MEMS:- Micro Electro Mechanical Systems.

Introduction to Microsystems:-

A radical change in the entire field of electronics began in 1947 when the transistor was invented; 11 year later in 1958 the first integrated semiconductor circuit was built.

Milestones of the development of microsystem technology.

Year	Event
1939	PN-Junctions in Semiconductors (W. Schottky).
23-12-1947	Invention of the transistor (J. Bardeen, W. H. Brattain, W. Shockley; Bell Telephone laboratories Nobel prize 1948).
1953	Discovery of the piezoresistive effect in semiconductors (C.S. Smith; Case Institute of Technology and Bell Telephone Laboratories respectively).
1957	First Commercial Planar transistor (Fairchild Semiconductor.
1958	Production of the first integrated Semiconductor Circuit (J.S. Kilby; Texas Instruments, Nobel Prize 2000).
1953	Oxidation demonstrated by Brattain and Bardeen at Bell Telephone laboratories

In 1947 one transistor today there are about 20 billion-billion transistors on earth and this number is roughly doubling every 18 months.

First Integrated circuit ~~transistor~~ made in 1960s which is monolithic which have four BJT's and several resistors connected together.

In the early 1990's Integrated Circuits have nearly 1 Million MOS transistors.

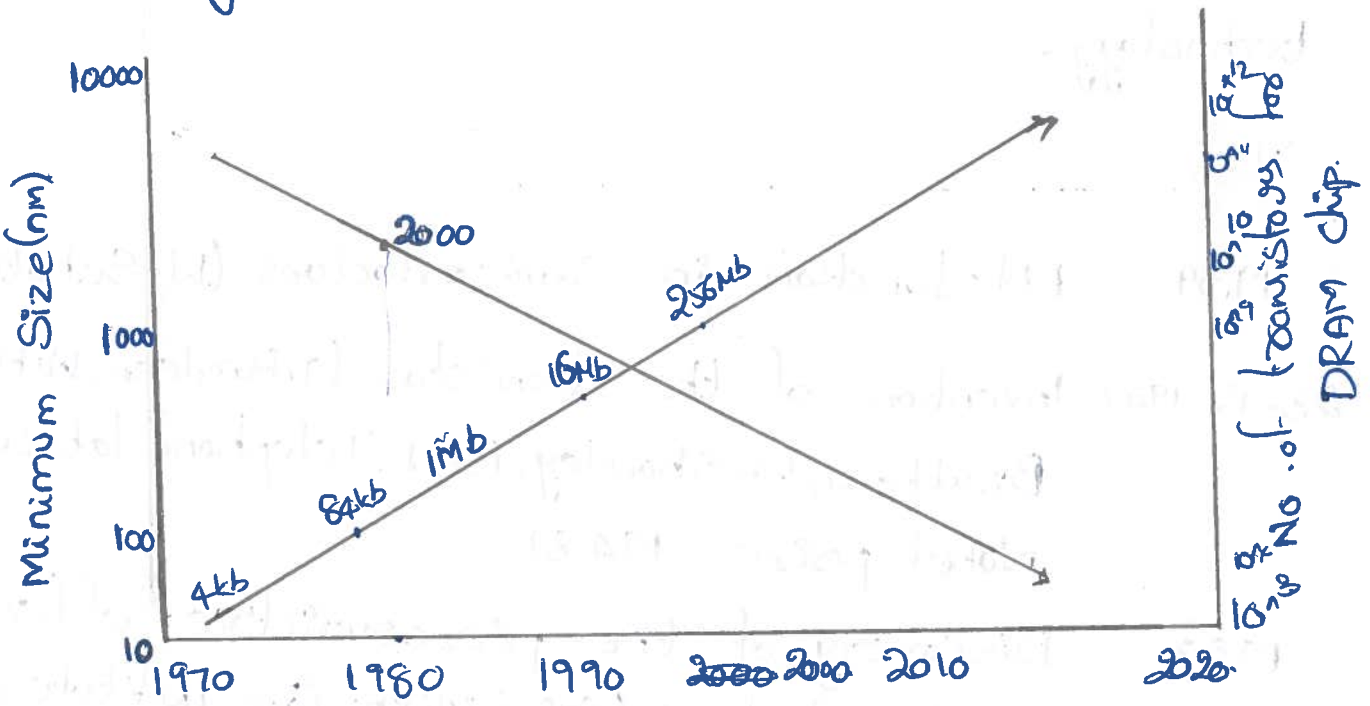


fig:- Trends of Silicon ICs.

