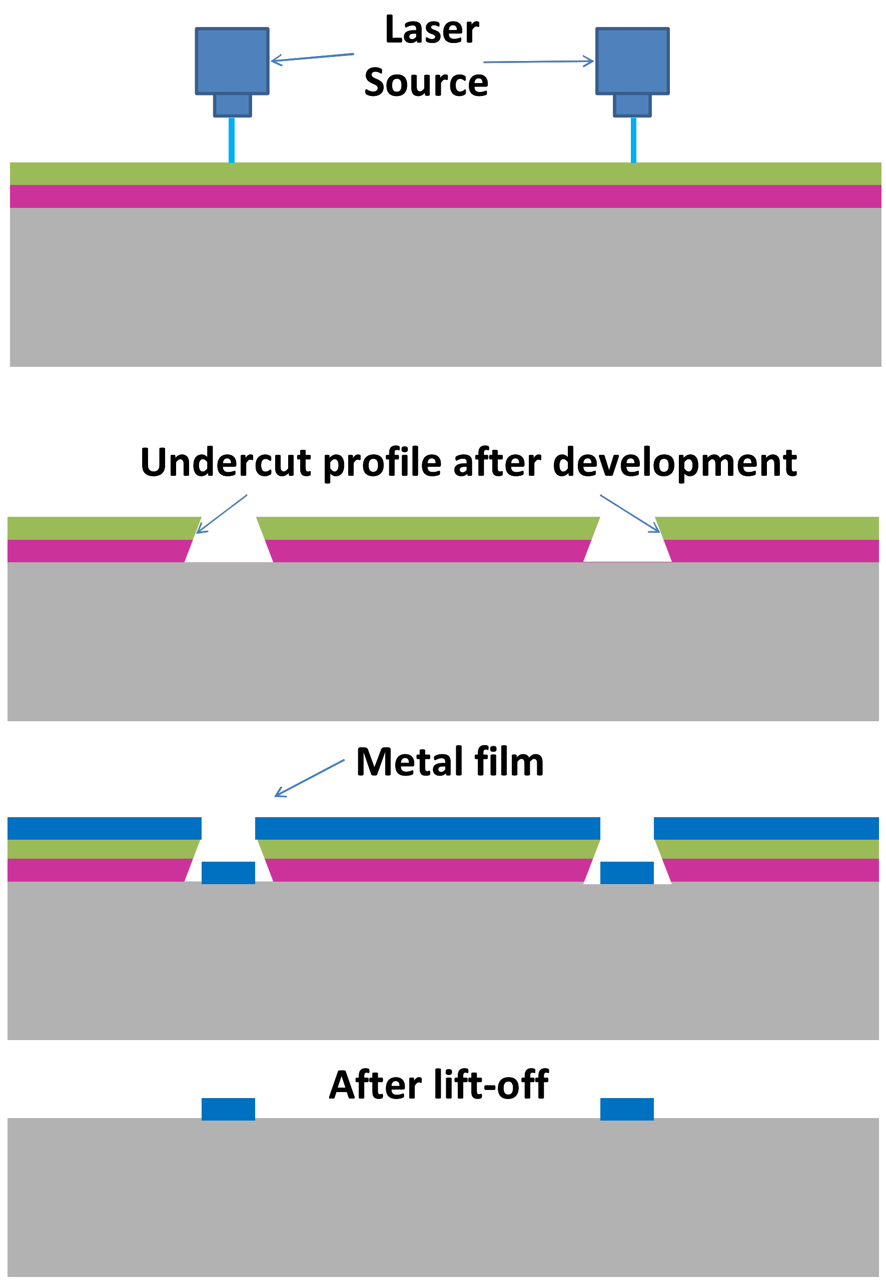


**Post exposure Bake in an oven at 100°C
for 30 min**

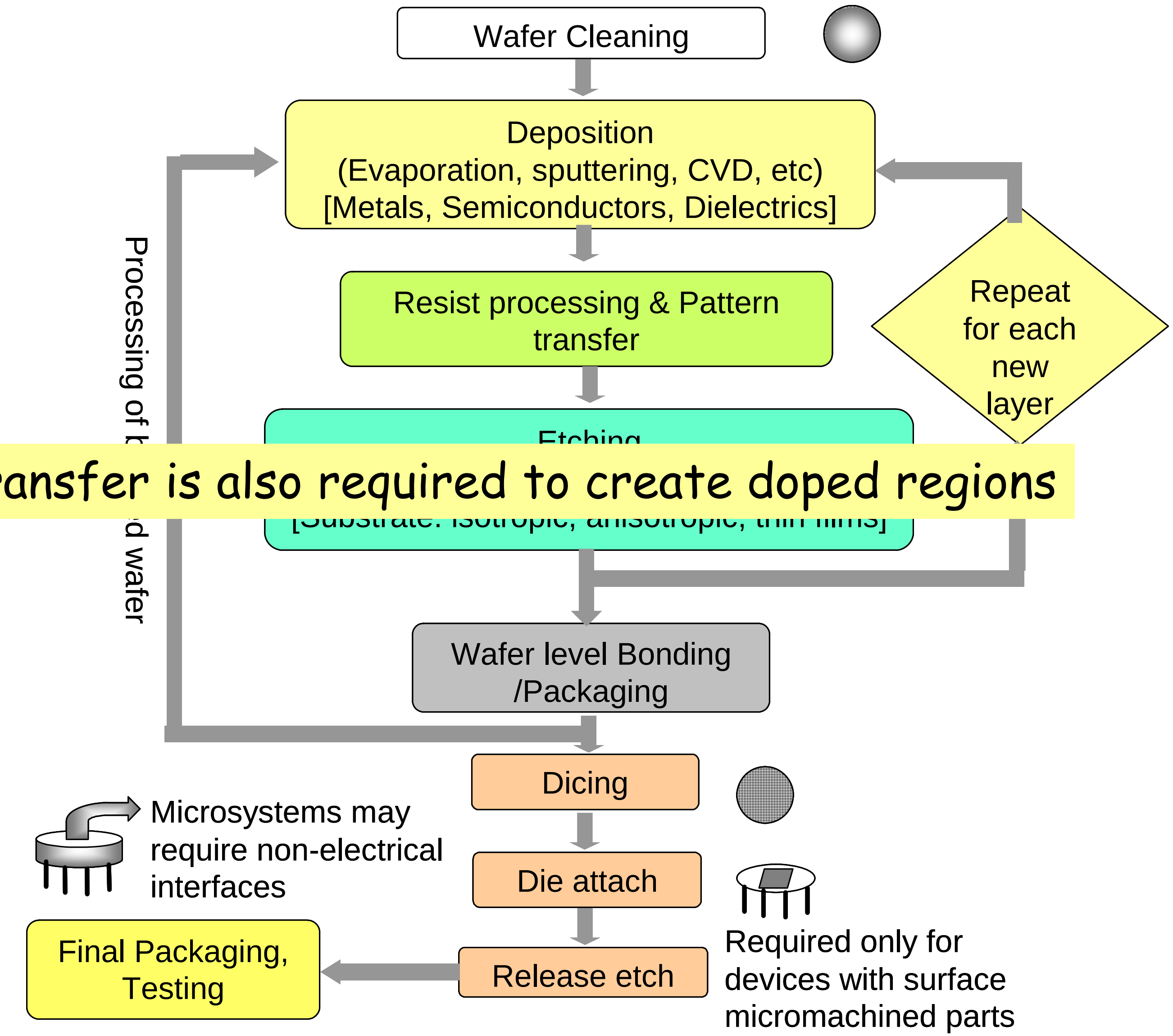
Salt Formation



Process Steps (Contd)



Fabrication of Microsystems



Pattern transfer is also required to create doped regions

Diffusion and Ion Implantation

- **For doping of semiconductors, controlled quantities of impurity atoms are introduced into the selected regions of the surface through masks on the top of the wafer.**
- **Diffusion and Ion implantation are common methods for this.**
- **N and P regions can be formed for active semiconductos**
- **Also used as etch stop layers**
- **Diffusion**
  - Wafer placed in a high temp furnace and a carrier gas is passed. Boron and phosphorous are commonly used dopants
  - The deposited wafer is heated in a furnace for drive in; oxidising or inert gas to redistribute dopants in the wafer to desired depth
  - Silicon dioxide is used as the masking layer

Phosphorus Diffusion

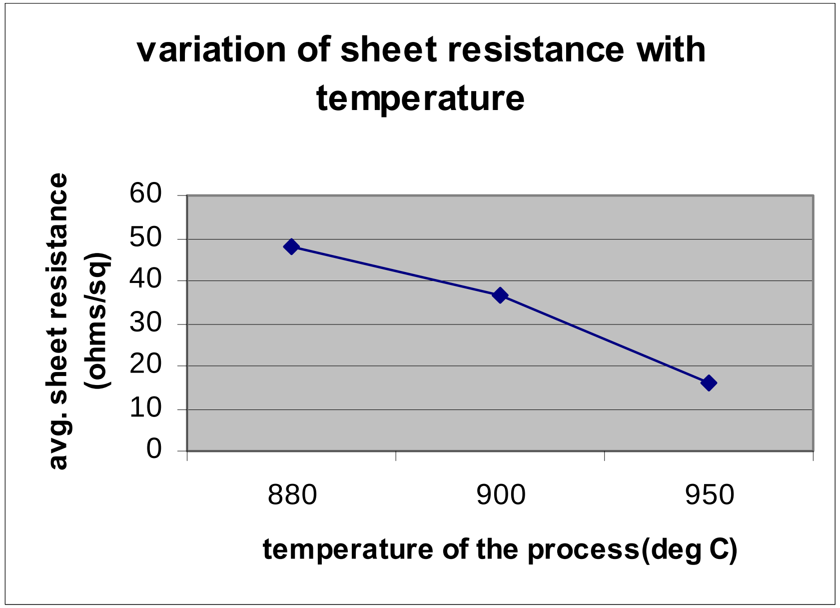
Make	Tempress
Temperature Range	800- 1200 ˚C
Dopant Source	$POCl_3$
Bubbler Gas	Nitrogen (0.4ltr/min)
Carrier Gas	Nitrogen (4 ltr/min)
Flow rate of Oxygen	0.6 l/min

Boron Diffusion

Make	Tempress
Temperature Range	900-1200˚C
Dopant Source	Boron Nitride Disc
Process Ambient	Nitrogen
Flow rate of N_2	4 ltr/min

Diffusion at CEN/IISc

Phosphorous



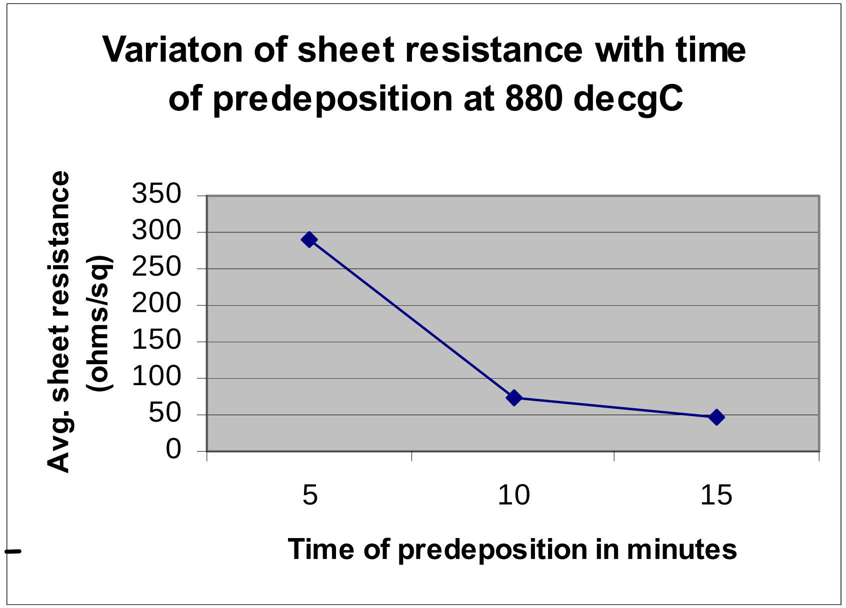
Boron Diffusion

Step.1: Pre-deposition for 1hr

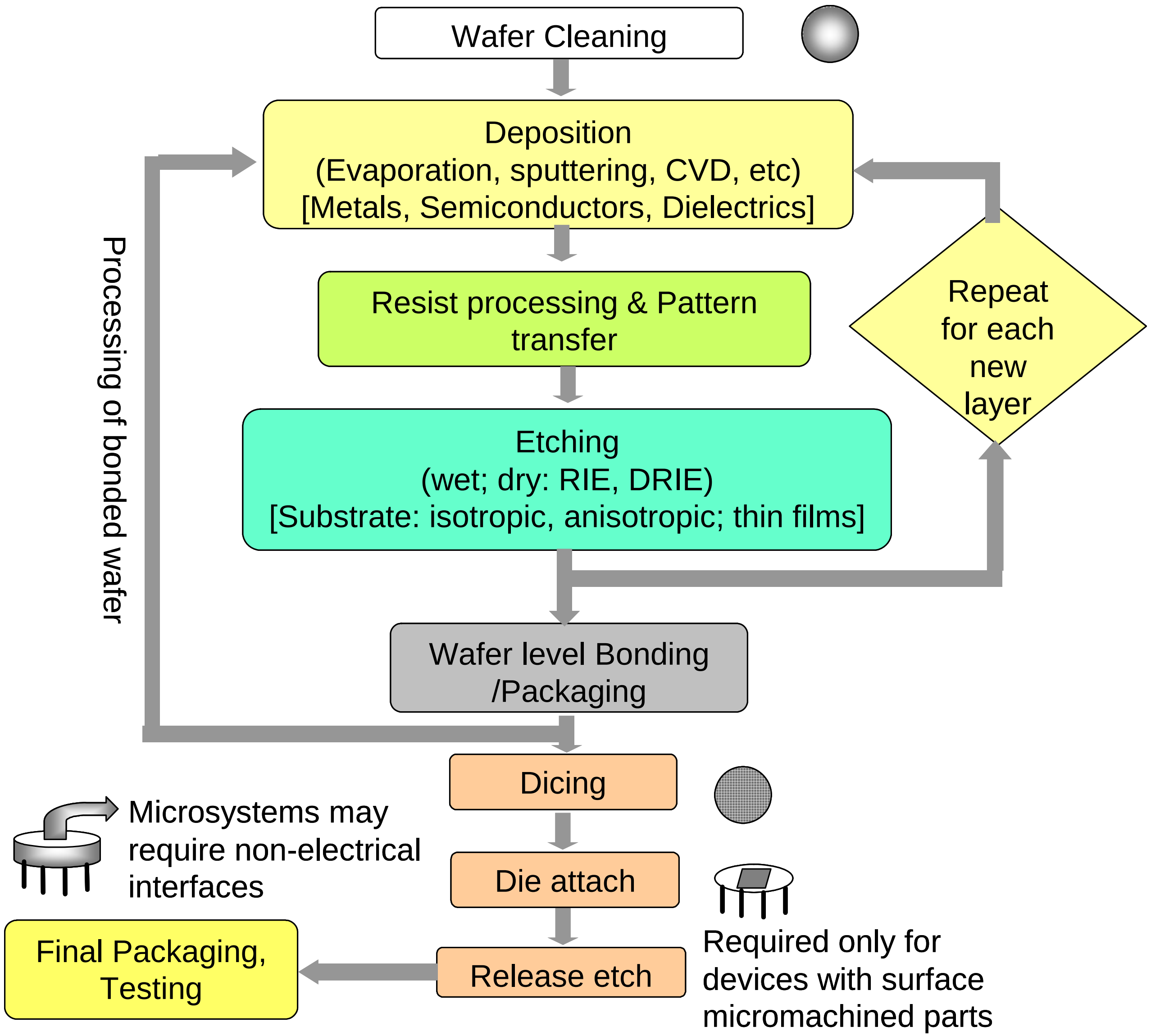
Temp. 1050° - 1070°C
Source: BN disc
Gas: N_2 (Flow rate = 3L /min)

Step.2: Drive-In for 2 hrs

Temp. 1150°C
Gas : N2 (Flow rate = 0.5-1L /min)



Fabrication of Microsystems



Emerging Lithographic Techniques

- **Embossing lithography (nano imprinting)**
  - Molds made by e-beam lithography
  - Re-used several times
  - Lower resolution
  - Much higher throughput
- **Stamp lithography (soft lithography)**
- **Probe lithography**
  - Oxidation by ‘arcing’ through a scanning probe (AFM probe)
  - Slow speed
  - Features < 100nm possible
- **Self-assembly lithography**
  - Molecular level
  - Stereo lithography for 3D (?)

Building 3D Structures on Silicon

- **Lithography and other IC techniques are PLANAR**
  - These are used to pattern the topmost layer on a substrate
    - The focus of the beam is best over several wavelengths (~ nm)
  - These fail for deep structures because
    - The accuracy and energy of the beam deteriorates
- **How can thick structures be built?**
  - Built it a layer at a time
    - Deposit – pattern – deposit - pattern - etc…
  - But thin film properties can not be relied up on after a certain number of layers
    - Limits the height of the structure
  - Alternately, sometimes we can use the substrate itself as building blocks
    - The 3D structure would consist of several layers of the substrate(s)
    - Substrates are bonded together and diced
  - Non-silicon approaches

Silicon Micromachining

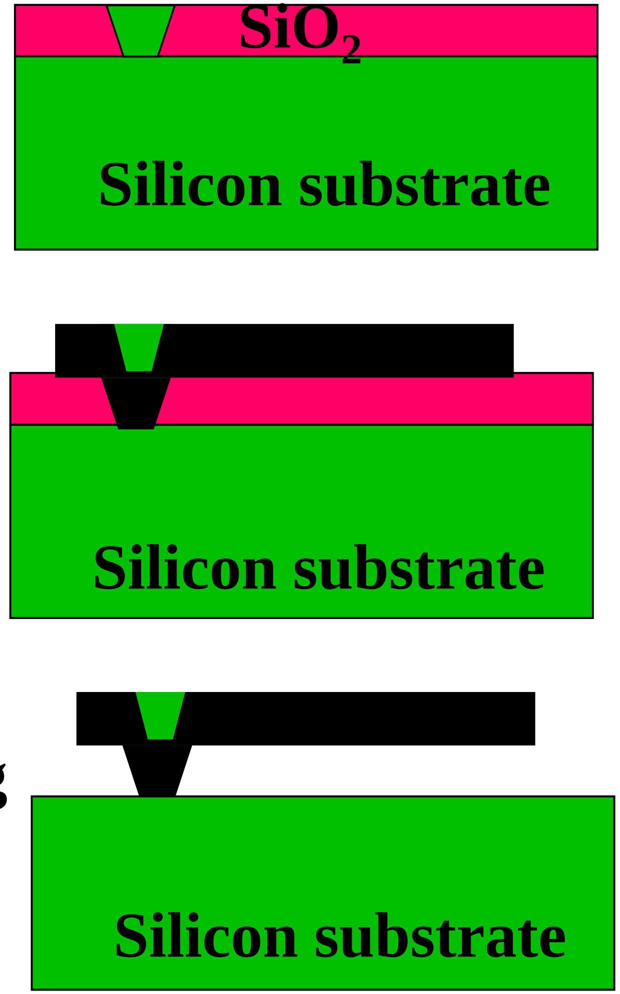
Based on Photolithography

- Photolithography defines regions on silicon wafers where machining is done.
- Machining includes etching, doping and deposition of thin films.
- Fabrication of three- dimensional structures with complexes forms only in two dimensions is possible.
- Extension to 3D structures can be accomplished to using wafer bonding.

Surface Micromachining

- Microstructures are fabricated on a Silicon substrate by deposition and selective etching of multiple layers of structural and sacrificial films

Steps to realize a Poly anchored Cantilever



Patterned Polysilicon

Free standing Cantilever

Polysilicon is structural layer and SiO_2 is the sacrificial layer

UNIT-III

Micro Sensors: MEMS Microsensors, Thermal Microsensors, Mechanical Micromachined Microsensors, MEMS Pressure Sensor, MEMS Flow Sensor, Micromachined Flow Sensors, MEMS Inertial Sensors, MEMS Gyro Sensor

Microsensors

Device that converts a non-electrical physical or chemical quantity into an electrical signal.

A sensor may be simply defined as a device that converts a nonelectrical input quantity into an electrical output signal; conversely, an actuator may be defined as a device that converts an electrical signal into a nonelectrical quantity *E* (see Figure 8.1). A transducer is a device that can be either a sensor or an actuator. Some devices can be operated both as a sensor and an actuator. For example, a pair of interdigitated electrodes lying on the surface of a piezoelectric material can be used to sense surface acoustic waves (SAWs) or to generate them. This device is referred to as an *interdigitated transducer* (IDT). The importance of this device is such to describing its applications as a microsensor microelectromechanical system (MEMS) devices.

A sensor or actuator can be classified according to the energy domain of its primary input-output (I/O). There are six primary energy domains and the associated symbols are as follows:

- Electrical E
- Thermal T
- Radiation R
- Mechanical Me
- Magnetic M
- Bio(chemical) C

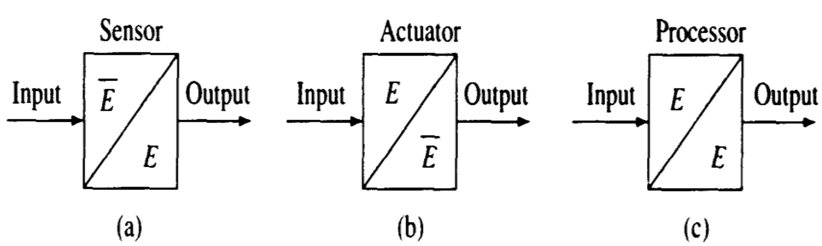


Figure 8.1 Basic input–output representation of (a) a sensor; (b) an actuator; and (c) a processor in terms of their energy domains

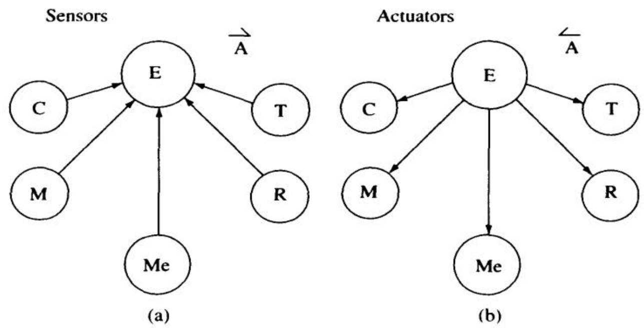


Figure 8.2 Vectorial representation of (a) a sensor and (b) an actuator in energy domain space. A processor would be represented by a vector that maps from *E* and back onto itself

Various kinds of microsensors which are fabricated using MEMS technologies and which are integrated with microstructures that are fabricated using either bulk micromachining or surface micromachining or LIGA or stereolithography.