In 1980 where the min feature size was nearly 2000nM.

In 2004 the feature size is nearly 100nM.

For a 256MB DRAM (256 Megabyte) which is early in 1998 & 1999 the count of transistors is 10^9

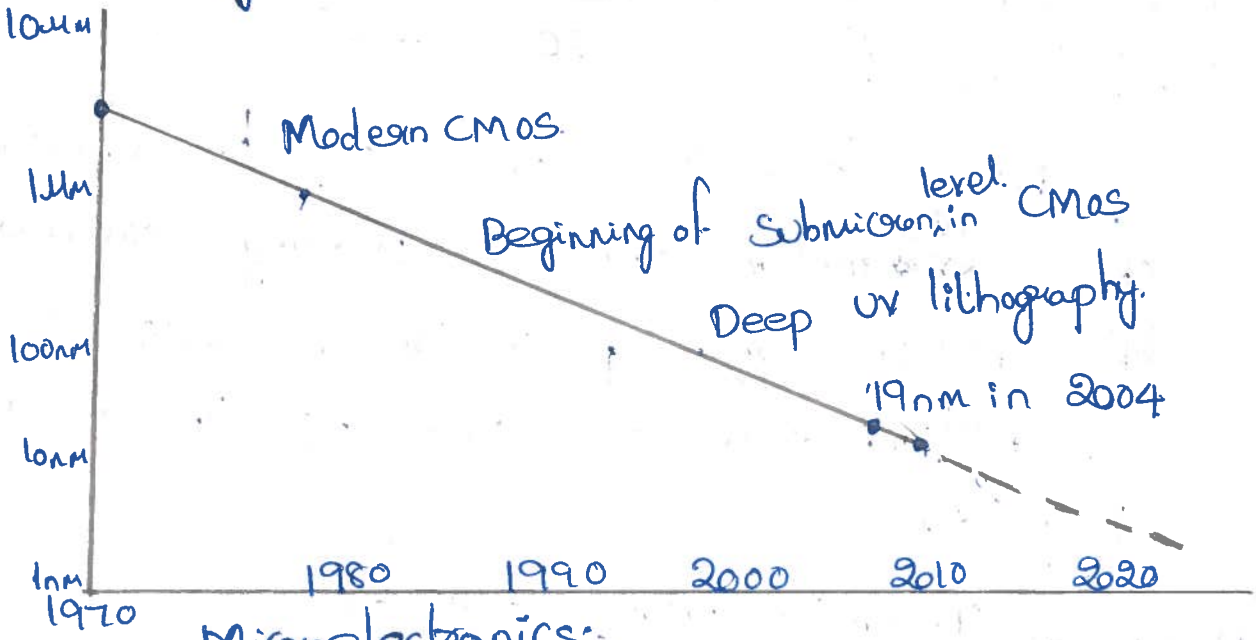
Moore's law which gives you the scaling of the CMOS.

In 1980 which is nearly ~~[illegible]~~ 1μm i.e 1 micron.

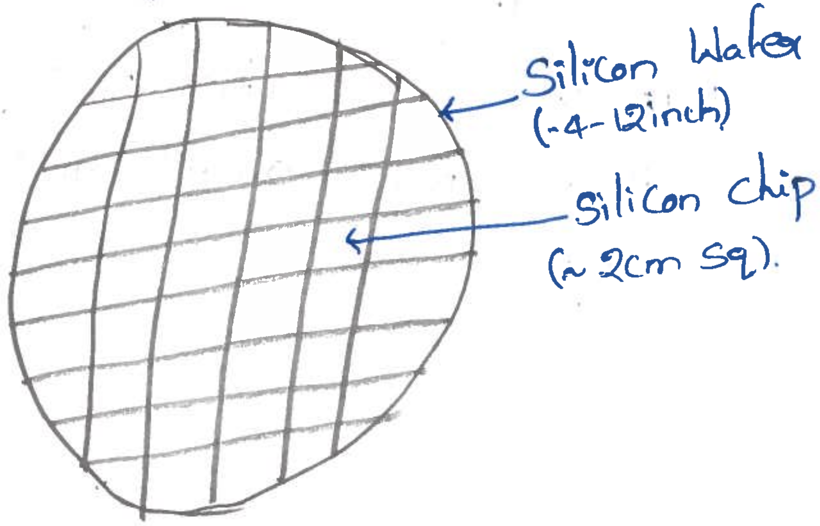
In 2004 the transistor size has come down to 19nm(nano meter).