Form of signal	Measurands
Thermal	Temperature, heat, heat flow, entropy, heat capacity etc.
Radiation	Gamma rays, X-rays, ultra-violet, visible and infrared light, micro-waves, radio waves etc.
Mechanical	Displacement, velocity, acceleration, force, pressure, mass flow, acoustic wavelength and amplitude etc.
Magnetic	Magnetic field, flux, magnetic moment, magnetisation, magnetic permeability etc.
Chemical	Humidity, pH level and ions, gas concentration, toxic and flammable materials, concentration of vapours and odours, pollutants etc.
Biological	Sugars, proteins, hormones, antigens etc.

Why microsensors

lower manufacturing cost (mass-production, less materials)
wider exploitation of IC technology (integration)
wider applicability to sensor arrays
lower weight (greater portability)

Applications

- Automotive industry
  average electronics content of a car is today 20%
  to increase safety (air bag control, ABS), reduce fuel consumption and pollution
- Medical applications
  measurement of physical/chemical parameters of blood (temperature, pressure, pH)
  integrated sensors in catheters
- Consumer electronics
- Environmental applications
  determination of concentration of substances (carbon monoxide, heavy metals, etc.)

- Food industry
  contaminants and impurities
- Process industry
- Robotics
  distance, acceleration, force, pressure, temperature

1. THERMAL SENSORS

Thermal sensors are sensors that measure a primary thermal quantity, such as temperature, heat flow, or thermal conductivity. Other sensors may be based on a thermal measurement; for example, a thermal anemometer measures air flow.

Almost every property of a material has significant temperature dependence. For example, in the case of a mechanical microstructure, its physical dimensions - Young's modulus, shear modulus, heat capacity, thermal conductivity, and so on - vary with operating temperature. The effect of temperature can be minimised by choosing materials with a low temperature coefficient of operation (TCO). However, when forced to use standard materials (e.g. silicon and silica), the structural design can often be modified (e.g. adding a reference device) to compensate for these undesirable effects.

Microdevices that possess an integrated temperature microsensor and microcontroller can automatically compensate for temperature and thus offer a superior performance to those without. This is why temperature sensors are a very important kind of sensors and are commonly found embedded in microsensors, microactuators, MEMS, and even in precision microelectronic components, such as analogue-to-digital converters.

Temperature Sensor Types

Temperature detection is the foundation for all advanced forms of temperature control and compensation. The temperature detection circuit itself monitors ambient temperature. It can then notify the system either of the actual temperature or, if the detection circuit is more intelligent, when a temperature control event occurs. When a specific high temperature threshold is exceeded, preventative action can be taken by the system to lower the temperature. An example of this is turning on a fan.

Similarly, a temperature detection circuit can serve as the core of a temperature compensation function. Consider a system such as liquid measuring equipment. Temperature, in this case, directly affects the volume measured. By taking temperature into account, the system can compensate for changing environment factors, enabling it to operate reliably and consistently.

There are four commonly used temperature sensor types:

1. Negative Temperature Coefficient (NTC) thermistor

A thermistor is a **thermally sensitive resistor** that exhibits a large, predictable, and precise change in resistance correlated to variations in temperature. **An NTC thermistor** provides a very high resistance at low temperatures. As temperature increases, the resistance drops quickly. Because an NTC thermistor experiences such a large change in resistance per °C, small changes in temperature are reflected very fast and with high accuracy (0.05 to 1.5 °C). Because of its exponential nature, the output of an NTC thermistor requires linearization. The effective operating range is -50 to 250 °C for **glass encapsulated thermistors** or 150°C for standard.

2. Resistance Temperature Detector (RTD)

An RTD, also known as a resistance thermometer, **measures temperature by correlating the resistance of the RTD element with temperature**. An RTD consists of a film or, for greater accuracy, a wire wrapped around a ceramic or glass core. The most accurate RTDs are made using platinum but lower-cost RTDs can be made from nickel or copper. However, nickle and copper are not as stable or repeatable. Platinum RTDs offer a fairly linear output that is highly accurate (0.1 to 1 °C) across -200 to 600 °C. While providing the greatest accuracy, RTDs also tend to be the most expensive of temperature sensors.

3. Thermocouple

This temperature sensor type consists of two wires of different metals connected at two points. The varying voltage between these two points reflects proportional changes in temperature. **Thermocouples** are nonlinear, requiring conversion when used for temperature control and compensation, typically accomplished using a lookup table. **Accuracy is low**, from 0.5 °C to 5 °C. However, they operate across the **widest temperature range**, from -200 °C to 1750 °C.

4. Semiconductor-based sensors

A semiconductor-based temperature sensor is placed on **integrated circuits** (ICs). These sensors are effectively two identical diodes with **temperature-sensitive voltage** vs current characteristics that can be used to monitor changes in temperature. They offer a linear response but have the lowest accuracy of the basic sensor types at 1 °C to 5 °C. They also have the slowest responsiveness (5 s to 60 s) across the narrowest temperature range (-70 °C to 150 °C).

Resistive Temperature Microsensors

Conventionally, the temperature of an object can be measured using a platinum resistor, a thermistor, or a thermocouple. Resistive thermal sensors exploit the basic material property that their bulk electrical resistivity *p*, and hence resistance *R*, varies with absolute temperature *T*. In the case of metal chemoresistors, the behaviour is usually well described by a second-order polynomial series, that is,

$$\rho(T) \approx \rho_0(1 + \alpha_T T + \beta_T T^2) \text{ and } R(T) \approx R_0(1 + \alpha_T T + \beta_T T^2)$$

where *po/Ro* are the resistivity or resistance at a standard temperature (e.g. 0 °C) and α_T and $ß_T$ are temperature coefficients. TCR is a sensitivity parameter and is commonly known as *the linear temperature coefficient of resistivity or resistance* (TCR) and is defined by

$$\alpha_T = \frac{1}{\rho_0}\frac{d\rho}{dT}$$

Platinum is the most commonly used metal in resistive temperature sensors because it is very stable when cycled over a very wide operating temperature range of approximately —260 to +1700°C, with a typical reproducibility of better than ±0.1°C. Platinum temperature sensors are very nearly linear, and α_T takes a value of +3.9 x 10^{-4}/K and $ß_T$ takes a value that is four orders of magnitude lower at —5.9 x $10^{-7}/K^2$. In contrast, thermistors, that is, resistors formed from semiconducting materials, such as sulfides, selenides, or oxides of Ni, Mn, or Cu, and Si have highly nonlinear temperature-dependence. Thermistors are generally described by the following equation:

$$\rho(T) \approx \rho_{ref} \exp[B(1/T - 1/T_{ref})]$$

where the reference temperature is generally 25 °C rather than 0°C and the material coefficient *ß* is related to the linear TCR by *—B/T2*. The high negative TCR means that the resistance of a pellet falls from a few megaohms to a few ohms over a short temperature range.

Microthermocouples

Unlike the metal and semiconducting resistors, a thermocouple is a potentiometric temperature sensor in that an open circuit voltage V_T appears when two different metals are joined together with the junction held at a temperature being sensed *T*s and the other ends held at a reference temperature T_{ref} (see Figure 8.5). The basic principle is known as the *Seebeck effect* in which the metals have a different thermoelectric power or Seebeck coefficient *P*; the thermocouple is conveniently a linear device, with the voltage output (at zero current) being given by

$$V_T = (V_B - V_A) = (P_B - P_A)(T_s - T_{ref}) = (P_B - P_A)\Delta T$$

Thermocouples are also widely used to measure temperature

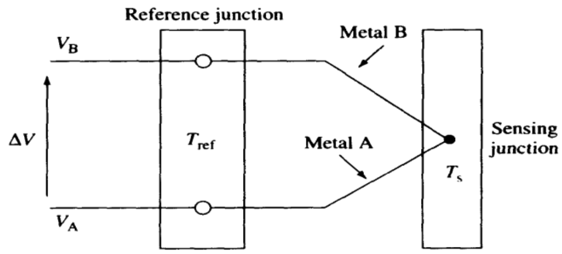


Figure 8.5 Basic configuration of a thermocouple temperature sensor (a type of potentiometric thermal sensor)

Table 8.2 summarises the typical properties of conventional temperature sensors and, more importantly, whether they can be integrated into a standard integrated circuit (1C) process.

Table 8.2 Properties of common temperature sensors and their suitability for integration. Modified from Meijer and van Herwaarden (1994)

Property	Pt resistor	Thermistor	Thermocouple	Transistor
Form of output	Resistance	Resistance	Voltage	Voltage
Operating range (°C)	Large −260 to +1000	Medium −80 to +180	Very large −270 to +3500	Medium −50 to +180
Sensitivity	Medium 0.4%/K	High 5%/K	Low 0.05 to 1 mV/K	High ~2 mV/K
Linearity	Very good < ±0.1 K	Very nonlinear	Good ±1 K	Good ±0.5 K
Accuracy:				
–absolute	High over wide range	High over small range	Not possible	Medium
–differential	Medium	Medium	High	Medium
Cost to make	Medium	Low	Medium	Very low
Suitability for IC integration	Not a standard process	Not a standard process	Yes	Yes–very easily

Thermodiodes and Thermotransistors

The simplest and easiest way to make an integrated temperature sensor is to use a diode or transistor in a standard IC process. The *I-V* characteristic of a *p-n* diode is nonlinear and follows Equation

$$I = I_s[\exp(\lambda q V / k_B T) - 1]$$

where I_S is the saturation current, typically 1 nA and λ is an empirical scaling factor that takes a value of 0.5 for an ideal diode. Rearranging Equation in terms of the diode voltage gives

$$V = \frac{k_B T}{q} \ln\left(\frac{I}{I_s} + 1\right)$$

Therefore, when the diode is operated in a constant current *I* circuit, the forward diode voltage Vout is directly proportional to the absolute temperature.

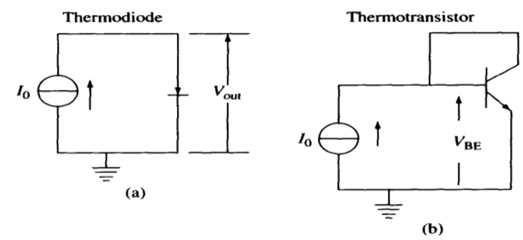


Figure 8.9 Basic temperature microsensors: (a) a forward-biased *p-n* diode and (b) an *n-p-n* transistor in a common emitter configuration with V_{CE} set to zero

$$V_{out} = \frac{k_B T}{q} \ln\left(\frac{I_0}{I_s} + 1\right) \text{ and } S_T = \frac{dV_{out}}{dT} = \frac{k_B}{q} \ln\left(\frac{I_0}{I_s} + 1\right)$$

The overall temperature sensitivity of the diode depends on the relative size of the drive current and saturation.

2. MECHANICAL SENSORS

Mechanical microsensors are the most important class of microsensor because of both the large variety of different mechanical measurands and their successful application in mass markets, such as the automotive industry. Table 8.4 lists some 50 or so of the numerous possible mechanical measurands and covers not only static and kinematic parameters, such as displacement, velocity, and acceleration, but also physical properties of materials, such as density, hardness, and viscosity.

The most important classes of mechanical microsensors to date is a subset of only six or so and these constitute the majority of the existing market for micromechanical sensors. Thus, the main measurands of mechanical microsensors are as follows in alphabetical order:

- Acceleration/deceleration
- Displacement
- Flow rate
- Force/torque
- Position/angle
- Pressure/stress

Table 8.4 List of mechanical measurands. Adapted from Gardner (1994)

Acceleration	Flow rate (mass)	Momentum	Sound level
Acoustic energy	Flow rate (volumetric)	Orientation	Stiffness
Altitude	Force (simple)	Path length	Tension
Angle	Force (complex)	Pitch	Thickness
Angular velocity	Frequency	Position	Torque
Angular acceleration	Friction	Pressure	Touch
Compliance	Hardness	Proximity	Velocity
Deflection	Impulse	Reynolds number	Vibration
Deformation	Inclination	Roll	Viscosity
Density	Kinetic energy	Rotation	Volume
Diameter	Length	Roughness	Wavelength
Displacement	Level	Shape	Yaw
Elasticity	Mass	Shock	Young's modulus

Therefore, we describe in detail here four of the most important types of mechanical microsensors, namely,

- Pressure microsensors
- Microaccelerometers
- Microgyroscopes
- Flow microsensors

Micromechanical Components and Statics

There are a number of micromechanical structures that are particularly important because they are used as the basic building blocks for a whole host of different microsensors (and for microactuators and MEMS). In their simplest form, these micromechanical structures are simply

- A cantilever beam
- A bridge
- A diaphragm or a membrane

Figure 8.20 shows a schematic diagram of each of these three types of microstructures in both plane view and in cross section. The physical dimensions of the structures are defined in the figures, such as length *l*, width *w*, thickness *d*, and breadth *b*. In this example, the bridge is shown on the top of the supporting structure, which as we shall see subsequently, is a common feature of microbridges.

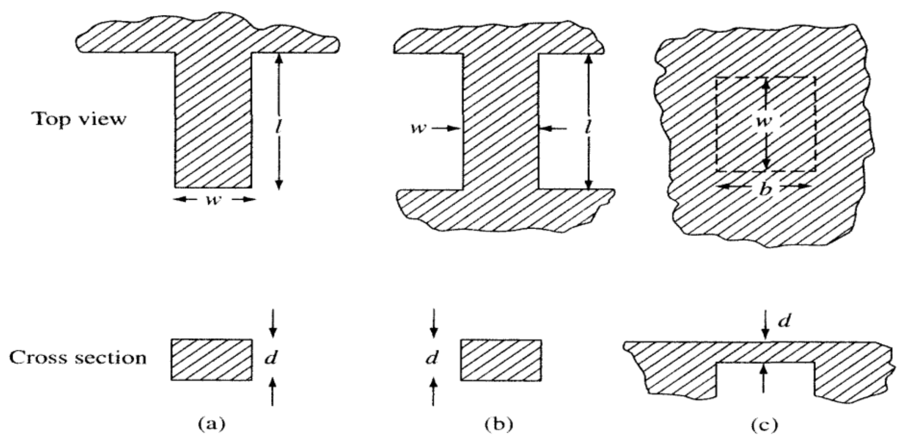


Figure 8.20 Basic microstructures: (a) cantilever beam; (b) bridge; and (c) diaphragm or membrane.

If we assume that these microstructures are made of a uniform, homogeneous, and elastic material, we can apply a simple theory to describe the way in which they deform when a mechanical load is applied, such as a force, torque, stress, or pressure. For example, the free end of a cantilever beam will deflect by a distance Δx when a point load F_x is applied to it (Figure 8.21 (a)). If we ignore gravitational forces and assume that there is no residual stress in the beam, then the deflection is simply given by

$$\Delta x = \frac{l^3}{3E_m I_m} F_x \tag{8.21}$$

where *Em* is the Young's modulus of the material and *I*m is the second moment of area of the beam and related to its width and thickness by

$$I_m = \frac{wd^3}{12} \tag{8.22}$$

Equation (8.21) may be rewritten as,

$$F_x = k_m \Delta x \text{ where } k_m = \frac{3E_m I_m}{l^3} \tag{8.23}$$

where the constant of proportionality *k*m is called the *stiffness* or *spring constant.*

The simple cantilever beam can thus be used to convert a mechanical force into a displacement. In a similar way, a cantilever beam, bridge, and diaphragm can be used to measure not only a point force but also a distributed force, such as stress. In addition, a diaphragm can be used to measure a hydrostatic or barometric pressure. However, in all these cases, the deflection of the structure has a more complex analytical form, which depends on the precise nature of the built-in supports.

Cantilever beams are often used as test structures on silicon wafers to show that the film deposited has no residual stress. In fact, bridges can be used to measure the axial compressive load *Fy* rather than the transverse load shown earlier (Figure 8.2l(b)). In this case, the deflection is not linearly related to the applied load but a solution can be obtained from the buckling equation of Euler where

$$\frac{d(\Delta x)}{dy^2} = -\frac{F_y \Delta x}{E_m I_m} \tag{8.24}$$

The solution for a bridge of length / fixed at both ends is a sinusoidal one where

$$\Delta x = A \sin(\sqrt{F_y / E_m I_m y}) \tag{8.25}$$

where A is a constant. The beam will buckle when the load reaches a critical value of

$$F_c = \pi^2 E_m I_m / l^2 \tag{8.26}$$

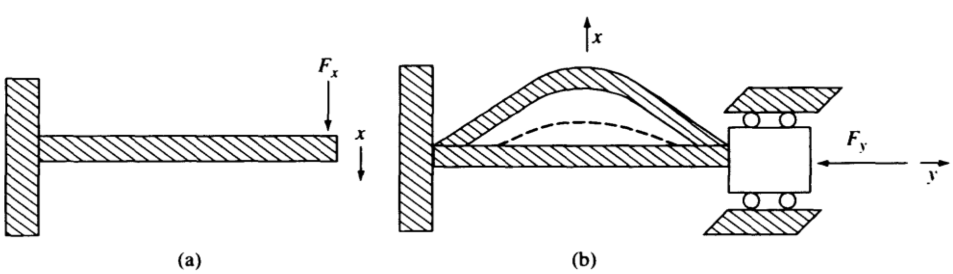


Figure 8.21 (a) Deflection of a cantilever beam by a vertical point force F_x and (b) buckling of a beam by an axial compressive load F_y

Mechanical Microstructures

The two most important questions that need to be asked by the designer are as follows. First, if these mechanical structures can be made on the micron scale and second, if they still follow classical theory, for example, the linear theory of elasticity. We know that microbeams, microbridges, and microdiaphragms can all be made in silicon using the bulk- and surface-micromicromaching techniques.

Clearly, the microstructures can then be fabricated from single-crystal silicon, polycrystalline silicon, and also from metals and other types of material. Table 8.8 summarises the mechanical properties of some of the materials that have been used to make micromechanical structures and are important in their practical design
and usage.

Table 8.8 Some mechanical properties of bulk materials used to make micromechanical sensors

Material Property	Si (SC)	Si (poly)	SiO_2	Si_3N_4	SiC	Diamond	Al	PMMA
Young's modulus (GPa)	190[a]	160	73	385	440	1035	70	–
Yield strength (GPa)	6.9	6	8.4	14	10	53	0.05	0.11
Poisson's ratio	0.23	0.23	0.20	0.27	–	–	0.35	–
Fracture toughness (MN/m^2)	0.74	–	–	4–5	3	30	30	0.9–1
Knoop hardness ($10^9 kg/m^2$)	0.8	–	0.8	3.5	–	7.0	–	–

The two most commonly used forms of transduction are capacitive and resistive. Figure 8.25 shows a microflexure in which its end is capacitively coupled to a stationary sense electrode.

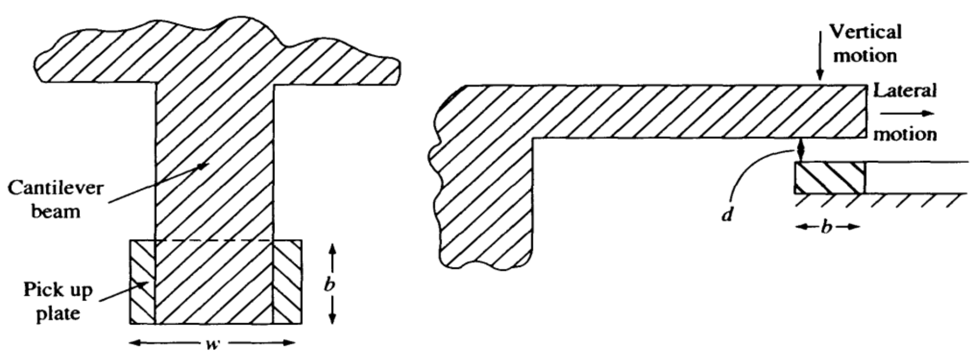


Figure 8.25 Capacitive measurement of the deflection of a simple cantilever beam

The capacitance C and change in capacitance δC are given by

$$C = \frac{\varepsilon A}{d} \text{ and hence } \frac{\delta C}{C} = \frac{\delta \varepsilon}{\varepsilon} + \frac{\delta A}{A} - \frac{\delta d}{d} \qquad (8.30)$$

Therefore, a change in capacitance is related to changes in the plate separation d, area of overlap A, and dielectric permittivity e. The capacitance of a structure with a 200 urn square area and a separation of 4 urn is about 0.1 picofarads. Therefore, it is necessary to measure changes in capacitance to a resolution on the order of 10 fF or less!

Many silicon mechanical microsensors use this principle to measure a *vertical* deflection (with A and ε constant) because the area can be made relatively large and the gap size small, that is, a few microns. This means that the change in capacitance can be measured using integrated electronics with an acceptable sensitivity. Another advantage of a capacitive pickup is that the input impedance is high and so little current is consumed; hence, the method is suitable for use in battery-operated devices with integrated CMOS circuitry. However, it is difficult to sense *lateral* deflections of silicon structures fabricated by standard surface-micromachining techniques because the resulting structures are only a few microns high.

The other important type of pickup is through a piezoresistor (see Figure 8.26). Piezoresistors can be made easily either as a region of doped single-crystal silicon (SCS) in a bulk-micromachined structure or as a doped polysilicon region in a surface-micromachined structure. The gauge factor K_{gf} of a strain gauge defines its sensitivity and simply relates the change in fractional electrical resistance ΔR to the mechanical strain ε_m

$$\frac{\Delta R}{R} = K_{gf}\varepsilon_m \tag{8.31}$$

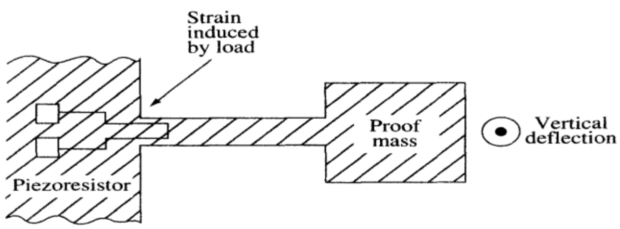


Figure 8.26 Piezoresistive measurement of the deflection of a cantilever beam

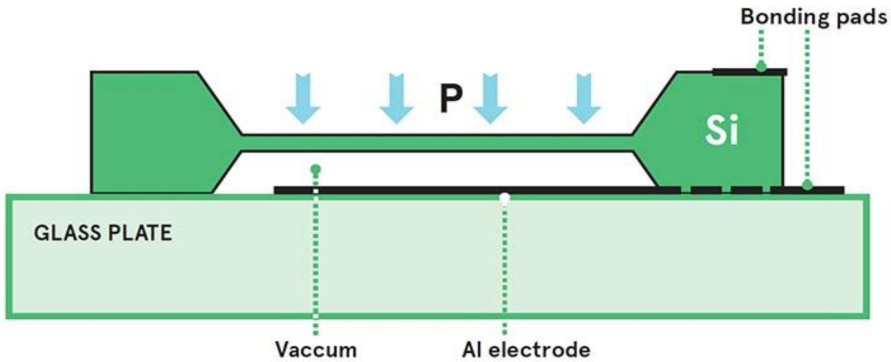
2.1. MEMS pressure sensors

The fabrication techniques used for creating transistors, interconnect and other components on an integrated circuit (IC) can also be used to construct mechanical components such as springs, deformable membranes, vibrating structures, valves, gears and levers. This technology can be used to make a variety of sensors including several types of pressure sensor.

Several types of pressure sensor can be built using MEMS techniques. Two of the most common: piezoresistive and capacitive. In both of these, a flexible layer is created which acts as a diaphragm that deflects under pressure but different methods are used to measure the displacement.

2.1.1. MEMS CAPACITIVE PRESSURE SENSORS

To create a capacitive sensor, conducting layers are deposited on the diaphragm and the bottom of a cavity to create a capacitor. The capacitance is typically a few picofarads.



A cross section of a MEMs capacitive pressure sensor

Deformation of the diaphragm changes the spacing between the conductors and hence changes the capacitance (see right). The change can be measured by including the sensor in a tuned circuit, which changes its frequency with changing pressure.

Capacitive pressure sensors measure pressure by detecting changes in electrical capacitance caused by the movement of a diaphragm.

Construction

The diaphragm can be constructed from a variety of materials, such as plastic, glass, silicon or ceramic, to suit different applications. The capacitance of the sensor is typically around 50 to 100 pF, with the change being a few picofarads.

The stiffness and strength of the material can be chosen to provide a range of sensitivities and operating pressures. To get a large signal, the sensor may need to be fairly large, which can limit the frequency range of operation. However, smaller diaphragms are more sensitive and have a faster response time.

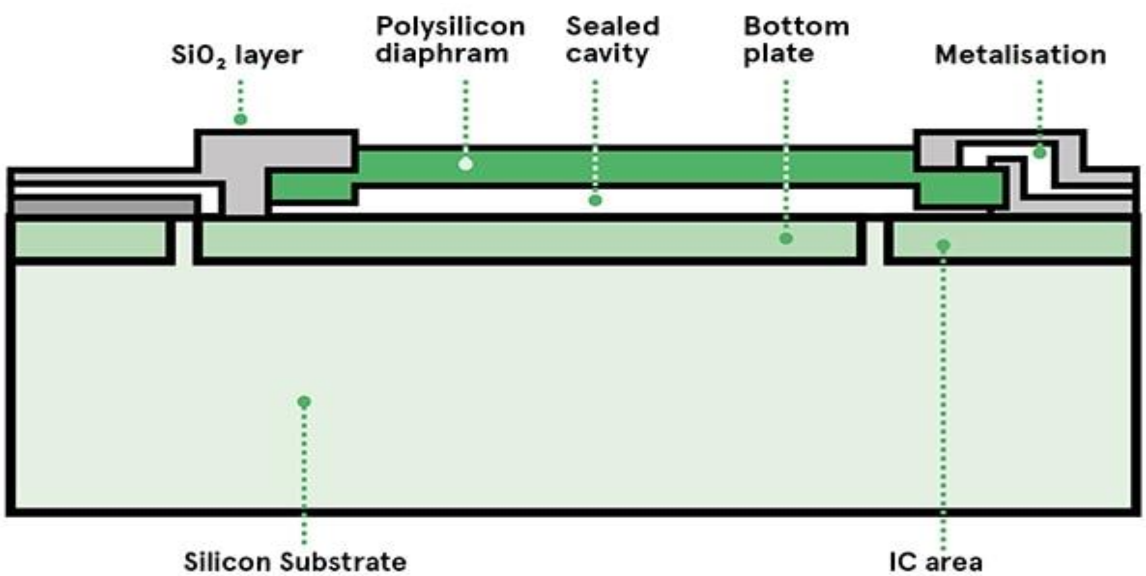
A large thin diaphragm may be sensitive to noise from vibration (after all, the same basic principle is used to make condenser microphones) particularly at low pressures.

Thicker diaphragms are used in high-pressure sensors and to ensure mechanical strength. Sensors with full-scale pressure up to 5,000 psi can readily be constructed by controlling the diaphragm thickness.

By choosing materials for the capacitor plates that have a low coefficient of thermal expansion, it's possible to make sensors with very low sensitivity to temperature change. The structure also needs to have low hysteresis to ensure accuracy and repeatability of measurements.

Because the diaphragm itself is the sensing element, there are no issues with extra components being bonded to the diaphragm, so capacitive sensors are able to operate at higher temperatures than some other types of sensor.

Capacitive pressure sensors can also be constructed directly on a silicon chip with the same fabrication techniques that are used in manufacturing semiconductor electronic devices (see diagram to the left). This allows very small sensing elements to be constructed and combined with the electronics for signal conditioning and reporting. Pressure sensors using microelectronic mechanical systems (MEMS) are given below



A cross section of capacitive sensor construction

Working principle

A capacitor consists of two parallel conducting plates separated by a small gap. The capacitance is defined by:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

where:

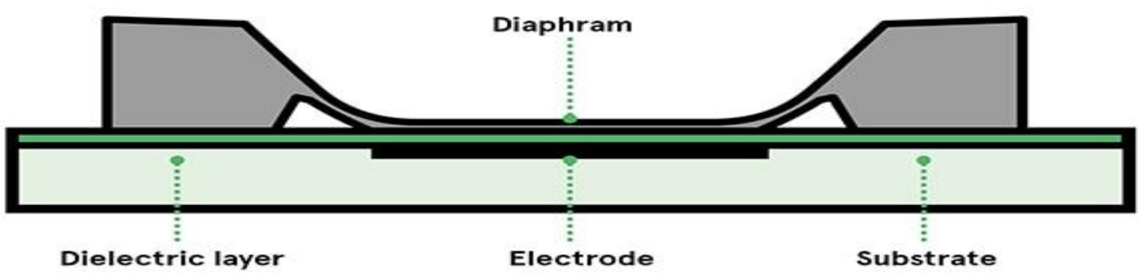
- εr is the dielectric constant of the material between the plates (this is 1 for a vacuum)
- ε_0 is the electric constant (equal to 8.854x1012 F/m),
- A is the area of the plates
- d is the distance between the plates

Changing any of the variables will cause a corresponding change in the capacitance. The easiest one to control is the spacing. This can be done by making one or both of the plates a diaphragm that is deflected by changes in pressure.

Typically, one electrode is a pressure sensitive diaphragm and the other is fixed. The change in capacitance can be measured by connecting the sensor in a frequency-dependent circuit such as an oscillator or an LC tank circuit. In both cases, the resonant frequency of the circuit will change as the capacitance changes with pressure.

An oscillator requires some extra electronic components and a power supply. A resonant LC circuit can be used as a passive sensor, without its own source of power.

The dielectric constant of the material between the plates may change with pressure or temperature and this can also be a source of errors. The relative permittivity of air, and most other gasses, increases with pressure so this will slightly increase the capacitance change with pressure. Absolute pressure sensors, which have a vacuum between the plates, behave ideally in this respect.



A more linear sensor can be constructed by using ‘touch mode’ where the diaphragm makes contact with the opposite plate (with a thin insulating layer in between) throughout the normal operating range (as shown to the right). The geometry of this structure results in a more linear output signal.

This type of sensor is also more robust and able to cope with a larger over-pressure. This makes it more suited to industrial environments. However, this structure is more prone to hysteresis because of friction between the two surfaces

Applications

Capacitive pressure sensors are often used to measure gas or liquid pressures in jet engines, car tyres, the human body and many other places. But they can also be used as tactile sensors in wearable devices or to measure the pressure applied to a switch or keyboard.

They are particularly versatile, in part due to their mechanical simplicity, so can be used in demanding environments.

Advantages and disadvantages

Capacitive pressure sensors have a number of advantages over other types of pressure sensors.

They can have very low power consumption because there is no DC current through the sensor element. Current only flows when a signal is passed through the circuit to measure the capacitance. Passive sensors, where an external reader provides a signal to the circuit, do not require a power supply – these attributes make them ideal for low power applications such as remote or IoT sensors.

The sensors are mechanically simple, so they can be made rugged with stable output, making them suitable for use in harsh environments. Capacitive sensors are usually tolerant of temporary over-pressure conditions.

They have low hysteresis with good repeatability and are not very sensitive to temperature changes.

On the other hand, capacitive sensors have non-linear output, although this can be reduced in touch-mode devices. However, this may come at the cost of greater hysteresis.

Finally, careful circuit design is required for the interface electronics because of the high output impedance of the sensor and to minimise the effects of parasitic capacitance.

2.2.2. PIEZORESISTIVE PRESSURE SENSING MECHANISM

Among these pressure sensor transduction principle, piezoresistive and capacitive transduction mechanisms have been widely adopted in various fields. Many commercialized MEMS pressure sensor uses a piezoresistive transduction mechanism in order to shows the pressure change in the resistance. The design of piezoresistive pressure sensor consists of piezoresistive element placed on a top of the diaphragm.

Placement of piezoresistive element on the square diaphragm is very important design consideration to achieve the required sensitivity. The optimal location to place the piezoresistive material would be in the region of high stress on the diaphragm. Then these resistors are connected in the form of Whetstone's bridge.

The application of pressure beneath the sensor causes a deflection of the membrane and this causes a change in resistance of the piezoresistive elements. As a result, the calculation of stress distribution and deflection in accordance with the applied pressure becomes pivotal. These forms of piezoresistive based transducers depend on the piezoresistive effect which occurs when the change in electrical resistance of a material in response to the mechanical strain is applied. In metals, this effect is realized when the change in geometry with applied mechanical strain results in a small increase or decrease in the resistance of the metal.

The piezoresistive effect in silicon is primarily due to its atomic level. As stress is applied, the average effective mass of the silicon carrier will either increases or decreases (depending on the orientation of the crystallographic, direction of the stress, and the direction of the current flow). This type of change alters the silicon carrier mobility and hence it results in the change in its resistivity.

When piezoresistive element are placed in the Wheatstone bridge configuration and it is attached to the pressure-sensitive diaphragm, a resistance change in the material is converted in to an output voltage which is proportional to the applied pressure as shown in the Fig.1.

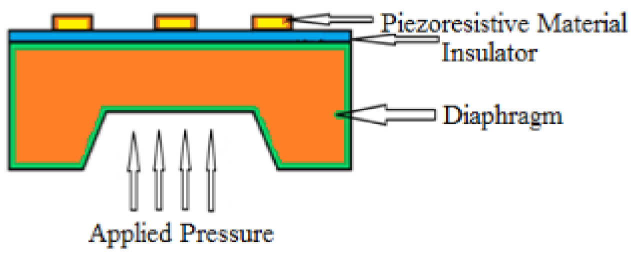


Fig.1. Conventional pressure sensor model

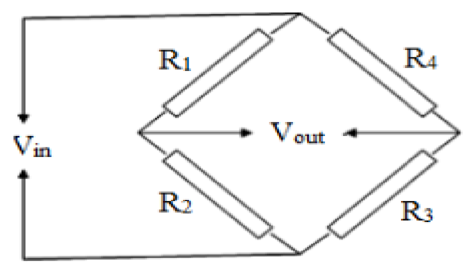


Fig.2. Wheatstone bridge circuit.

Fig.2.shows the Wheatstone bridge circuit, a Wheatstone bridge consists of a four piezoresistive material labeled as R1, R2, R3and R4respectively. The resistance [R] of a piezoresistive material is given by $R = \rho \boldsymbol{L}/\boldsymbol{A}$ (1)

. Where ρ is the resistivity of a piezoresistor, L is the length of a piezoresistor; A is the area of a piezoresistor.

Wheatstone bridge is mounted on the diaphragm. When the pressure is applied to the diaphragm, the diaphragm experiences the sheer stress due to which the diaphragm deforms in the direction of pressure imposed. Due to the deformation of the diaphragm, the piezoresistors mounted on the diaphragm in a Wheatstone bridge format stretches. As the piezoresistors stretches, the length increases while the area decreases. From equation (1), if length increases and area decreases, there will be incremental change in the resistance of a piezoresistors and effectively decreases the output voltage.

Applications

The robustness, high frequency and rapid response time of piezoelectric pressure sensors means they can be used in a wide range of industrial and aerospace applications where they'll be exposed to high temperatures and pressures.

They are often used for measuring dynamic pressure, for example in turbulence, blast, and engine combustion. These all require fast response, ruggedness and a wide range of operation.

Their sensitivity and low power consumption also makes them useful for some medical applications. For example, a thin-film plastic sensor can be attached to the skin and used for real-time monitoring of the arterial pulse.

Advantages and disadvantages

One of the main advantages of piezoelectric pressure sensors is their ruggedness. This makes them suitable for use in a variety of harsh environments.

Apart from the associated electronics, piezoelectric sensors can be used at high temperatures. Some materials will work at up to 1,000ºC. The sensitivity may change with temperature but this can be minimised by appropriate choice of materials.

The output signal is generated by the piezoelectric element itself, so they are inherently low-power devices.

The sensing element itself is insensitive to electromagnetic interference and radiation. The charge amplifier and other electronics need to be carefully designed and positioned as close as possible to the sensor to reduce noise and other signal errors.

Piezoelectric sensors can be easily made using inexpensive materials (for example quartz or tourmaline), so they can provide a low cost solution for industrial pressure measurement.

2.2.3. Capacitive Vs Piezoresistive Vs Piezoelectric Pressure Sensors

The first pressure gauges were purely mechanical. They used mechanisms such as a diaphragm or a "Bourdon tube" that changed shape under pressure to move a pointer on a dial.

Various techniques have since been developed to convert mechanical displacements into electrical signals. Here we'll consider the relative advantages of piezoresistive, capacitive and piezoelectric pressure sensors.

Principles of operation

In a piezoresistive strain gauge sensor, the change in electrical resistance of one or more resistors mounted on a diaphragm is measured. The change in resistance is directly proportional to the strain caused by pressure on the diaphragm. The resistors are connected in a Wheatstone bridge circuit, which is a very sensitive way of converting the small changes to an output voltage.

Capacitive pressure sensors measure changes in electrical capacitance caused by the movement of a diaphragm. A capacitor consists of two parallel conducting plates separated by a small gap. One of the plates acts as the diaphragm that is displaced by the pressure, changing the capacitance of the circuit. The resulting change of resonant frequency of a circuit can be measured. Or, in a digital system, the time taken to charge and discharge the capacitor can be converted to a series of pulses.

Piezoelectric sensors use materials, such as quartz crystals or specially formulated ceramics, which generate a charge across the faces when pressure is applied. A charge amplifier converts this to an output voltage proportional to the pressure. A given force results in a corresponding charge across the sensing element. However, this charge will leak away over time meaning that the sensor cannot be used to measure static pressure.

All three types of sensors can be miniaturised using silicon fabrication techniques and combined with electronics as microelectromechanical systems (MEMS). This allows very small sensing elements to be constructed and combined with the electronics for signal conditioning and readout.

Piezoresistive and capacitive pressure sensors can be used for absolute, gauge, relative or differential measurements.Piezoelectric sensors are sensitive to changes in pressure so the output is usually treated as a relative pressure measurement, referenced to the initial state of the piezoelectric material.

2.3. MICROACCELEROMETERS

Microaccelerometers are based on the cantilever principle in which an end mass (or shuttle) displaces under an inertial force. Figure 3.3 shows the basic principle of the two most important types: capacitive pickup of the seismic mass movement and piezoresistive pickup.

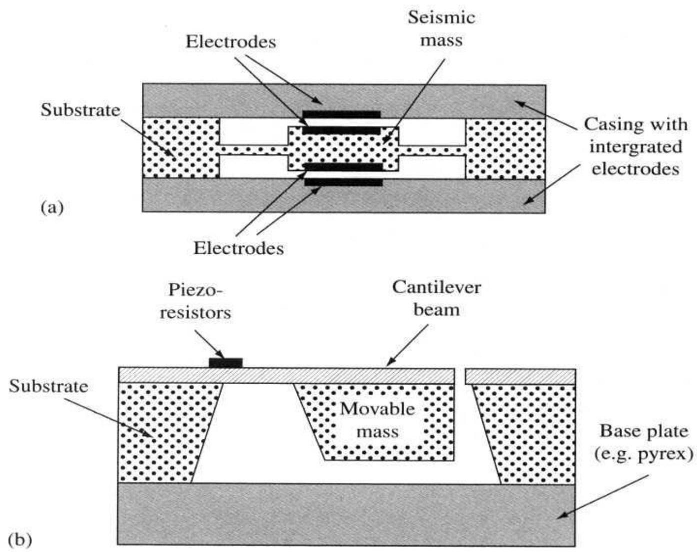


Figure 3.3 Basic types of microaccelerometers: (a) capacitive and (b) piezoresistive.

MEMS AS INERTIAL SENSORS

MEMS sensors have many useful applications in measuring linear acceleration along one or several axis, or angular motion about one or several axis as an input to control a system Figure 1.

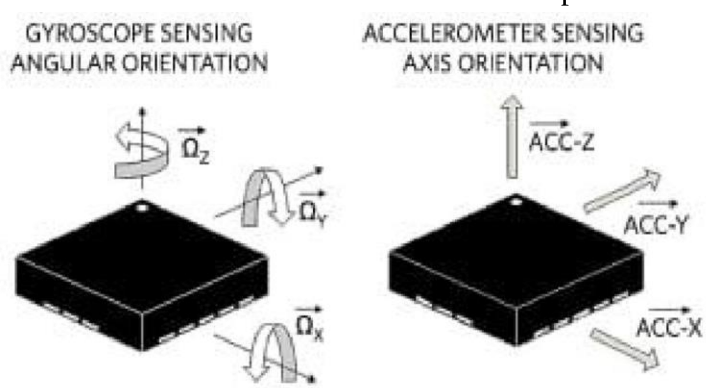


Figure 1. Angular versus linear motion.

All MEMS accelerometer sensors measure the displacement of a mass with a position measuring interface circuit. That measurement is then converted into a digital electrical signal through an analog-to-digital converter (ADC) for digital processing. Gyroscopes are the devices which measure both the displacement of the resonating mass and its frame because of the Coriolis acceleration.

Basic Accelerometer Operation

According to Newton's Second law of the acceleration (m/s^2) of a body is directly proportional to, and in the same direction as, the net force (Newton) acting on the body, and inversely proportional to its mass (kilogram).

Acceleration (m/s^2) = Force(N)/ Mass(kg) Eq. 1

The important point to note that acceleration creates a force that is sensed by the force-detection mechanism of the accelerometer.So the accelerometer actually measures force, not acceleration; it basically measures acceleration indirectly through a force appliedto one of the accelerometer's axes.

Using microfabrication technology an accelerometer is also an electromechanical device, including holes, cavities, springs, and channels, that is machined. By using multilayer wafer process, measuring acceleration forces by detecting the displacement of the mass relative to fixed electrodes accelerometers are fabricated.

Accelerometer Operating Principle

An accelerometer can be modeled as a second order spring-mass-damper system (Figure 1).

When an acceleration (a) is applied to proof mass (m) suspended by springs with a spring constant (k), and having a damping (b), then the force (Fapplied) acting on the proof mass is given by:

$$F_{applied} = ma_{applied} \tag{1}$$

The force exerted by springs and damping in the system can be defined as:

$$F_{spring} = kx \tag{2}$$

$$F_{damping} = b\dot{x} \tag{3}$$

Applying Newton's second law which states that the algebraic sum of all the forces equals the inertial force of the proof mass, we get:

$$F_{applied} - F_{spring} - F_{damping} = m\ddot{x} \tag{4}$$

$$m\ddot{x} + b\dot{x} + kx = F_{applied} = ma_{applied} \tag{5}$$

The transfer function $H(s)$ of the system is given by:

$$ms^2x(s) + bsx(s) + kx(s) = F(s) = ma(s) \tag{6}$$

$$s^2x(s) + \frac{b}{m}sx(s) + \frac{k}{m}x(s) = \frac{F(s)}{m} = a(s) \tag{7}$$

$$H(s) = \frac{x(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} = \frac{1}{s^2 + \frac{\omega_0}{Q}s + {\omega_0}^2} \tag{8}$$

In Equation (8), ω_0 is the resonance frequency and Q is the quality factor given by:

$$\omega_0 = \sqrt{k/m} \tag{9}$$

$$Q = \frac{m\omega_0}{b} \tag{10}$$

Accelerometers work in the low frequency domain ($\omega \ll \omega_0$) with their mechanical sensitivity calculated by setting $s = 0$ in the transfer function $H(s)$ to get

$$\frac{x}{a} \sim \frac{m}{k} = \frac{1}{{\omega_0}^2} \tag{11}$$

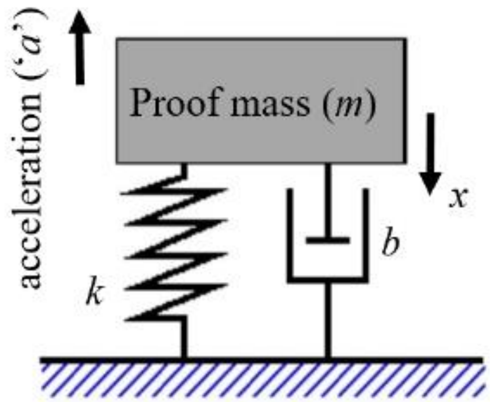


Figure 1. Model of accelerometer.