In future routemap in the last 34 years of scaling history feature size sinks by 70 perecent every generation.

Here generation is on an average of 2.9 years.



Silicon Microelectronics:



The standard size of silicon wafer in industry is 12 inches.

Many circuits made of silicon wafer and individual single chip size is of 2 centimeter square

If we go for larger chip which can make now days is of the order of 2cm.sq.

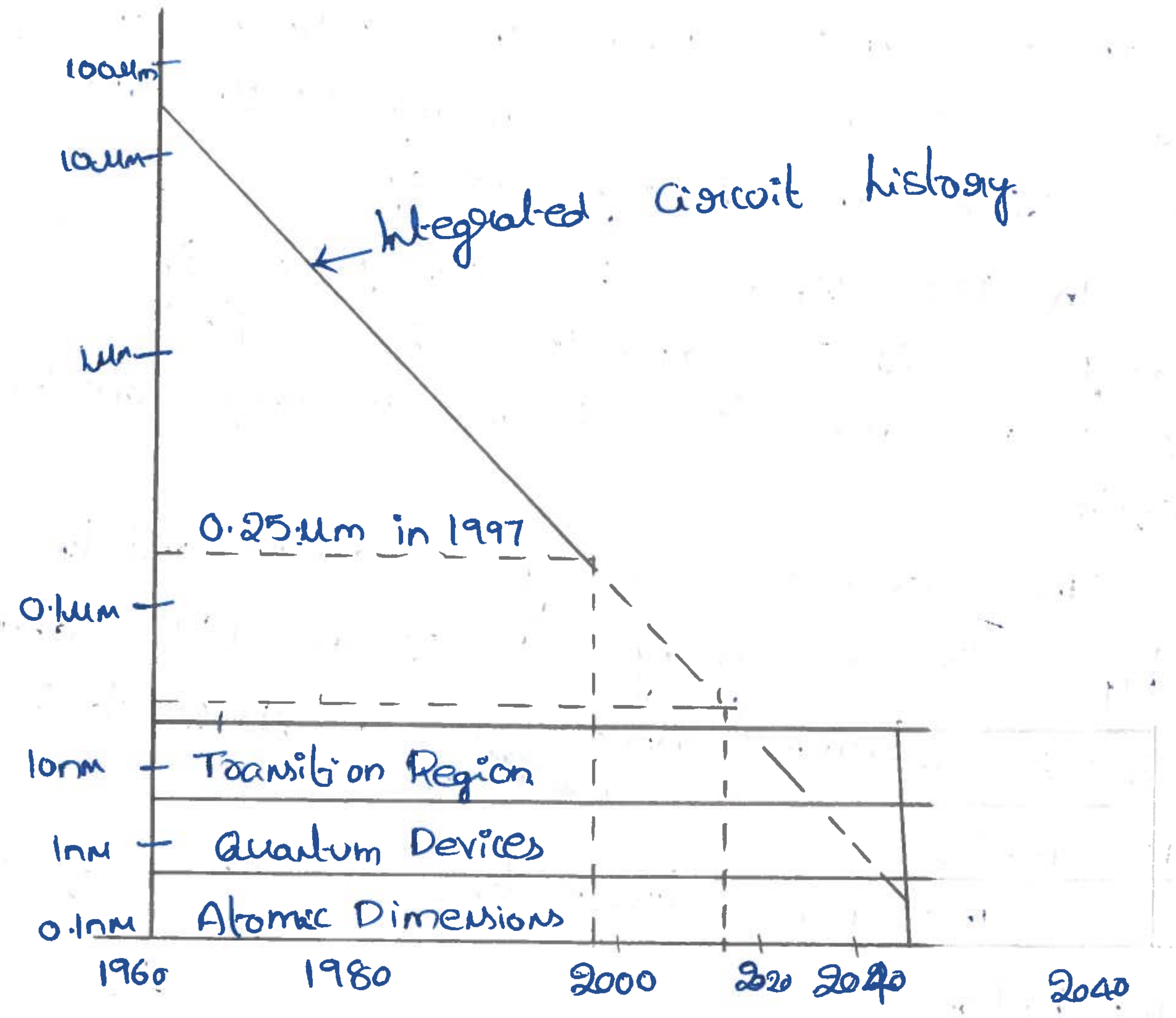
It does not mean feature size is also large.