The Accelerometer's Sensing Mechanism

An often used sensing approach used in accelerometers is capacitance sensing in which acceleration is related to change in thecapacitance of a moving mass (Figure 2). This sensing technique is known for its high accuracy, stability, low power dissipation,and simple structure to build. It is not prone to noise and variation with temperature. Bandwidth for a capacitive accelerometeris only a few hundred Hertz because of their physical geometry (spring) and the air trapped inside the IC that acts as a damper

$$C = \varepsilon_0 \text{ x } \varepsilon_r \text{ x } A / D$$

where

ε_0 = Permitted free space

ε_r = Relative material permitted between plates

A = Area of overlap between electrodes

D= Separation between the electrodes

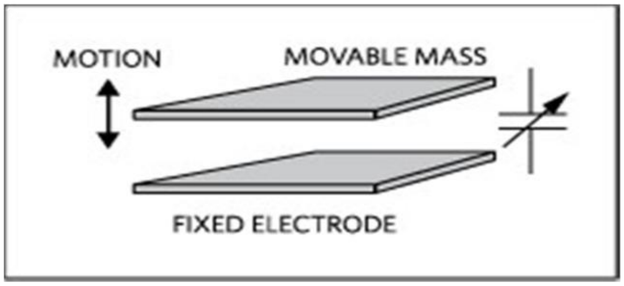


Figure 2. Moving mass and capacitance.

The capacitance can either be arranged as single-sided or a differential pair. Let's look at accelerometers arranged as a differential pair (Figure 3). It is composed of a single movable mass (one planar surface), that is placed along with a mechanical spring between two, fixed, reference silicon substrates or electrodes (another planar surface). It is obvious that the movement of the mass (Motion x) is relative to the fixed electrodes (d1 and d2), and causes a change in capacitances (C1 and C2). By calculating the difference between C2 and C1 we can derive the displacement of our mass and its direction.

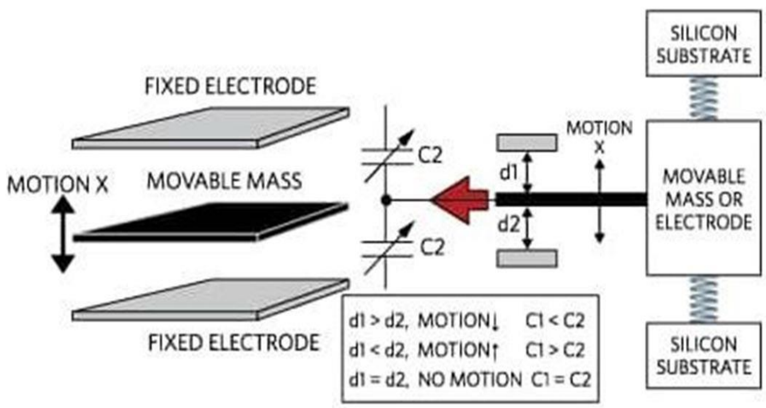


Figure 3. Acceleration associated with a single moving mass.

The displacement of the non-fixed mass (in micrometre) is kindle by acceleration, and it creates very minute change in capacitance for proper detection (Equation 1). This authorized for using multiple movable and set electrodes, all connected in a parallel layout. This design enables a greater change in capacitance, which can both be detected more accurately, which ultimately makes capacitance sensing a more feasible technique [8]. Force causes a displacement of the mass which, in return, causes a change in capacitance. Now, placing multiple electrodes in parallel allows a larger capacitance, which will be more easily detected (Figure 4). V1 and V2 are electrical connections to each side of the capacitors and form a voltage-divider with the center point as the voltage of our mass.

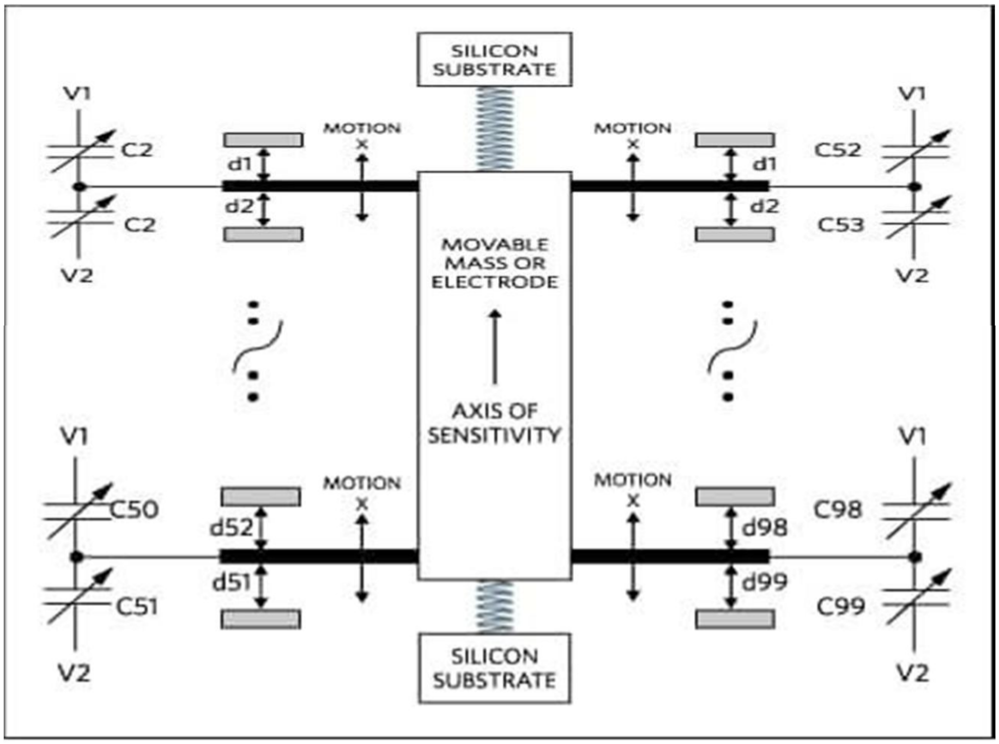


Figure 4. Acceleration associated with multiple moving masses.

The analog mass voltage will go through charge amplification, signal conditioning, demodulation, and lowpass filtering before it gets converted into a digital domain using a sigma-delta ADC. The ADC provide serial digital bit stream is passed to a FIFO (First in first out) buffer that converts the serial signal into a parallel data stream.

Multi axis Accelerometer

Let's take another look at Figure 3 and add an actual manufactured accelerometer as shown in Figure 6. Now we can clearly relate each component of an accelerometer to its mechanical model.

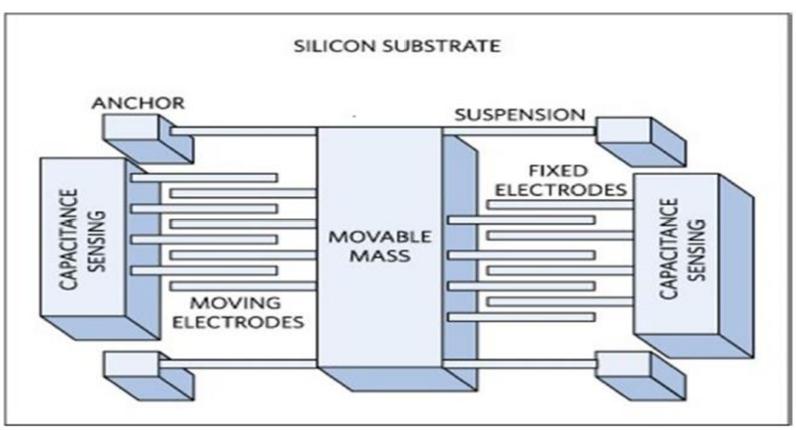


Figure 6. A mechanical model of an actual accelerometer.

By simply placing an accelerometer differently 90 degrees as shown in Figure 7, we can create a 2-axis accelerometer needed for more sophisticated applications.

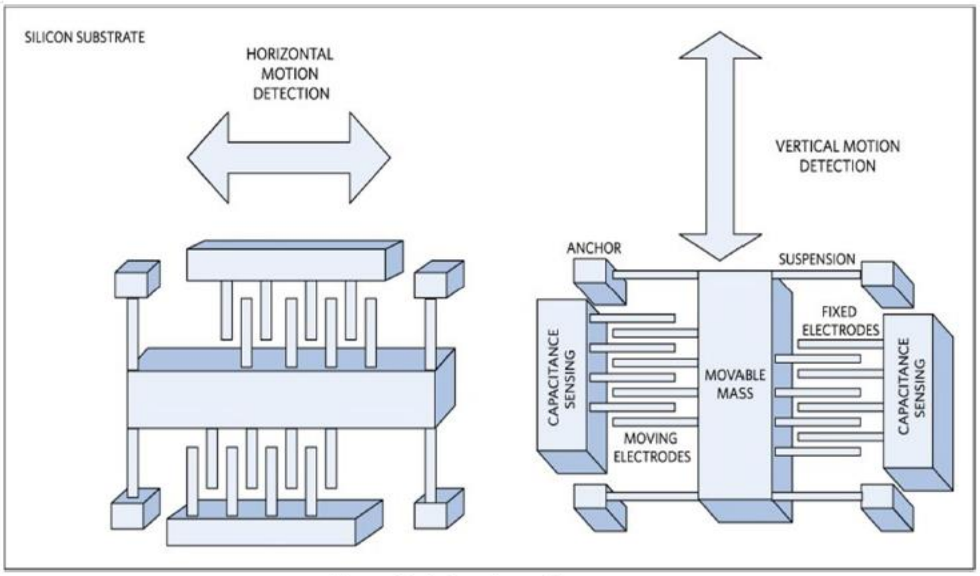


Figure 7. A 2-axis accelerometer.

There are two ways to construct a two-axis accelerometer: lay out the two different single-axis accelerometer sensors perpendicular to each other, or use a single mass with capacitive sensors arranged to measure movement along both axes.

MEMS Accelerometers – Applications.

1. Used in latest mobile phones and gaming joysticks as step counters, user interface control, and also for switching between different modes.
2. Used in mobile cameras for a tilt sensor so as to tag the orientation of photos taken.
3. To provide stability of images in camcorders and also to rotate the image to and fro when you turn the mobile.
4. As Nokia 5500 used a 3D accelerometer so as to provide easier tap and change feature by which you can change mp3's by tapping on the phone when it is lying inside the pocket.
5. Used to protect hard disk drives in laptops from getting damaged when the PC falls to the ground. The device senses the free fall and automatically switches off the hard disk.
6. Used in car crash airbag sensors, where it senses the sudden negative acceleration and determines the correct time to open the airbag.
7. Used in Practical applications like military monitoring, missile launching, projectiles, and so on.

2.4. MEMS Gyro Sensors / Microgyrometers

Gyroscope is type of inertial sensor that measures the change in orientation of an object. Silicon-micromachined gyroscopes have been fabricated on the basis of coupled resonators. The basic principle is that there is a transfer of energy from one resonator to another because of the Coriolis force. Thus, a simple mass *m* supported by springs in the *x*- and y-axes and rotated around the z-axis at an angular velocity Ω has the following equations of motion.

$$m\ddot{x} + b\dot{x} + k_x x - 2m\Omega\dot{y} = F_x$$

$$m\ddot{y} + b\dot{y} + k_y y + 2m\Omega\dot{x} = F_y$$

where the terms $2m\Omega x$ and $2m\Omega y$ describe the Coriolis forces and the resonant frequencies are

$$\omega_{0x} = \sqrt{k_x/m} \quad \text{and } \omega_{0y} = \sqrt{k_y/m}$$

Now assume that the resonators are excited and behave harmonically with the amplitudes a(t) and *b(t)*. By fixing the amplitude of one oscillator (a_0) by feedback and then for synchronous oscillators $(w_0x = w_0y)$, the equations simply reduce to

$$\frac{db}{dt} + \left(\frac{c}{2m}\right) b + \Omega a_0 = 0$$

Under a constant rotation, the steady-state solution to Equation is a constant amplitude b_0 where

$$b_0 = -\left(\frac{2m}{c}\right) a_0 \Omega$$

Therefore, the amplitude of the undriven oscillator is linearly proportional to the rotation or precession rate Ω.

The first silicon coupled resonator gyrometer was developed by Draper Laboratory in the early 1990s and its arrangement is shown in Figure 8.33. The device is bulkmicromachined and supported by torsional beams with micromass made from doped *(p++)* single-crystal silicon (SCS). The outer gimbal was driven electrostatically at a constant amplitude and the inner gimbal motion was sensed. The rate resolution was only 4 deg s^{-1} and bandwidth was just 1 Hz.

More advanced gyroscopes have been fabricated using surface micromachining of poly silicon.

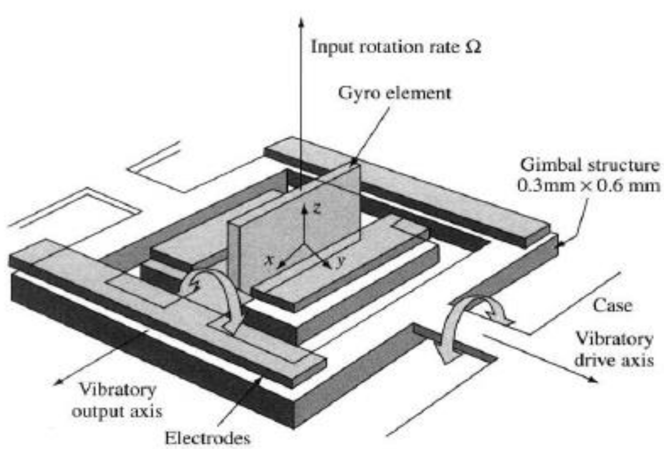
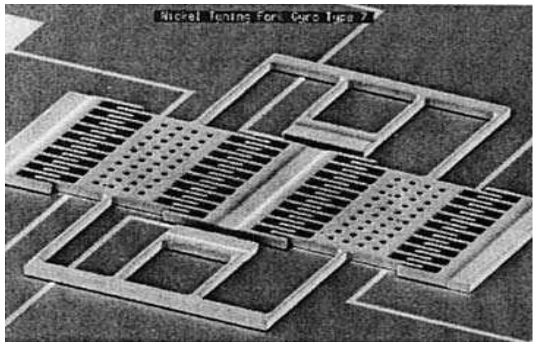


Figure 8.33 Early example of a silicon-micromachined coupled resonant gyrometer.

Tuning Fork Gyroscopes contain a pair of masses that are driven to oscillate with equal amplitude but in opposite directions. When rotated, the Coriolis force creates an orthogonal vibration that can be sensed by a variety of mechanisms. Figure below. uses comb-type structures to drive the tuning fork into resonance.

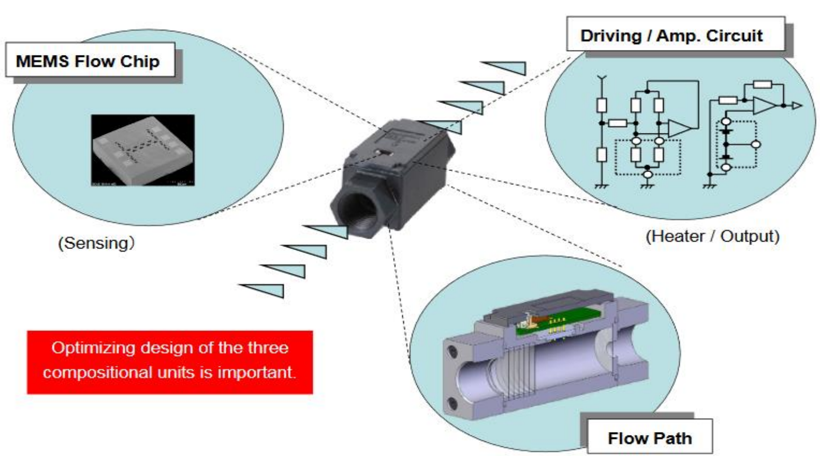


Rotation causes the proof masses to vibrate out of plane, and this motion is sensed capacitively with a custom CMOS ASIC.

2.5. Flow sensor

A flow sensor is a sensor that detects the flow rate and flow velocity of a gas. In general, there are various types of flow sensors, such as a propeller type, a float type, an ultrasonic type, a hot wire type, and so on. MEMS Flow sensors adopt a MEMS heat wire type, and have relatively excellent characteristics in comparison with other types of flow sensors

Structure Basic composition of flow sensors MEMS flow sensors are dedicated to gas, it can be used for detecting the mass flow of various types of gases. The basic composition of flow sensors consist of a MEMS flow sensor chip that can detect the flow rate, the amplifier circuit for amplifying sensor output and the optimized flow path that is designed for each application by CAE (Computer Aided Engineering).Optimizing these three compositions is very important because gas flow is a vector volume.



flow sensor lineup consists of three categories, Mass flow sensors that output a flow rate, Flow velocity sensors that output a flow velocity and Differential pressure sensors that can detect a small pressure drop. A flow sensor‘s shape and size will differ depending on the type of gas to be measured, the flow rate, and the port style.

Operating principle

Basic structure of MEMS flow sensor chip

The basic structure of a MEMS flow sensor chip is shown in Fig.3. This sensor chip adopts a mass flow sensing method by using heat wire. It has a heater in the center of the chip, and the upstream thermopile (A) and the downstream thermopile (B) are located on either side of the heater, the base thermo-scope near the thermopile is made by a semiconductor process. The cavity is formed at the bottom of the heater and the thermopile arrays, so then it is possible to detect the heat from the heater effectively.

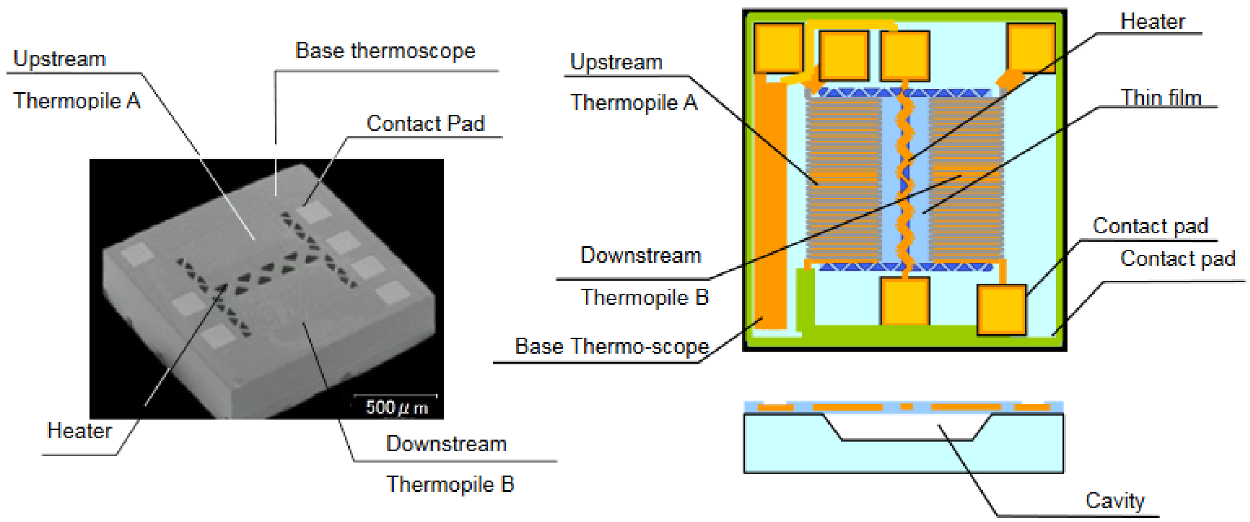


Fig.3. Flow Sensor Chip Structure

Detecting principle of mass flow sensor

As shown in Fig. 4, the constant current is flowing to the heater at the center of the chip and the heater becomes hot. When there is no flow, the heat distribution around the heater is symmetric, so Vu and Vd of the electromotive force from both thermopiles will be equal. On the other hand, when there is a flow of gas on the sensor surface, the heat source is biasedon the downstream side according to the flow of gas. The electromotive force of the downstream thermopile will be larger than the upstream thermopile (Vd > Vu). The output difference betweenthe two thermopiles is approximately proportional to the square root of the mass flow rate of the gas through the sensor surface. The output sensitivity and the mass flow rate depend on the composition ratio of the gas. Through amplification, it is possible to electronically detect the flow rate of the gas. The flow velocity sensor is adjusted so that it can output a voltage that corresponds to the flow velocity at the condition of 25°C, 101.3kPa from the mass flow rate.

When the flow direction is perpendicular to the thermopiles and heater.

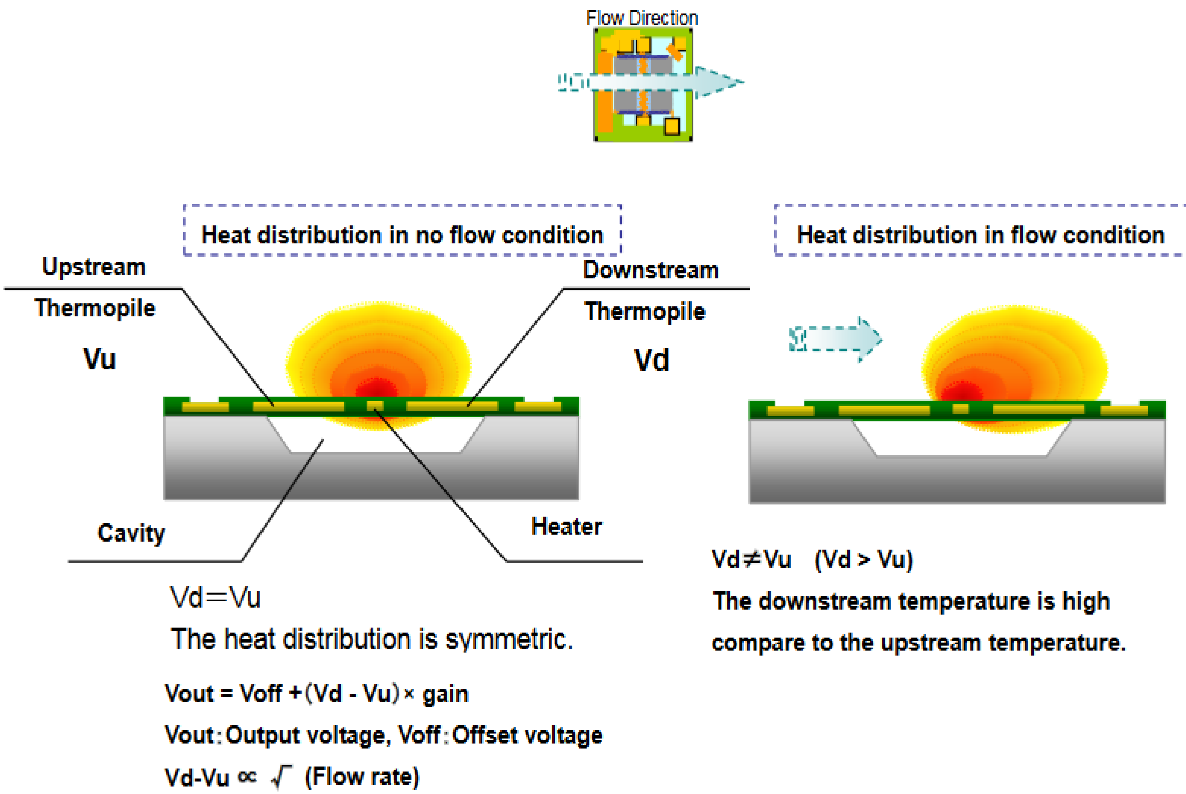


Fig4. Sensing image of mass flow sensor using heat wire

Fabrication Steps

1. Starting material : Double side polished silicon wafer of n-type.
2. Thermal oxidation(dry-wet-dry) Sio_2
3. Photolithography for pattering of front side oxide (using front etch mask) while protecting backside oxide with photoresist.
4. Photolithography for pattering of back side (using bottom mask) while protecting front side oxide with photoresist. This step requires both side (top and bottom) alignments.
5. Thermal evaporation of Chromium or nickel film to form resistors.
6. Photomasking for Cr-Ni pattering.
7. Thermal evaporation of Cr/Ni film to form contact.
8. Photomasking for Cr-Ni pattering.
9. silicon etching has beendone with KOHnat 25^0C from back side only while protecting front side with black wax and silicon < 111 >wafer.

UNIT IV

MEMS Accelerometers: *Micromachined Micro accelerometers for MEMS, MEMS Accelerometers for Avionics, Temperature Drift and Damping Analysis, Piezoresistive Accelerometer Technology, MEMS Capacitive Accelerometer, MEMS Capacitive Accelerometer Process, MEMS for Space Application.*

Microelectromechanical systems (MEMS) accelerometers have been widely used in various application fields, such as consumer electronics, automobiles, medical, structural health monitoring, and inertial navigation. According to the displacement or force transduction mechanisms, MEMS accelerometers can be categorized as different types, including piezoelectric, capacitive , piezoresistive, tunneling, resonant, optical, thermal , and electromagnetic accelerometers.

1. CAPACITIVE ACCELEROMETERS

Capacitive transduction is one of the most commonly used technologies for high-performance MEMS accelerometers since it takes advantage of simple structure, low noise, low power consumption, cost-effectiveness, and reliability

One of the main reasons is that area-variation capacitive accelerometers are difficult to be fabricated by either bulk silicon wet etching or silicon-on-insulator-based processes that are widely used for fabricating high-performance gap-variation based MEMS accelerometers. Through-silicon-wafer-etching process that offers a solution of fabricating high-performance accelerometers by keeping both wafer-thick bulk proof mass and the area-variation capacitive displacement transducer. Based on this fabrication technology, a high-performance open-loop MEMS capacitive accelerometer has been developed.

The MEMS accelerometer consists of a silicon-based acceleration-sensitive spring-mass structure which is sandwiched by the upper and lower glass cover plates, as illustrated in Figure 1. The in-plane motion of the proof mass is sensed capacitively between the array of parallel-plate electrodes on the proof mass and the matching array of electrodes on the upper glass plate which is separated by a fixed gap above the proof mass.

Figure 1. Schematic of the proposed MEMS accelerometer.

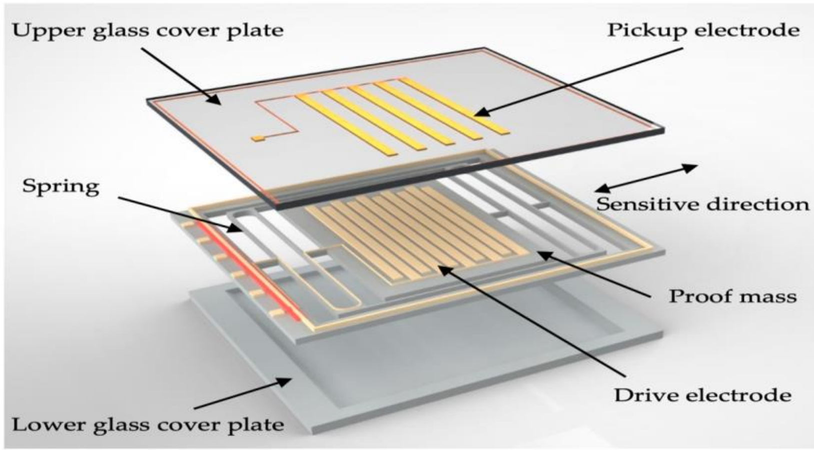
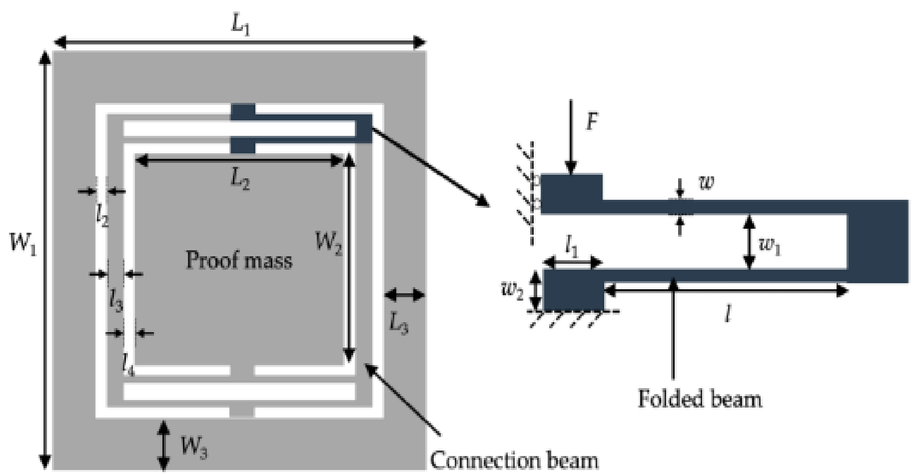


Figure 2. Structure of the spring-mass system.



Area-Variation Capacitive Displacement Transducer Design

The spring-mass system of the accelerometer transforms the external accelerations to displacements of the proof mass. In order to measure accelerations, it is necessary to convert the displacement into other measurable quantities. By applying capacitive displacement sensing technology, the displacement can be transduced into capacitance changes which can then be converted to voltage or current through the signal conditioning circuit. In this case, the capacitive accelerometer performs as an acceleration ratio-meter. An area-variation periodic array capacitive displacement transducer is introduced with the schematic illustrated in Figure 4. Each set of the periodic array capacitive transducer consists of two drive electrodes plated on the movable proof mass and one pickup electrode plated on the upper glass cover plate with a gap of d. The overlapping length of the drive and pickup electrodes is l_e. The width of both drive electrodes is defined as a and the separation between each drive electrode is g_1. While the width of the pickup electrode is b and the separation between each other is g_2. When the electrodes pairs are located in the null position where the pickup electrode is right in the middle of two drive electrodes, the overlapping width of the pickup electrode to each drive electrode is x_0. In this case, the sensing capacitors C_1, constructed by the positive drive electrode and the pickup electrode, and C_2, constructed by the negative drive electrode and the pickup electrode, have the same capacitance:

$$C_1 = C_2 = C_0 = \frac{\varepsilon l_e x_0}{d}, \quad (7)$$

where C_0 is the nominal capacitance of one period and ε is the permittivity. When there is a relative displacement Δx between the proof mass and the upper cover plate along the sensitive direction, the overlapping areas of C_1 and C_2 change in opposite, having

$$C_1 = \frac{\varepsilon l_e (x_0 + \Delta x)}{d}, \; C_2 = \frac{\varepsilon l_e (x_0 - \Delta x)}{d}. \quad (8)$$

Thus, the capacitance difference of these two capacitors can be obtained,

$$\Delta C = C_1 - C_2 = \frac{2\varepsilon l_e \Delta x}{d}. \quad (9)$$

It can be seen from Equation (9) that the displacement variation caused by accelerations can be converted into capacitance change by the area-variation capacitive displacement transducer with differential configuration, thus realizing capacitive displacement sensing.

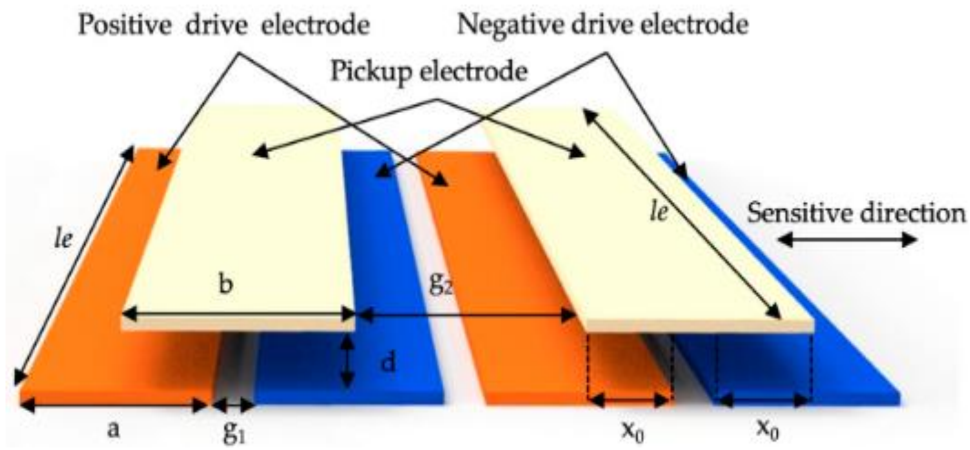


Figure 4. Schematic of the area-variation capacitive displacement transducer configuration.

In the actual device design, in order to increase the gain of displacement-to-capacitance, arrays with N periods of the three-electrode differential configuration unit are applied. The capacitance change of periodic transducer in terms of the relative displacement is N times of the single three-electrode unit. Therefore, the displacement-to-capacitance gain is significantly increased. In order to make the displacement-to-capacitance gain as large as possible, the electrodes take the entire surface area of the proof mass to maximize the periods. In addition, the periodic width should match the travel range of the proof mass to ensure the movement within a single period.

Fabrication Process

The functional features of the proposed accelerometer are based on single-crystal silicon substrate and glass substrate which require to be fabricated separately. The silicon substrate includes the spring-mass movable structure, the drive electrodes of the capacitive transducer, and the packaging and wire-bonding pads, while the glass substrate consists of the pickup electrodes and the packaging pads. The microfabrication flow chart is illustrated in Figure 6 with the silicon-substrate process in the left column and the glass-substrate and packaging process in the right column.

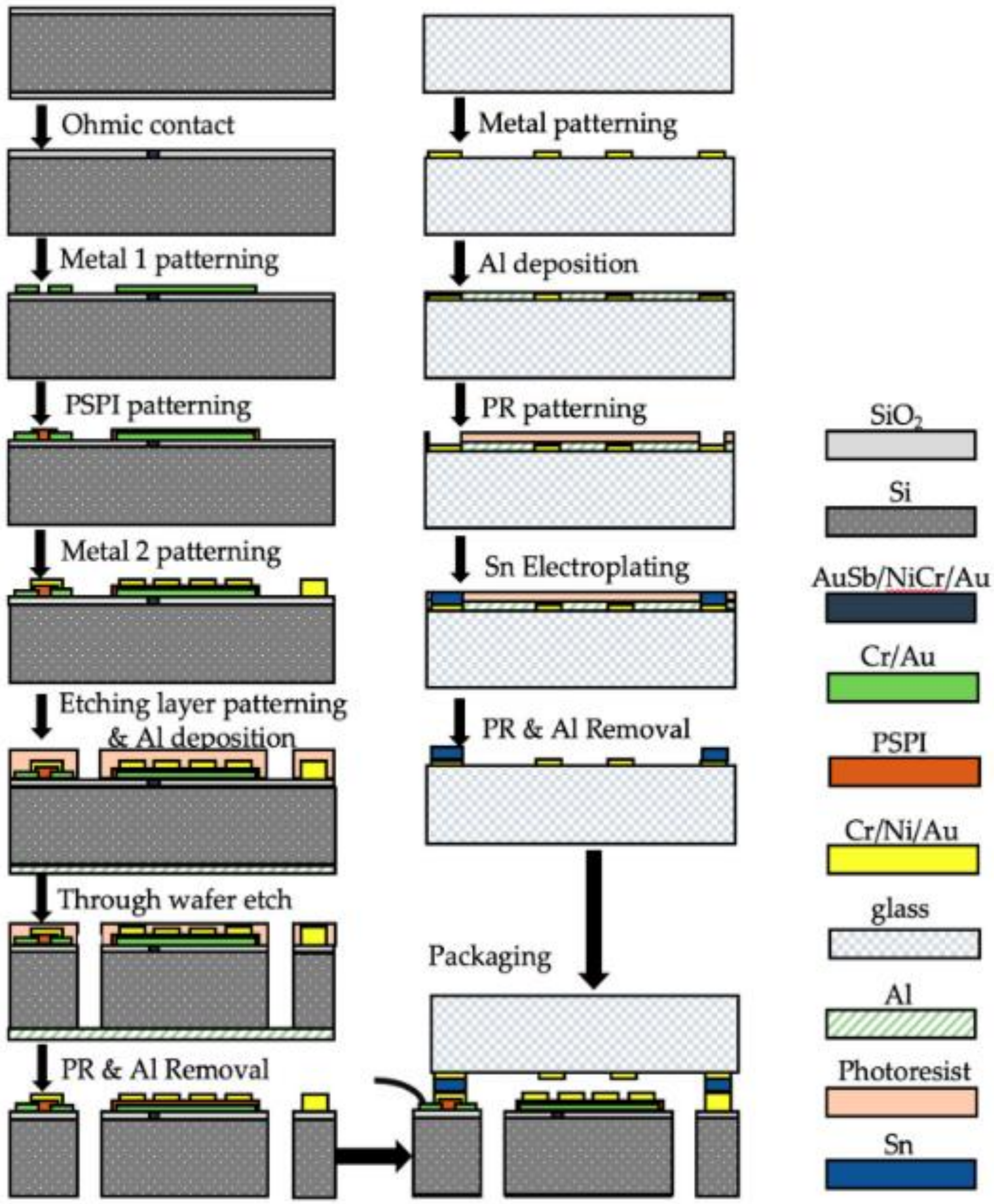


Figure 6. The microfabrication process flow of the proposed MEMS accelerometer.

1. Silicon wafer with double side oxidation is prepared.
2. The backside oxidation layer is stripped by reactive ion etching (RIE), followed by the front side window patterning through photolithography.
3. Then, the exposure pattern is etched by RIE to form an ohmic contact window. The ohmic contact is formed by AuSb/NiCr/Au laminated metal annealing at 420 °C for 1 h.

4. In order to form the electrical ground for capacitive shielding and build the interconnections between different pads, the Metal 1 layer, which had a chrome adhesive layer and a gold layer, was deposited on the substrate surface by E-beam evaporation.
5. Then, a layer of photosensitive polyimide (PSPI) is spin-coated and patterned. The solidified PSPI features performed as the insulation layer between the Metal 1 features and the Metal 2 features
6. Then, the Metal 2 layer of Cr is deposited by evaporation and patterned by lift-off technology to form the electrodes, signal traces, and packaging pads.
7. In the following, a thick photoresist is spin-coated and patterned to form the spring-mass structure mask.
8. In the following, an aluminum layer is deposited on the backside of the wafer to alleviate the notching phenomena during the following through-silicon-wafer deep reactive ion etching (DRIE).
9. A backing wafer is attached on the bottom of the device wafer by thick photoresist layer. After photoresist and aluminum stripping, the silicon-based spring-mass structure was released and free to move.
10. Dicing-free technology was used to singulate each individual die from the wafer.

The ***upper glass cover plate*** of the proposed accelerometer was fabricated based on glass wafer.

1. Firstly, the metal features of Cr /Ni /Au were fabricated by evaporation and lift-off technologies. Then, an aluminum layer was deposited and patterned to perform a hard mask for the following tin electroplating.

2. A tin electroplating process at room temperature for 10 min was conducted to form the spacing and packaging features with a thickness of 15 µm. Then, the photoresist and aluminum layers were stripped. The glass wafer was then diced into individual dies.

The accelerometer chip is in sandwich structure. The silicon-based spring-mass layer and the glass-based upper cover plate were flip-chip packaged. The MEMS accelerometer chip is shown in Figure 8. The electrical input/output pads were wire-bonded by gold wires on a customized chip carrier.

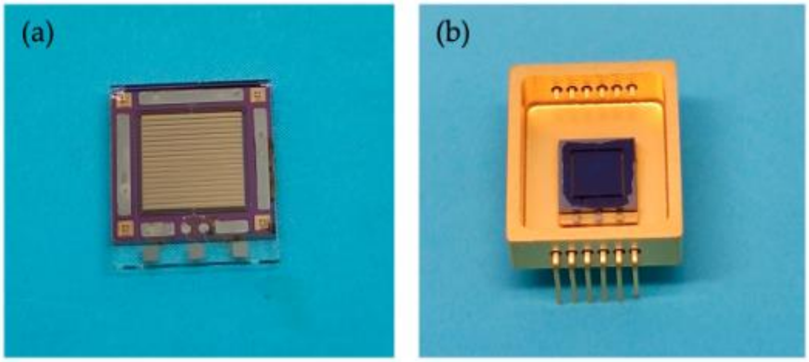


Figure 8. Diagrams of the accelerometer bare die and wire-bonding with the chip carrier: (**a**) the bare die of the MEMS accelerometer; (b) the customized chip carrier

2. PIEZORESISTIVE ACCELEROMETER

The developed sensor design contains a silicon beam with four integrated piezoresistors. Figure 1 shows a sketch of the top view of the sensor design.

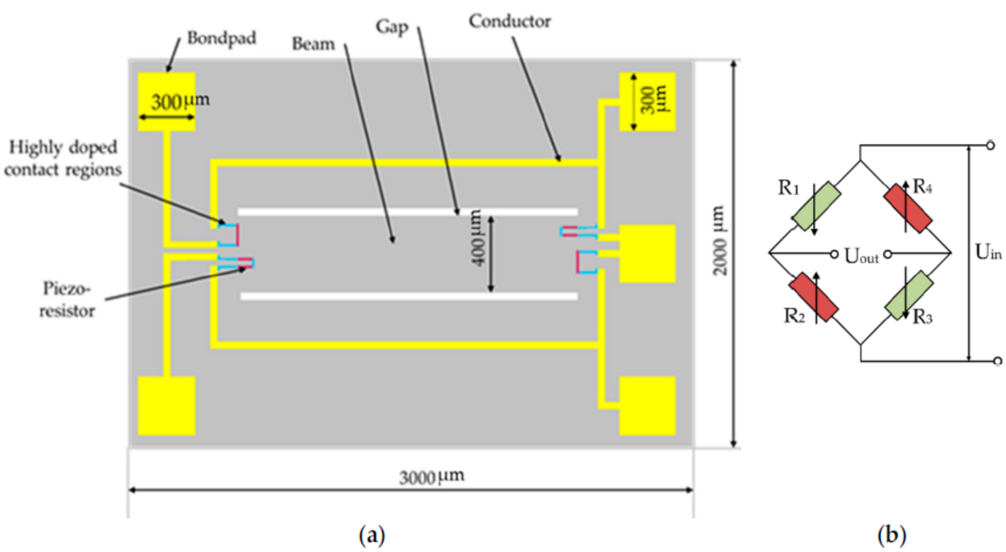


Figure 1. (**a**) Sketch of top view of sensor design, featuring one double-clamped beam carrying one transversal and one longitudinal piezoresistor on each end of the beam; (**b**) the Wheatstone bridge for equivalent circuit.

Piezoresistors and conductors are connected to form an open full Wheatstone bridge. It contains one double-clamped beam and carries one transversal and one longitudinal piezoresistor on each end of the beam. Highly doped contact regions are employed to connect the piezoresistors to conductors. According to Equation (1), a change of mechanical strain on the Wheatstone bridge is transformed into a change of output voltage of the piezoresistive acceleration sensor.

$$\Delta U = U_0 \cdot \varepsilon \cdot k \quad (1)$$

where ΔU represents the change of the output voltage and

U_0 the supply voltage of the Wheatstone bridge.

The gauge factor of silicon depends on the dopant concentration. Piezoresistors with a high gauge factor are more sensitive to changes of temperature, i.e., they have a higher temperature coefficient of resistance (TCR). The high influence of temperature on such piezoresistors is accepted to obtain a very high sensitivity without coming close to the yield strain of silicon.

$$\varepsilon = \frac{\rho \cdot f \cdot g}{2 \cdot E \cdot t} \cdot l^2 \quad (2)$$

The mechanical strain can be calculated with Equation (2), which is based on the beam theory for a double-clamped beam. Where the density ρ and Young's modulus E are fixed material parameters, and load f and gravity g are determined by external factors, only the geometrical parameters of beam thickness t and of beam length l can be modified to increase the strain.

While the sensitivity of the sensor is increased by increasing the beam length, its resonance frequency decreases (stability). Sensor design is therefore always a compromise between high sensitivity and high resonance frequency. Another parameter that should be considered is the beam width, because all four of the piezoresistors should be placed on the beam ends to form a full Wheatstone bridge configuration within the areas of high strain on the beam ends.