Feature size is very small and if you can get larger die ~~side~~ Size that is another achievement.

No. of transistors per chip has exceeded the 100 million this is heading towards the billion and projection in 2014 is 20 billion transistors per chip this is just Projection.

Historical Trends & future projections:-

The size of integrated circuit goes down if we see the history of integrated circuits. it is from 0.1 micrometer and 10 nanometer range



1nM (nanometer) is basically the size of quantum devices.

Now the Constant of silicon is nearly 3 or 4 or 5 nanometer.

Year of DRAM shipment	1997	1999	2003	2006	2009	2012
Minimum feature size	250nM	180nM	130nM	100nM	70nM	50nM
DRAM bits/chip	256M	1G	4G	16G	64G	256G
DRAM Chip Size (mm²)	280	400	560	790	1120	1580
Microprocessor transistors/chip	11M	21M	76M	200M	520M	1.40B
Min Supply voltage (volts)	1.8–2.5	1.5–1.8	1.2–1.5	0.9–1.2	0.6–0.9	0.5–0.6

The above table shows the trend of the feature size as well as wiring levels the mask Count and supply voltage.

In 1997 Where the supply voltage is nearly 2 Volts and in 2003 it is 1.2 Volts and in 2012 it ranges 0.5 to 0.6 Volts.

The feature size goes down and the chip size is going up ∵ in 1997 chip size is $280mm^2$ where as in 2012 it is $1580mm^2$.

The no.of transistors in the region is 1.4 billion.

Mask count going to increase as no.of wiring levels increases.

MicroSystem :- Definition.

Micro Systems literally Very Small systems or "Systems made of Very Small Components.

Micro establishes a dimensional Scale.

Espically a System using microscopic electromechanical Components.

Introduction to MEMS:-

In United States the technology is known as microelectromechanical Systems (MEMS) in Europe it is called microsystems technology (MST).

MEMS is a technology can be defined as miniaturized mechanical and electro-mechanical elements that are made using the techniques of microfabrication.

Bacteria size is the 1µm to 10µm and Plant and animal cells size is about 10 to 100µm. This is the area where basically the MEMS are made of the size can vary from ~~100µm~~ 100nm to 100µm.

MEMS History:-

1959	"Theres a plenty of room at the bottom" Nobel Prize Winner - Richard Feynman.
1967	"Resonant Gate Transistor" Wasting House.
1989	MEMS Micromotor at UC Berkley.
1991	Texas Instrument Digital Light processing MEMS - based projector.
1993	Commercial MEMS-based Accelerometer Analog Device.
2001	Commercial optical Cross-connect/switch.

Science of Miniaturization:-

Miniaturization is the trend to manufacture ever smaller mechanical, optical and electronic Products and devices.

Ex:- In Case of machine how the size has been reduced because of MEMS Can be seen below.

	Conventional Accelerometer	MEMS Accelerometer.
Mass:-	1.5kg	10 grams.
Size:-	15cm x 8cm x 5cm	2cm x 2cm x 0.5cm.
Power:	35 Watts	1mW
cost :	20,000 Dollars	500 Dollars.

at present the price is further down and you can get it for nearly 10 or 50 or 100 Dollars to have MEMS devices.