Fabrication Flow of piezoresistive accelerometer

The first processing step aimed at etching the alignment marks into the device layer of the wafers (see Figure4a). For this purpose, a standard photolithographic process flow composed of photoresist spin coating, prebake, exposure, development, and postbake was implemented.

The second step to implant the contact region and the piezoresistors. Before the implantation, a layer of thick silicon oxide grown in a furnace at 1000 °C (stray oxide). Then the implantation of contact regions and piezoresistors was accomplished with the standard photolithographic process. A dopant boron ions/cm^2 are used for the contact regions and piezoresistors, respectively.

After the implantation, the wafers is cleaned and prepared for the annealing and oxidation process. Annealing and oxidation took place simultaneously in a furnace at 1000 °C. At the beginning of the annealing, oxygen should added to the furnace gas to grow a layer of insulating silicon oxide. After the annealing and oxidation, a silicon nitride layer was deposited through a low-pressure chemical vapor deposition (CVD) process.

The next step was to establish electrical contact between the metallization layer and the contact regions. In order to form conductors and bond pads, the standard photolithographic process and dry etching process were employed to open the contact areas.

As demonstrated in Fig.4c, a thin AlSiCu layer is then sputtered onto the surface and into the contact holes of the wafer. After structuring the AlSiCu layer by chemical wet etching and removing the photoresist, the metal layer was annealed in a forming gas atmosphere at 450 °C to establish ohmic contact between the metallization layer and the implanted contact regions.

To realize the mechanical sensor structure, the process started by coating the back side of the wafer with a thick photoresist layer (see Figure4d). This layer served as an etch mask for deep silicon etching, and therefore it is typically spun at a low rotational speed to obtain a thickness of over 4 µm. The photoresist edge bead is removed with acetone on a spin coater after the prebake to ensure good wafer clamping during the deep silicon etching.

After exposure, development, and postbake, the back side photoresist mask featured openings for the back side cavities. Before deep silicon etching was conducted, the passivation and insulation layers needed to be removed locally. Removal of the silicon nitride was conducted by dry etching, and wet etching was used to remove the silicon oxide. The silicon oxide insulation was etched within a few minutes. After the wafer was rinsed and dried, the protective foil was removed manually. Alternatively, protection of the aluminum was possible by coating the wafer top side with photoresist. The wafer was etched from its back side with the Bosch process until the BOX layer was reached and exposed to the entire cavity bottom, as seen in Figure4e

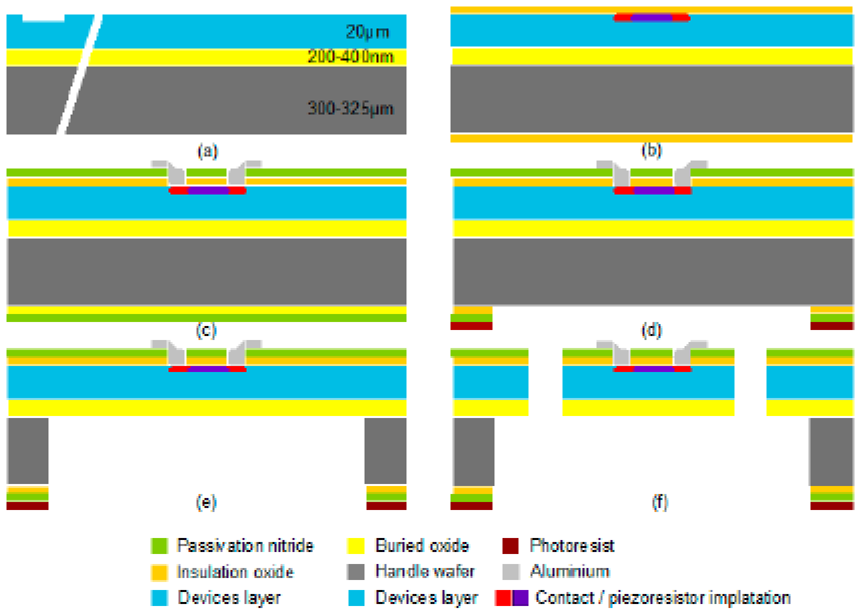
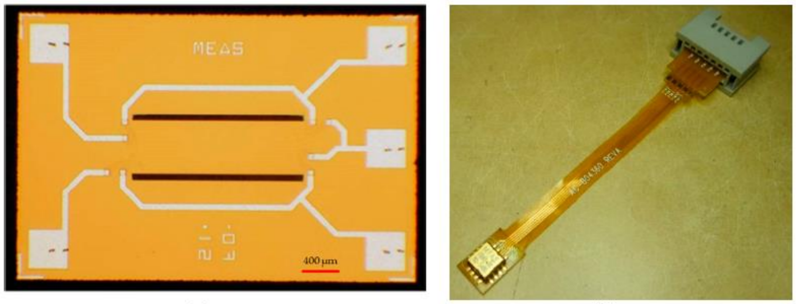


Figure 4. Fabrication flow of acceleration sensor. (**a**) Cross-section of SOI wafer after dry etching of the alignment marks; (**b**) after contact and piezoresistor implantation and photoresist removal; (**c**) after structuring of the metallization layer. (**d**) After structuring of the backside nitride and oxide layer; (**e**) after etching of the handling wafer from the back side; (**f**) after release of the beam structure by wet etching.

The photoresist mask was removed subsequently. To form a double-clamped beam, two trenches per chip needed to be etched through the device layer, where deep silicon etching was also applied (see Fig.4f). Moreover, a standard photolithographic process was utilized, and after the postbake, the nitride and the oxide layers were removed locally by dry etching. After the release of the beam structure and the removal of the photoresist, the chips were finished and tested.



(a) (b)

Figure 5. (**a**) A realized MEMS sensor element. On top, the silicon beam with integrated piezoresistors, the leads, and the bond pads can be clearly seen; (**b**) packaged high-g-sensor system.

MEMS for space applications

Promising space application

• Inertial sensor

– accelerometer, gyroscope

• High frequency (RF)applications

• Optical sensor, mirror

• Etc..

1. RF(Radio Frequency) applications

• High stable oscillator

– For High precision measurement of distance and high quality communication

– Ultra stable MEMS oscillator can be alternative to the quartz type USO (Ultra-Stable Oscillator)

• RF switch

– Low loss, Low impedance

– For phase shifter, TX-RX switch

2. MEMS Oscillator

• Alternative quartz oscillator

• The structure does not depend on the crystal orientation

• Smaller than the quartz oscillator with the same performance.

• Suitable for mass production

Possibility of MEMS OSC for space application

• If MEMS USO is realized, it can be alternative quartz type USO.

– Deep space mission

– rover

• The vibrator is robust for radiation due to mechanical structure. However control circuit is not robust.

Reliability, stability and downsizing are required.

3. MEMS RF switch application

• TX-RX switching

• Phase shifter of phased array antenna

Features of MEMS RF switch

Disadvantages

• Slow switching speed (~1MHz)

• A few experiences

• Low reliability (recently, improved)

Advantages

• Low loss @ high frequency

• High ON-OFF contrast

• The performance does not depend on frequency

MEMS RF switch has more advantages at very high frequency (>10GHz) than others

Possibility of MEMS RF SW for space applications

• Smaller phase-shifter

• Robust for vibration and shock due to small

size

• High robustness for radiation

RF switch is promising device for the space application

4. Inertia sensor

Requirements

• High stability

• High sensitivity

•Attitude control of the satellites and rover

•ION thruster acceleration measurement

•Moonquake observation

•Gravity measurement of small planets

5. MEMS accelerometer

• It can use attitude measurement of the rovers and the small explorers

• Poor performance for scientific observation and precise attitude control for the satellite

6. Gyroscope

• Poor performance for scientific observation and precise attitude control for the satellite

– High Stability < 0.1 deg/h

– High sensitivity <0.1 deg/h

• It can use attitude measurement of the rovers and the small explorers

MEMS applications

Technology/ Sensors	**Aerospace Defense and Automotive Applications**
Inertial sensors	Missile guidance, navigation, laser range finder, Airbags, vehicle dynamic control, navigation systems, active suspension, roll
RF MEMS	Switches and tunable capacitors for radar and communications
Pressure sensors	Flight control systems, cabin pressure, hydraulic systems Manifold Air Pressure, Tire Pressure Management Systems
Flow sensors	Air intake of engine, air quality in cabin
IR sensors	Fingerprint sensors for authentication, Security monitoring

Why MEMS for spacecraft?—

- Short development time
- Diversification of risks
- Low cost

Smaller spacecrafts are desirable.

But the functions and the performance should be the same or better.

Small and power-saving parts that equip special functions and performance necessary for space mission are required.

Type	Spacecraft	purpose	Launch	Note
Acceleration sensor	MARS Polar Lander	Practical use	1999	
RF switch	PICOSAT	Experi-mental	2000	
Gyroscopic acceleration sensor	MEPSI	Experi-mental	2002	
RF switch	ARCADE (balloon)	Practical use	2006	35 km high
Vibration gyroscopic sensor	TacSat-2	Practical use	2006	Inertial compass combined with a star camera

DARPA: the Defense Advanced Research Projects Agency

Avionics

The Attitude Heading Reference System (AHRS) provides data for primary flight instruments, head-up displays, autopilots, and moving map navigation systems. MEMSIC's solid-state MEMS rate sensors, coupled with Kalman filter algorithms are designed to mitigate high drift rates, provide the basis for low-cost, high-performance AHRS for general aviation. The MEMSIC AHRS is ideal for incorporation into current and next generation glass cockpit systems, autopilots and standby instruments, and unmanned vehicles

Benefits:

- High Reliability: Inertial systems that provide attitude and heading measurement with static and dynamic accuracy superior to traditional spinning mass vertical and directional gyros.
- Standard Aircraft Digital Bus Support: A comprehensive Built-in-Test (BIT) architecture continuously monitors all sensors, internal electronics, power circuitry and system calibration during operation, and updates the system BIT status in every output message. Output data is provided via a standard ARINC429 data bus.
- No External Sensor Inputs Required: As a standalone system MEMSIC's AHRS functions as a truly independent device while still providing the user with optional external aiding inputs from Air Data or GPS.

Glass Cockpit Systems

MEMSIC has been a leader in MEMS based certified avionics systems for more than a decade, serving the certified and experimental glass panel markets. MEMSIC produced one of the first FAA certified AHRS systems (AHRS500) which has been installed in over 1,000 different aircraft since its introduction. MEMSIC has continued to be a leader in MEMS based AHRS systems with next generation AHRS510. We are proud to have been part of the FAA's Capstone program and to have been a key supplier for the one of the first VLJ's on the market.

MEMSIC's advanced calibration techniques coupled with our patented Kalman filter algorithm have allowed us to maintain maximum performance at an attractive price. Compared to most modern Ring Laser Gyros and Fiber Optic Gyro Systems, our MEMS based AHRS systems can provide similar performance at a fraction of the price. MEMSIC uses an FAA authorized production facility and has maintained an impressive track record of reliability and performance for all aviation products.

Unmanned Vehicles

Unmanned vehicles require highly reliable and repeatable inertial sensors and systems that are capable of effective feedback for control and guidance. MEMSIC has developed a broad line of Fiber Optic Gyroscopes (FOG), Inertial Measurement Units (IMU's), GPS-Aided Vertical Gyros (VG), and GPS-Aided Attitude & Heading Reference Systems (AHRS) that are well tested and proven in demanding land, marine and airborne applications..

UNIT V

MEMS Applications: Polymer MEMS & Carbon Nano Tubes CNT, Wafer Bonding & Packaging of MEMS, Interface Electronics for MEMS, Introduction to BioMEMS and Micro Fluidics, Introduction to Bio Nano Technology, Bio Sensors, Fluidics, MEMS for Biomedical Applications (Bio-MEMS)

I. Polymer Materials

Polymer materials are created by a long repeating series of smaller molecules (chains of smaller molecules).
The smaller molecules have a 'natural tendency' to link together with each other, when subjected to a 'driving force' to form long chains, that cross-link with other chains, again and again, to form a 'solid material'.

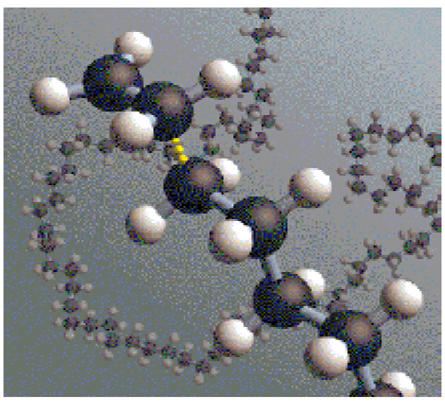


Image of polyethylene polymer chain
[Image from University of Florida]

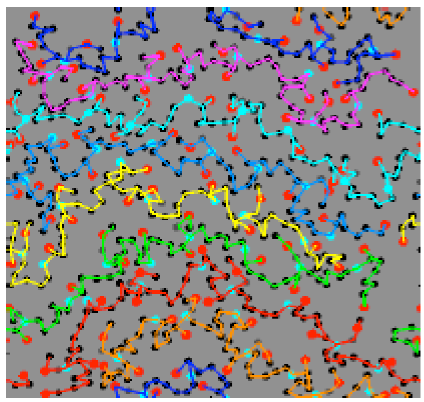


Image of 'cross-linked' polymer chains
[Center for Polymer Studies]

Characteristics:

- Low mechanical strength
- Low melting point
- Poor electric conductivity

Polymer Categories

Polymers can be categorized into three major classes:
1.Fibers
Natural Fibres -Hair, Cotton, Cellulose, Silk, etc...
Synthetic Fibres - Polyester, Polyamide Nylon, etc...
2.Plastics
Polyethylene, Polypropylene, Polyvinyl Chloride (PVC)
Polymethyl methacrylate (Acrylic), etc...
3.Elastomers
Rubber, etc...

Polymer Categories

Polymers can also be categorized in terms of temperature response:

1. Thermal Plastic Polymers (Thermalplasts)
   -Can be re-melted and re-shaped repeatedly (e.g. acrylic, and PVC)
2. Thermal Setting Polymers (Thermalsets)
   -Take on a permanent shape once polymerized/processed (e.g. epoxy, and phenolic)

Polymers in Microelectronics

The use of Polymers in microelectronics and MEMS is a growing area.

In microelectronics, polymer technology is being developed for applications such as:

-Plastic transistors,
-Organic thin-film displays
-Plastic Memory

The motivation for the use of plastics is:

-Unique properties: Flexibility, Bio-compatibility, etc...
-Lower cost of materials
-Lower cost of fabrication: Injection molding, screen printing of layers, thermal embossing, etc....

Polymers in MEMS

The advantages that apply to microelectronics, apply similarly to MEMS. Especially the unique aspects of plastic material properties.

Typical Polymers that are used in MEMS include:

- Polyimide
- SU-8
- Liquid Crystal Polymer
- PDMS (poly dimethylsioxane)
- PMMA (poly methyl methacrylate, 'acrylic')
- Parylene
- Teflon

Polymers for MEMS and Microsystems

Applications:

1. Photoresist polymers: used as masks for creating desired patterns on substrates by photolithography .
2. Photoresist polymers: used to produce the prime mold in the LIGA process.
3. Conductive polymers: used as organic substrates.
4. Ferroelectric polymers (which behave like piezoelectric crystals): used as a source of actuation in microdevices such as those for micropumping.
5. Thin Langmuir-Blodgett (LB) film: used for miltilayer microstructures

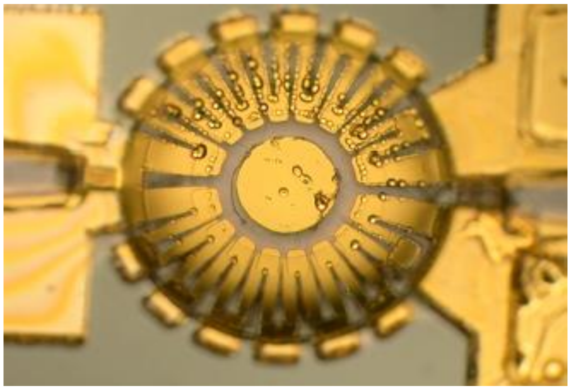
6. Used as a coating substances for capillary tubes to facilitate electro-osmotic flow in microfluidics
7. Thin polymer films: used as electric insulators in microdevices and asa dielectric substances in microcapacitors.
8. Used for electromagnetic interference (EMI) and radio-frequency interference (RFI) shielding in Microsystems.
9. Used for the encapsulation of microsensors and packaging of other microsystems.

Parylene Polymer Pressure Sensor

Shown below is a pressure sensor made with a polymer surface micromachining process.

-Membrane displacement up to 30 um

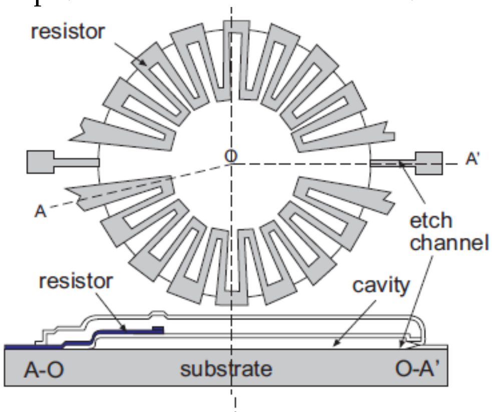
-Zigzag metal film layer serves as resistor



Polymer Pressure Sensor

Parylene Polymer Pressure Sensor

Consider the Schematic of the Top View and Cross-Sectional View:



Polymer Pressure Sensor,

II. Carbon Nanotubes

With an atomic number of 6, Carbon is the 4th most abundant element in the Universe by mass after (Hydrogen Helium and Oxygen). Carbon Nanotubes, long, thin cylinders of carbon, were discovered in 1991 by Sumio Iijima.

Nanotubes have a very broad range of electronic, thermal, and structural properties that change depending on the different kinds of nanotube (defined by its diameter, length, and chirality, or twist). To make things more interesting, besides having a single cylindrical wall (SWNTs), Nanotubes can have multiple walls (MWNTs)--cylinders inside the other cylinders.

Application areas

- Field Emitters/Emission:
- Conductive or reinforced plastics
- Molecular electronics: CNT based non volatile RAM
- CNT based transistors
- Energy Storage
- CNT based fibers and fabrics
- CNT based ceramics
- Biomedical applications etc ...

Properties of Carbon Nanotubes

1. Extraordinary electrical conductivity, heat conductivity, and mechanical properties.
2. They are probably the best electron field-emitter known, largely due to their high length-to-diameter ratios
3. As pure carbon polymers, they can be manipulated using the well-known and the tremendously rich chemistry of that element.

Carbon nanotubes have a range of electric, thermal, and structural properties that can change based on the physical design of the nanotube

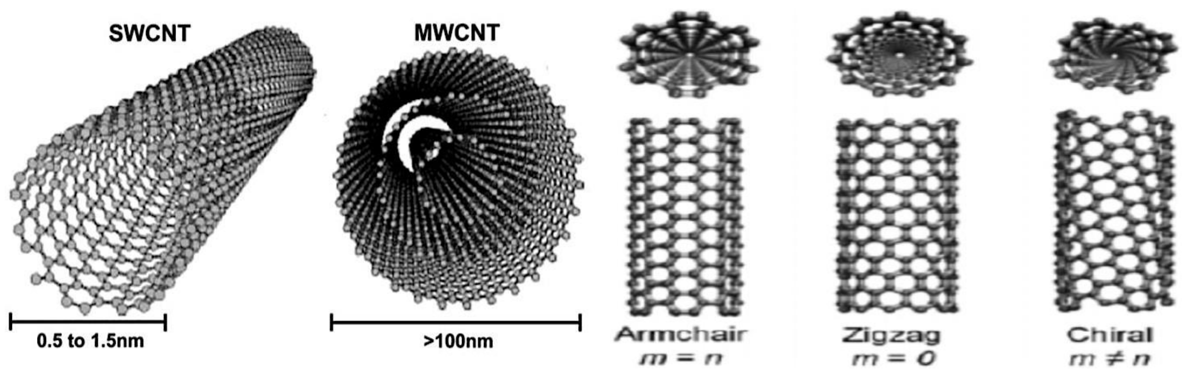
1. Single-walled carbon nanotube structure

Single-walled carbon nanotubes can be formed in three different designs: Armchair, Chiral, and Zigzag. The design depends on the way the graphene is wrapped into a cylinder. For example, imagine rolling a sheet of paper from its corner, which can be considered one design, and a different design can be formed by rolling the paper from its edge. A single-walled nanotube's structure is represented by a pair of indices (n,m) called the chiral vector. The chiral vector is defined in the image below.

The structural design has a direct effect on the nanotube's electrical properties. When n − m is a multiple of 3, then the nanotube is described as "metallic" (highly conducting), otherwise the nanotube is a semiconductor. The Armchair design is always metallic while other designs can make the nanotube a semiconductor.

2. Multi-walled carbon nanotube structure

There are two structural models of multi-walled nanotubes. In the Russian Doll model, a carbon nanotube contains another nanotube inside it (the inner nanotube has a smaller diameter than the outer nanotube). In the Parchment model, a single graphene sheet is rolled around itself multiple times, resembling a rolled up scroll of paper. Multi-walled carbon nanotubes have similar properties to single-walled nanotubes, yet the outer walls on multi-walled nanotubes can protect the inner carbon nanotubes from chemical interactions with outside materials. Multi-walled nanotubes also have a higher tensile strength than single-walled nanotubes



Strength

Carbon nanotubes have a higher tensile strength than steel and Kevlar. Their strength comes from the sp^2 bonds between the individual carbon atoms. This bond is even stronger than the sp^3 bond found in diamond. Carbon nanotubes are not only strong, they are also elastic. You can press on the tip of a nanotube and cause it to bend without damaging to the nanotube, and the nanotube will return to its original shape when the force is removed. A nanotube's elasticity does have a limit, and under very strong forces, it is possible to permanently deform to shape of a nanotube. A nanotube's strength can be weakened by defects in the structure of the nanotube. The tensile strength of a nanotube depends on the strength of the weakest segment in the tube similar to the way the strength of a cahin depends on the weakest link in the chain.

Electrical properties

As mentioned previously, the structure of a carbon nanotube determines how conductive the nanotube is. When the structure of atoms in a carbon nanotube minimizes the collisions between conduction electrons and atoms, a carbon nanotube is highly conductive. The strong bonds between carbon atoms also allow carbon nanotubes to withstand higher electric currents than copper. Electron transport occurs only along the axis of the tube. Single walled nanotubes can route electrical signals at speeds up to 10 GHz when used as interconnects on semi-conducting devices. Nanotubes also have a constant resistively.

Thermal Properties The strength of the atomic bonds in carbon nanotubes allows them to withstand high temperatures. Because of this, carbon nanotubes have been shown to be very good thermal conductors. When compared to copper wires, which are commonly used as thermal conductors, the carbon nanotubes can transmit over 15 times the amount of watts per meter per Kelvin. The thermal conductivity of carbon nanotubes is dependent on the temperature of the tubes and the outside environment.

Fabrication

1. Arc Discharge Method A chamber containing a graphite cathode and anode contains evaportated carbon molecules in a buffer gas such as helium. The chamber also contains some amount of metal catalyst particles (such as cobalt, nickel, and/or iron). DC current is passed through the chamber while the chamber is also pressurized and heated to ~4000K. In the course of this procedure, about half of the evaporated carbon solidifies on the cathode tip into a "cylindrical hard deposit." The remaining carbon condenses into "chamber soot" around the walls of the chamber and "cathode soot" on the cathode. The cathode soot and chamber soot yield either single-walled or multi-walled carbon nanotubes. The cylindrical hard deposit doesn't yield anything particularly interesting. The choice of buffer gas, the pressure of the chamber, and the metallic catalyst added to the chamber. Apparently the nanotubes grow from the surfaces of the metallic catalyst particles. These choices determine the shape and whether they are single- or multi-walled. The advantage of this method is that it produces a large quantity of nanotubes. But the main disadvantage is that there is relatively little control over the alignment (i.e. chirality) of the produced nanotubes, which is critical to their characterization and role. Furthermore, due to the metallic catalyst included in the reaction, the products need to be purified afterwards. Methods such as oxidation, centrifugation, filtration, and acid treatment have been used.

2. Laser Ablation Method

A quartz tube containing a block of graphite is heated in a furnace. A flow of argon gas is maintained throughout the reaction. A laser is used to vaporize the graphite within the quartz. The carbon vaporizes, is carried away by the argon, and condenses downstream on the cooler walls of the quartz.

This condensation is SWNT and metallic particles. Thereafter, purification methods are applied to this mixture. The key to the proper formation of the condensed nanotubes is that the location where the carbon atoms begin to condense should be set up as a curved sheet of graphene with a catalyst metallic atom nearby. As carbon atoms begin to attach and form rings, the metallic atom, if it has the proper electonegativity properties, will preserve the open edge of the tube and prevent it from drawing to a close. The authors of the paper describe this phenomenon as the "scooter" effect, because the metallic atom "scoots" around the open edge, preventing it from closing.

III. Bonding, Packaging

Bonding Why?
– Create channels or cavities
– Create isolation layers
(SOI wafers)
– Reduce complexity on each chip
– Packaging

Methods
1. Anodic bonding
2. Silicon fusion bonding
3. Photopolymers
4. Eutectic bonding
5. Others
    i. Press
    ii. Thermocompression metallic
    iii. Ultrasonic welding
    iv. Seam welding
    v. Laser welding
    vi. Low-temp glass bonding.

1.Anodic Bonding
- Also called electrostatic bonding
- Bonds glass to silicon
- Used to reduce temp to reasonable levels
- Performed at about 400 C with about 1.2 kV
- Positive ions in glass drift far away from silicon causing high field at interface
- Pull silicon and glass close together
- Silicon positive, glass negative
- Use glass with similar thermal expansion coefficient
- Cleanliness critical to prevent voids
- Thin metal lines can pass through bond
- Using deposited glass (thin layers) reduce voltage significantly
- Works with e-beamed, sputtered, and spin-on glass

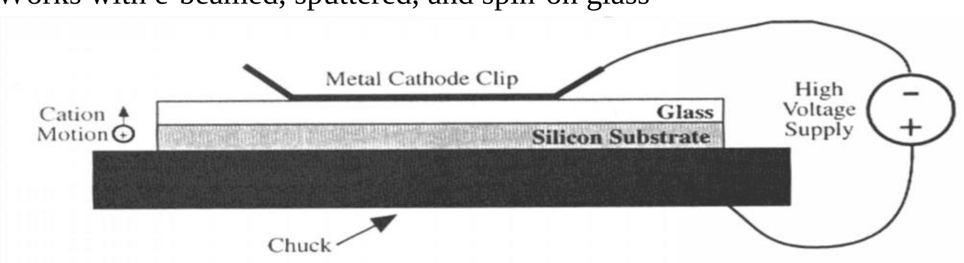
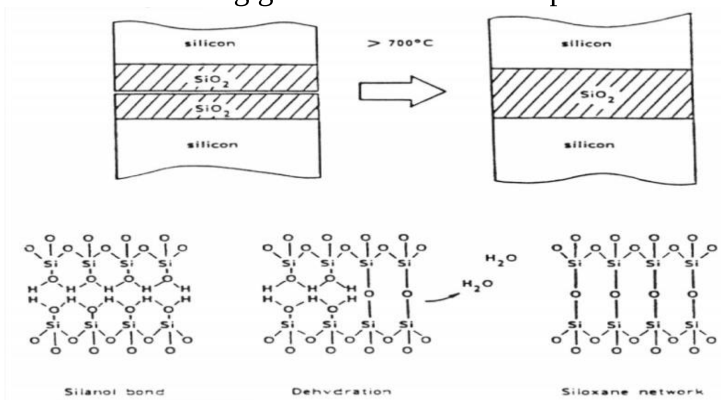


Illustration of a typical anodic bonding apparatus.

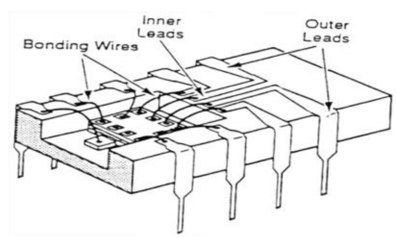
2. **Silicon Fusion Bonding**
   - Silicon to silicon bond, oxides also work
   - High physical strength
   - Require hydroxyl groups on surface
   - 300 to 800 C required for bond with higher anneals temps sometimes required
   - Use of low-melting glass allows lower temp bond



What Does "Packaging" Mean

- Connections from chip to outside world
- Packaging serves two main functions:
  – Protection of device from working environment
  – Protection of environment from device material and operation
- Protection from environment
  – Electrical isolation or passivation from electrolytes and moisture
  – Mechanical protection to ensure structural integrity
  – Optical and thermal protection to prevent undesired effects on performance
  – Chemical isolation from harsh chemical environment
- Protection from device
  – Material selection to eliminate or reduce host response
  – Device operation to avoid toxic products
  – Device isulation

Basic Package



Packaging

- One of least explored MEMS components
- No unique and generally applicable packaging method for MEMS
- Each device works in a special environment
- Each device has unique operational specs

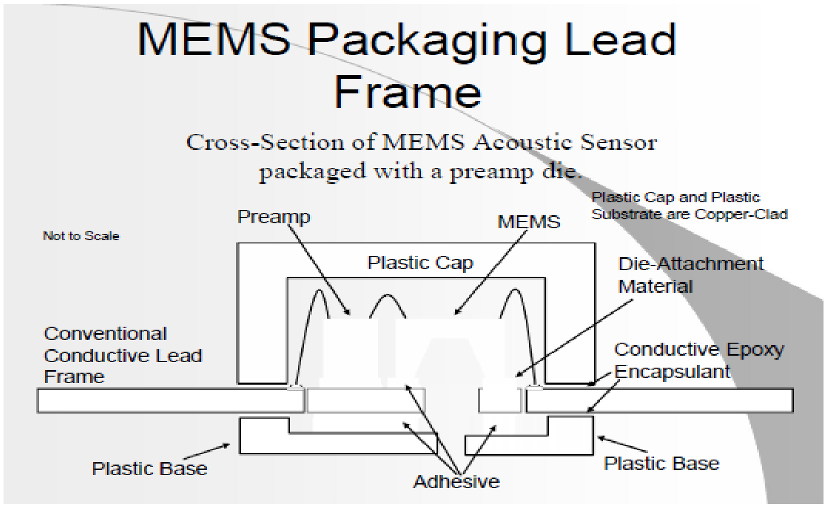
- Electrical protection
  - – Electrostatic shielding
  - – Moisture penetration (major failure mechanism for biosensors)
  - – Interface adhesion
  - – Interface stress
  - – Corrosion of substrate materials
- Mechanical protection
  - – Rigidity; must be mechanically stable throughout device life
  - – Weight, size, and shape for convenience in handling and operation

MEMS Packaging

1. Modular packaging needed to span large application areas
2. Just as in the IC and Discrete Electronics world, packaging for MEMS should be standardized for the sake of price and availability wherever possible.
3. MEMS will likely follow IC and discrete electronic package forms and types.
4. As MEMS become more and more mainstream, semiconductor manufacturers will likely use existing packages and adapt MEMS manufacturing to these well-established commercial form factors wherever the application of MEMS may be accommodated by IC packages which may open an 'Undiscovered Country'of applications.
5. MEMS will likely be electronically coupled with other devices in MCMs (Multi-Chip Module).
6. For MEMS to provide optimal functional sensitivity and bandwidth, they may be mounted in MCM–D-C-Ls (Multi-Chip Module, Discrete, Capsule, Local).
7. This matching of multiple technologies in a single package is paramount to MEMS technology applications.
8. If a single package houses multiple MEMS, Discretes, and ICs, there stems the dilemma of interfacing the MEMS with the environment (gas, fluids, light, RF, inertia, sound, vibration, biomass, etc.) and still protect the Electronics from the environment.
9. MEMS packaging may vary widely by special function as opposed to electronic packaging for board mounting.
10. Even though MEMS have been a laboratory curiosity for years, they are only now becoming mainstream discrete-packaged products.

11. MEMS technology lends itself to Flip-Chip & Un-Flip-Chip, back-etched thinned silicon with through-hole vias, and Direct- Chip-Attach application.
12. Whether attaching ICs to a MEMS substrate, attaching MEMS to an IC, or mounting MEMS, ICs and Discretes in an MCM, the possibilities of converging technologies for integrating MEMS and Electronics deserves great attention

MEMS Packaging LeadFrame



Packaging Materials

1. Silicone

– Excellent for short-term encapsulation
– Medical-grade silicone is biocompatible
– Easy to apply and sterilize
– Excellent adhesion characteristics; flexible
– Swells in most aqueous solutions
– Air bubble entrapment is a problem

2. Polyurethane

– Good humidity and chemical resistance
– High dielectric strength
– Good mechanical properties, flexible
– Attacked, swollen, or dissolved by many solvents

3.Epoxy

– Good mechanical properties
– Poor ion and moisture barriers
– Shrink when cured, changing mechanical, electrical, thermal properties

4. Fluorocarbon

– Most well known (polytetrafluoroethylene)
– Desirable electrical characteristics

– Poor adhesion and mechanical characteristics

5.Acrylic

– Good electrical properties
– Hard, rigid, and tough
– Little shrinkage during cure
– Poor solvent resistance

6. Parylene

– Can use CVD to deposit thin, uniform pinhole-free films
– Good electrical properties
– Low permeability to moisture and gases
– Poor adhesion

7. Polyimide

– Good mechanical and electrical properties
– Stable over wide range of temperatures
– Commonly used in microelectronics

8. Glass

– Thermal expansion coefficients must be matched
– High strength, especially in compression
– Good electrical properties
– Localized stress concentrations due to surface imperfections

9. Ceramic

– Chemically inert
– Brittle, low fracture toughness
– Good electrical properties
– Excellent moisture barrier
– Require high temperature for sealing
– Typically biocompatible

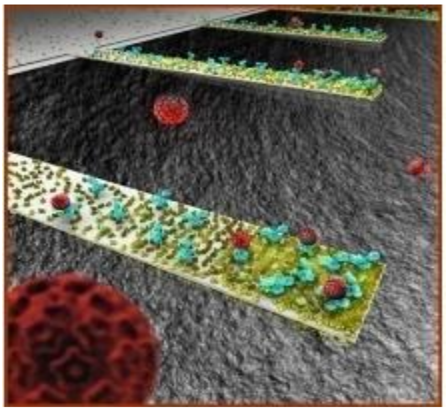
10. Metal

– Light weight
– Some metals (e.g., titanium) have excellent corrosion resistance
– Good mechanical properties

IV. MEMS vs. BioMEMS

MEMS are microelectromechanical systems that use micro-sized components such as sensors, transducers, actuators, and electronic devices. Many of the MEMS used in the medical field perform the same tasks as those used in other applications such as environmental, aerospace and consumer products. For example, the MEMS inertial sensor found in airbag deployment mechanisms is also found in a pacemaker. In a pacemaker the MEMS inertial sensor (specifically

an accelerometer) is used to sense a patient's activity. When the accelerometer senses acceleration in the patient's activity, its output causes the control circuitry of the MEMS to more quickly stimulate one or more electrodes connected to the heart muscle. This electrode stimulation causes the heart to beat faster. As the patient's activity slows, the MEMS in turn, slows the heart rate. Another category of MEMS used in the medical field incorporates biological molecules as an integral part of the device. For example, a micro cantilever transducer(graphic right)may be coated with antibodies (green spheres)that capture a virus (red sphere)in a blood sample while ignoring the other components in the sample.
Both types of MEMS are referred to as bioMEMS. BioMEMS isa general term for any MEMS used in biological applications.



The following is a brief overview of bioMEMS and select applications within the medical field.

BioMEMS Glucose Sensors with Microtransducer

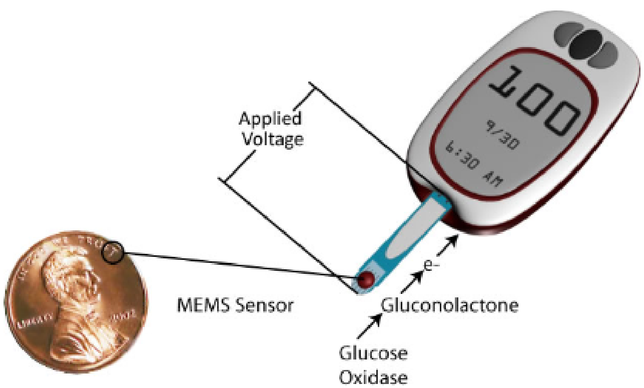
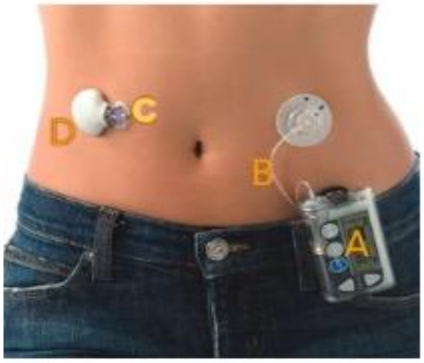


Diagram of a blood glucose monitor utilizing a biochemical transducer located at the very tip of the device. This transducer is about the size of one of the letters on the coin shown.

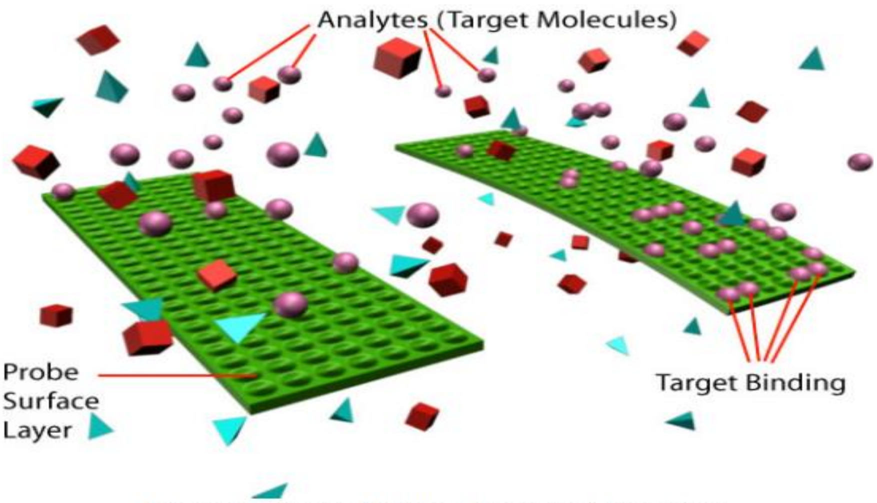
This blood glucose monitor (shown in the graphic) works on the basis of a glucose oxidase reaction with blood plasma. A transducer is located at the end of the sensor strip. The transducer is about as big as the "T" in the word "TRUST" on a penny (1mm long by 200 μm wide. Newer glucose sensors use even smaller transducers.) A drop of blood is placed on top of the transducer. The transducer has a thin film coating which starts the glucose oxidase reaction with the glucose in the blood plasma. Part of the output of the reaction is Gluconolactone and an electron. The electronic component of the sensor senses the released electrons as current and uses that as a measurement of the amount of glucose in the blood sample. Micro technology has revolutionized the area of glucose monitoring by allowing for the production of even smaller transducers and biocompatible transducers that can be implanted allowing for 24/7 monitoring. Following is an example of such a device.

BioMEMS Continuous Glucose Monitoring with Glucose Sensor and Micropump

The figure below shows a continuous glucose monitoring and drug delivery system. The glucose is continuously monitored using an in vivo (implanted) chemical transducer (C). A micropump in (A) delivers insulin via a cannula (B) on an as-needed basis. D is the transmitter that relays the information from the glucose sensor (C) to the computer (A).1These devices have greatly advanced over the past 10 years leading to a better quality of life for the patients.



Microcantilever Sensors



Microcantilever bending due to surface stress caused by the attachment of analytes to sensor's surface.

The microcantilever biosensor is an example of bioMEMS that incorporates biological molecules as part of its function. In a biosensor, the biological molecules are used to functionalize the sensing capability of the MEMS device. For example, microcantilevers are constructed with a specific probe surface layer used to detect a variety of analytes such as DNA, proteins, and antigens (see above graphic). In the detection of analytes such as a specific antigen, the antigen attaches to the probe molecules on the surface of the microcantilever. The collection of the specific analyte on the cantilever surface induces surface stress causing the cantilever to bend. The amount of bend is measured either electronically, using a piezoresistive film in the cantilever, or optically, using a laser reflected off the cantilever surface and measuring the change in the angle of reflection. This type of microsensor is referred to as a surface stress-based chemical sensor or biosensor.

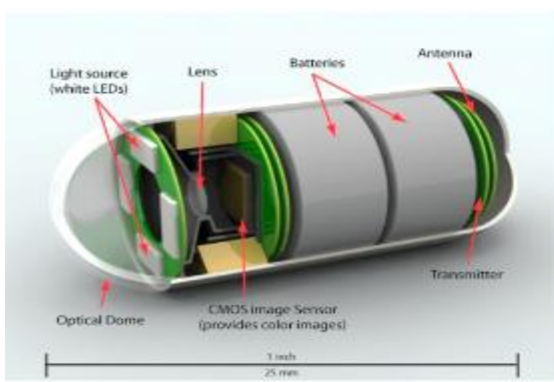
Applications of bioMEMS

Many areas are benefitting from the use of microtechnology to improve health care and serve to enhance the understanding of biological systems. Areas that would benefit from the enhancement of current methods include the following:

•Sample preparation
•Screening
•Diagnostics
•Monitoring
•Drug delivery
•Individualized treatment
•Less invasive surgical procedures

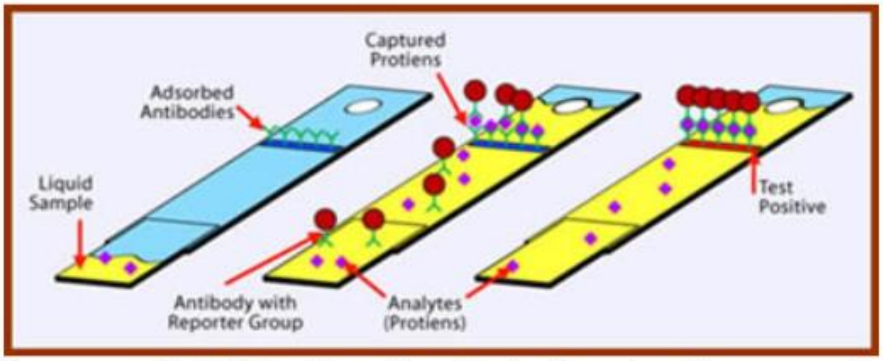
Shrinking Technologies

For the diabetic, a small monitoring and insulin delivery device greatly contributes to the ease of disease regulation, leading to a better quality of life. Persons undergoing somewhat invasive tests such colonoscopies or endoscopies appreciate a smaller detection device(see photo). Portability of small test devices makes it possible for testing in remote areas where clinical labs are not available, or onsite such as at an accident scene. From a money-making point of view, the development of disposable devices could also be desirable.



This "pill" that is used to look at the entire gastrointestinal(GI)tract, including the small intestine. The patient swallows the pill and as the pill travels through the GI track, it transmits high resolution video to an external receiver. The pill is later discharged naturally.

BioMEMS for Detection

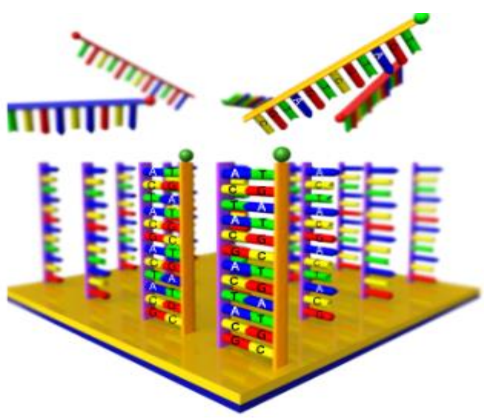


Home Pregnancy Test (Detection of protein in the urine of a pregnant woman)

BioMEMS for detection applications include the following:

- Sensors for chemical detection(e.g., toxins, ions, proteins)
- Bacterial, fungal, and viral detection
- Antibody detection
- Disease detection
- Examination devices (such as endoscopes and catheters)

BioMEMS for Analysis



DNA Microarrays identify complementary DNA through the hybridization process. This graphic illustrates what happens in a biochip or DNA microarray: The target DNA single strand (yellow rail) attaches to a complementary capture DNA probe on the substrate. (Notice that the matching base pairs in the sequence.)