Microfabrication was limited to silicon, now the field is open and started using other materials like polymers and ceramics for MEMS devices and microsystem fabrication.

Silicon is mature as it doesnot require any research for the processing of silicon i.e why they do not want to deviate from silicon.

→ In Miniaturization lithography has been the current method of defining patterns.

→ Traditional electroplating, molding and LIGA techniques used in MEMS

Important Characteristics of MEMS:-

→ Small Size
→ Rich performance
→ Low cost

Features of MEMS:-

Miniaturization:-

- micromachines can handle microobjects and move freely in small spaces.

Multiplicity:-

- Inexpensive to make many machines in parallel.
- Cooperative work from many small micromachines may be best way to perform a large task.

Microelectronis:-

- integrate microelectronic control devices with sensors and actuators.

Advantages:-

→ Minimize energy and materials use in manufacturing
→ Cost/performance advantages.
→ Improved reproducibility.
→ Improved accuracy and reliability.
→ Increased selectivity and sensitivity

Disadvantages

↓ Farm establishment requires huge investments
↓ Micro Components are costly Compare to macro Components
↓ Design includes very much complex process.

Micromachining:-

It is the set of design and fabrication tools that precisely machine and form structures and elements at a scale well below the limits of our human perceptive faculties. the microscale.

~~Macroscaling~~ Micromachining is the underlying foundation of MEMS fabrication.

It is the toolbox of MEMS

Example:-

Evolution of crash sensor's for airbag Safety systems. Early Sensors were merely mechanical ~~systems~~ Switches. They later evolved into micromechanical sensors that directly measure acceleration.

The next generation of devices will also incorporate the entire airbag deployment Circuitory that decides whether to inflate the airbag. As the technology matures, the airbag crash Sensor may be integrated one day with micromachined Yaw-rate and other inertial sensors to form a Complete microsystem responsible for passenger Safety and Vehicle Stability.

Introduction to Microsensors:-

Sensor is a device which detects or measures a physical property and records, indicates or otherwise responds to it.

(or)

A sensor is an electronic component, module or Subsystem whose purpose is to detect events or changes in it's environment and send the information to other electronics.

→ detect an input signal and Convert it to an appropriate output signal.

Normally we used semiconductor sensors ~~and again~~ as one can make the sensor out of the semiconductor material, then it will be easy for us to integrate both the sensor part and circuit part together.

Semiconductor Sensors:-

→ Small size and low cost

→ uses fabrication process of integrated circuits.

→ batch fabrication processing improves Performance/ Cost ratio.

→ integration with microelectronic circuit Possible (Called integrated microsensors).

Transducers:-

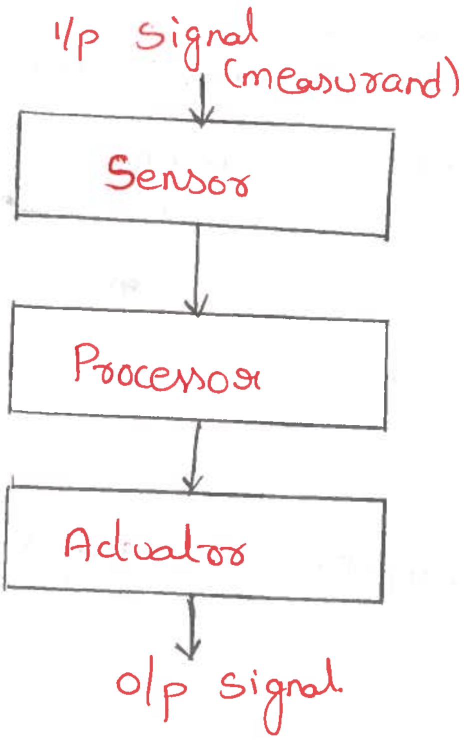
A device that converts energy from one system to another in the same or in different form.

Sensors and transducers are sometimes used as synonymous terms.

Information processing Systems:-

Measurand :- It is the quantity being measured by a sensor.

Sensor :- It is a device that converts a non-electrical quantity into an electrical signal.