BioMEMS that analyze specific analytes in a sample include the following:

- Bacterial identification and antibiotic susceptibility
- Clinical laboratory medicine (clinical chemistry)testing and analysis
- DNA analysis for forensics identification(see above graphic)
- DNA analysis for specific genes, gene mutations, and gene activity

BioMEMS for Monitoring

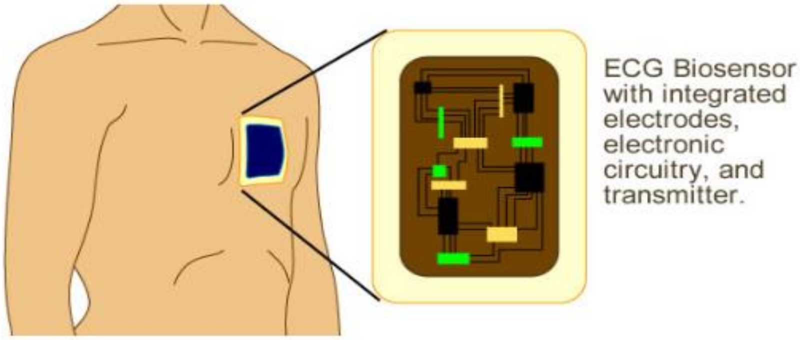


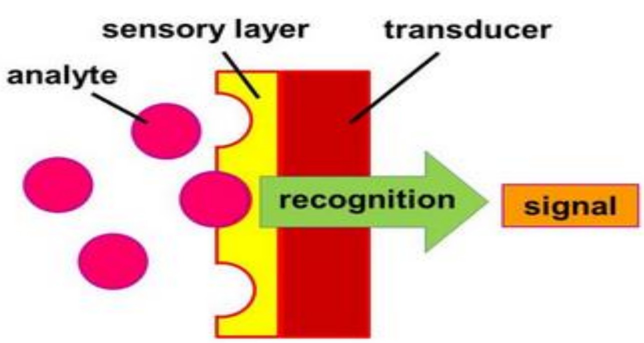
Illustration of a MEMS electrocardiogram (ECG) patch monitor. Such a device is being developed by Belgium's IMEC that " measures up to 3 lead ECG signals, tissue-contact impedance and includes a 3D-accelerometer for physical activity monitoring".[10]

Following are bioMEMS used for continuous as well as specific monitoring applications.

- Blood glucose level for diabetics
- Antibody level monitoring for HIV patients
- Blood cell concentrations for patients undergoingchemotherapy
- Continuous monitoring of high-risk patients *(The graphic illustrates an electrocardiogram(ECG) monitor which "integrates electrodes, a biochip sensor, an accelerometer, a microcontroller unit, and a transmitterin a package the size of a very thin wristwatch. Algorithms running on the patch's processor monitor patients for arrhythmias day and night. The patch can run on a small 200mAh Li-Po batteryfor up to a month, depending upon what is being measured and transmitted.10)*

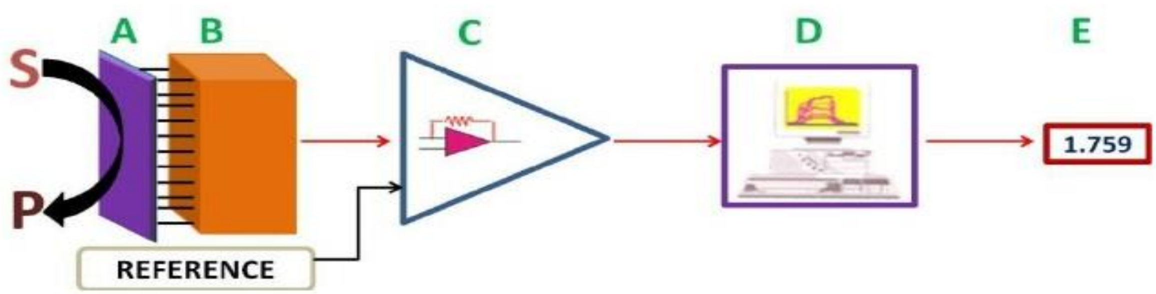
V. What is a Biosensor?

Biosensors can be defined as analytical devices which include a combination of biological detecting elements like sensor system and a transducer. When we compare with any other presently existing diagnostic device, these sensors are advanced in the conditions of selectivity as well as sensitivity. The applications of these Biosensors mainly include checking ecological pollution control, in agriculture field as well as food industries. The main features of biosensors are stability, cost, sensitivity, and reproducibility.



Components of a Biosensor

The **block diagram** of the biosensor includes three segments namely, sensor, transducer, and associated electrons. In the first segment, the sensor is a responsive biological part, the second segment is the detector part that changes the resulting signal from the contact of the analyte and for the results it displays in an accessible way. The final section comprises of an amplifier which is known as signal conditioning circuit, a display unit as well as the processor.



Working Principle of Biosensors

Usually, a specific enzyme or preferred biological material is deactivated by some of the usual methods, and the deactivated biological material is in near contact to the transducer. The analyte connects to the biological object to shape a clear analyte which in turn gives the electronic reaction that can be calculated. In some examples, the analyte is changed to a device which may be connected to the discharge of gas, heat, electron ions or hydrogen ions. In this, the transducer can alter the device linked converts into electrical signals which can be changed and calculated.

The electrical signal of the transducer is frequently low and overlay upon a fairly high baseline. Generally, the signal processing includes deducting a position baseline signal, obtained from a related transducer without any biocatalyst covering.

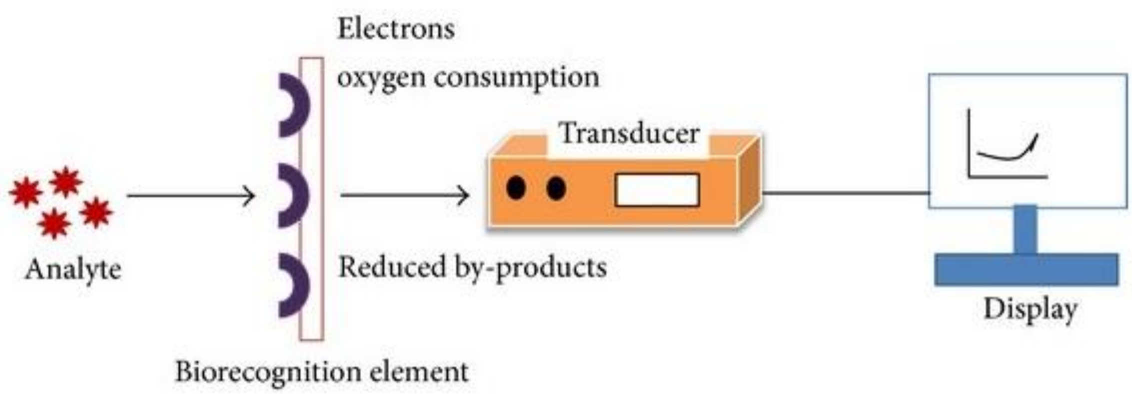
The comparatively slow character of the biosensor reaction significantly eases the electrical noise filtration issue. In this stage, the direct output will be an analog signal however it is altered into digital form and accepted to a microprocessor phase where the information is progressed, influenced to preferred units and o/p to a data store.

Types of Biosensors

The different types of biosensors are classified based on the sensor device as well as the biological material that is discussed below.

1. Electrochemical Biosensor

Generally, the electrochemical biosensor is based on the reaction of enzymatic catalysis that consumes or generates electrons. Such types of enzymes are named as Redox Enzymes. The substrate of this biosensor generally includes three electrodes such as a counter, reference, and working type.



The object analyte is engaged in the response that happens on the surface of an active electrode, and this reaction may source also electron-transfer across the dual layer potential. The current can be calculated at a set potential.

Electrochemical biosensors are classified into four types

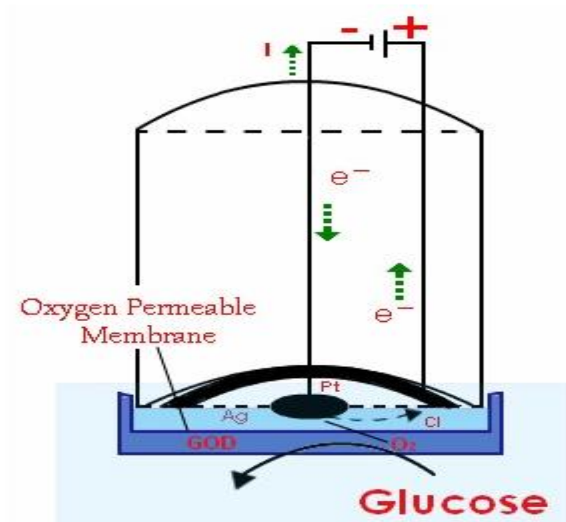
- Amperometric Biosensors
- Potentiometric Biosensors
- Impedimetric Biosensors
- Voltammetric Biosensors

2. Amperometric Biosensor

An amperometric biosensor is a self-contained incorporated device based on the amount of the current ensuing from the oxidation offering exact quantitative analytical information.

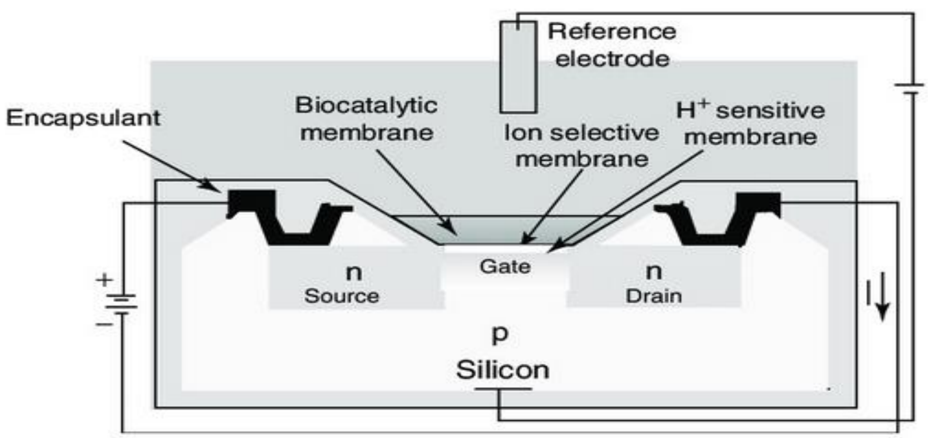
Generally, these Biosensors have reaction times, energetic ranges & sensitivities comparable to the Potentiometric-biosensors. The simple amperometric biosensor in frequent usage includes the "Clark oxygen" electrode.

The rule of this biosensor is based on the amount of the flow of current between Counter Electrode and the working which is encouraged by a redox response at the operational electrode. Choosing analyte centers is essential for a wide selection of uses, comprising high-throughput medicine screening, quality control, problem finding and handling, and biological checking.



3. Potentiometric Biosensors

This type of biosensor provides a logarithmic reply by means of a high energetic range. These biosensors are frequently complete by monitor producing the electrode prototypes lying on a synthetic substrate, covered by a performing polymer with some enzyme is connected.

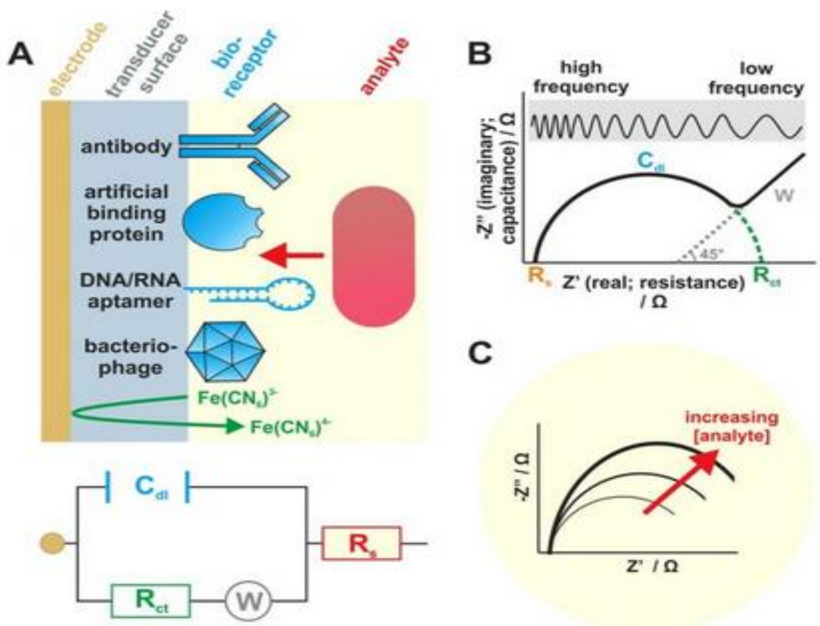


They comprise two electrodes which are enormously responsive and strong. They allow the recognition of analytes on stages before only attainable by HPLC, LC/MS & without exact model preparation.

All types of biosensors generally occupy least sample preparation because the biological detecting component is extremely choosy used for the analyte troubled. By the changes of physical and electrochemical the signal will be generated by in the layer of conducting polymer due to modifying happening at the outside of the biosensor.

4. Impedimetric Biosensors

The EIS (Electrochemical impedance spectroscopy) is a responsive indicator for a broad range of physical as well as chemical properties. A rising trend towards the expansion of Impedimetric-biosensors is being presently observed. The techniques of Impedimetric have been executed to differentiate the invention of the biosensors as well as to examine the catalyzed responses of enzymes lectins, nucleic acids, receptors, whole cells, and antibodies.



5. Voltammetric Biosensor

This communication is the base of a new voltammetric biosensor to notice acrylamide. This biosensor was built with a carbon glue electrode customized with Hb (hemoglobin), which includes four prostatic groups of the hem (Fe). This type of electrode shows a reversible oxidation or reduction procedure of Hb (Fe).

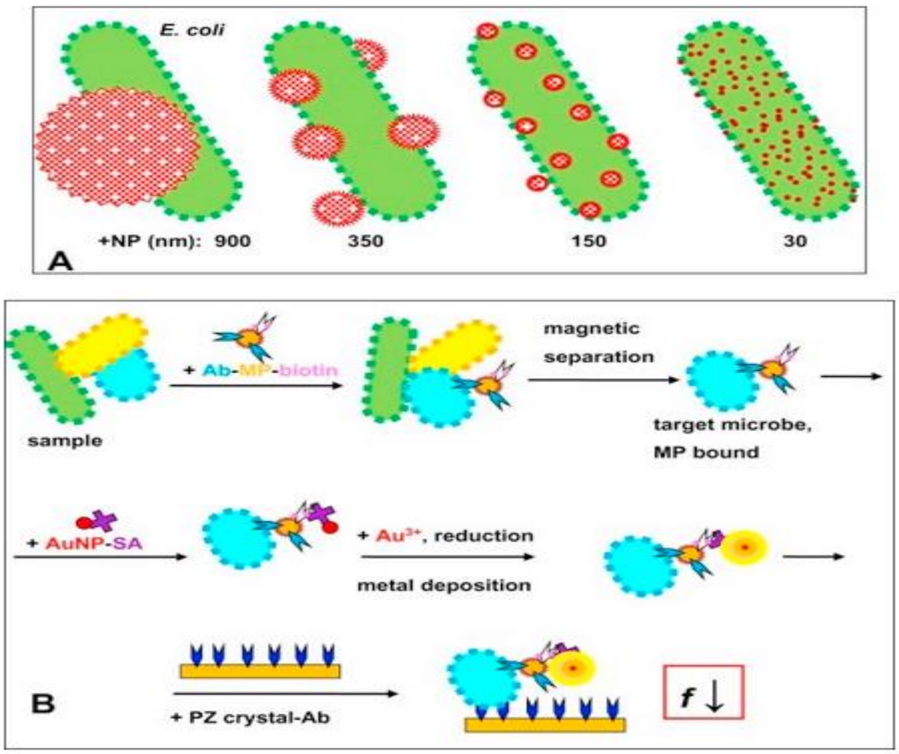
Physical Biosensor

In conditions of classification, physical biosensors are the most fundamental as well as broadly used sensors. The main ideas behind this categorization also happen from inspecting the human minds. As the general working method behind the intelligence of hearing, sight, touch is to react on the exterior physical stimuli, therefore any detecting device that offers reaction to the physical possessions of the medium was named as a physical biosensor.

The physical biosensors are classified into two types namely piezoelectric biosensor and thermometric biosensor.

Piezoelectric Biosensors

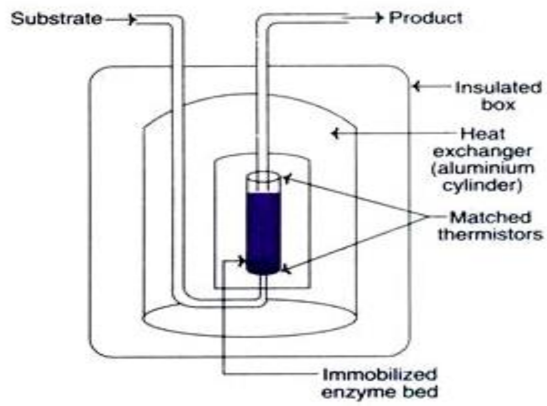
These sensors are a collection of analytical devices which works on a law of "affinity interaction recording". The platform of a piezoelectric is a sensor element works on the law of oscillations transform due to a collection jump on the surface of a piezoelectric crystal. In this analysis, biosensors having their modified surface with an antigen or antibody, a molecularly stamped polymer, and heritable information. The declared detection parts are normally united by using nanoparticles.



Thermometric Biosensor

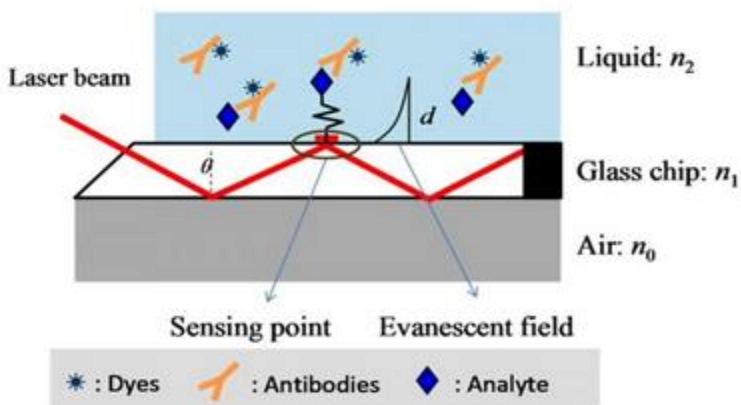
There are various types of biological reactions which are connected with the invention of heat, and this makes the base of thermometric biosensors. These sensors are usually named as thermal biosensors

Thermometric-**biosensor is used to measure** or estimate the serum cholesterol. As cholesterol obtains oxidized through the enzyme cholesterol oxidize, then the heat will be produced which can be calculated. Similarly, assessments of glucose, urea, uric acid, and penicillin G can be done with these biosensors.



Optical Biosensor

The Optical biosensor is a device that uses an optical measurement principle. They use the fiber optics as well as optoelectronic transducers. The term optrode represents a compression of the two terms optical & electrode. These sensors mainly involve antibodies and enzymes like the transducing elements.



Wearable Biosensors

The wearable biosensor is a digital device, used to wear on the human body in different wearable systems like smart watches, smart shirts, tattoos which allows the levels of blood glucose, BP, the rate of heartbeat, etc

Nowadays, we can notice that these sensors are carrying out a signal of improvement to the world. Their better use and ease can give an original level of experience into a patient's real-time fitness status. This data accessibility will let superior clinical choice and will effect in enhanced health results and extra capable use of health systems.

For the human beings, these sensors may assist in premature recognition of health actions and prevention of hospitalization. The possibility of these sensors to reduce hospital stays and readmissions will definitely attract positive awareness in the upcoming future. As well, investigate information says that WBS will definitely carry a cost-effective wearable health equipment to the world.

Biosensors Applications

In recent years, these sensors have become very popular, and they are applicable in different fields which are mentioned below

- Common healthcare checking
- Metabolites Measurement

- Screening for sickness
- Insulin treatment
- Clinical psychotherapy & diagnosis of disease
- In Military
- Agricultural, and Veterinary applications
- Drug improvement, offense detection
- Processing & monitoring in Industrial
- Ecological pollution control

From the above article, finally, we can conclude that **biosensors and bioelectronics** have been used in a lot of areas of healthcare, life science research, environmental, food & military applications. Further, these sensors can be enhanced as nanobiotechnology.

VI. Bionanotechnology

Bionanotechnology is a science that sits at the convergence of nanotechnology and biology. Nanobiology and nanobiotechnology are other names that are used interchangeably with bionanotechnology. The field applies the tools of nanotechnology to biological problems, creating specialized applications.

Nanotechnology is usually defined as the manipulation of materials that range from the nanometer (nm) to the micrometer (um) scale. For comparison, the cells of living organisms are typically around 10 um across. That puts the machinery and components of living cells within the nanoscale size range, making them ideal for interactions with functional nanoparticles and nanomachines.

Nanoscale materials have unusual properties distinct from bulk materials. Some of these enhanced properties include surface area, cation exchange capacity, ion adsorption, and complexation. A high proportion of the atoms in a nanoparticle are present on its surface, meaning that compared to macro-scale materials, nanoparticles have different surface compositions, different reactivity, and different types of surface interaction sites.

Bionanotechnology is defined as the incorporation of biological molecules into nanoartifacts. The highly refined molecular binding specificity is particularly valued and used to facilitate the assembly of unique structures from a solution of precursors and for capturing chemicals from the environment prior to registering their presence via a transducer (biosensors). Further applications involve using the widely encountered ability of biomolecules to easily accomplish actions associated with difficult and extreme conditions in the artificial realm, such as the catalysis of many chemical reactions, and exploiting optical nonlinearity with single photons, a feature that can be exploited to construct all-optical computers.