Processor:-

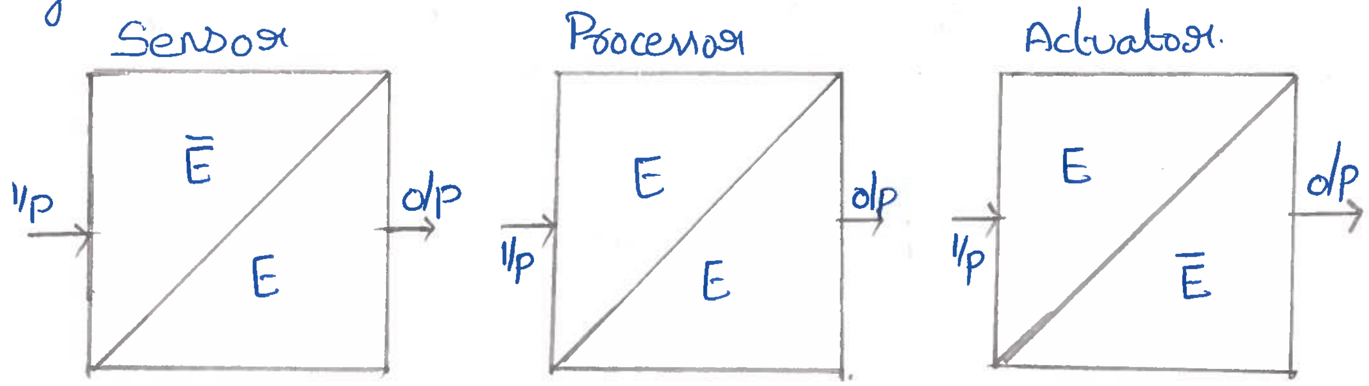
It is a device that performs a set of logical or mathematical operations.

Actuator:-

It is a device that converts an electrical signal into a non-electrical quantity.

The blocks sensor processor and actuator together they form information processing system or sometimes it is also known as microsystem.

* A Microsensor is a sensor that has atleast one physical dimension at the sub-millimeter level.



From above microsensors building block for each and every block has input and outpot.

Ē represents the non electrical quantity.

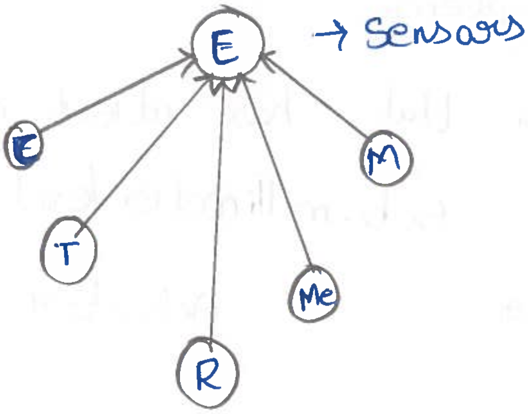
E represents the electrical quantity.

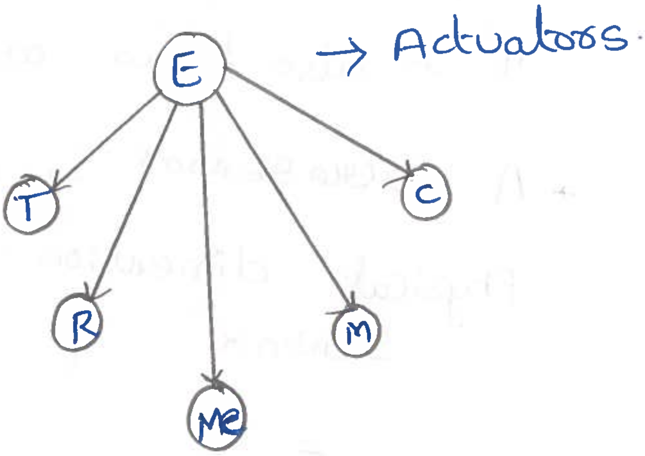
Non-electrical Signal may be Mechanical, it may be acoustical energy, optical energy or magnetic energy.

Processor input is electrical and output is also electrical.

At the output the amplitude or the frequency change occurs.

Energy Domains of Conventional Sensors and Actuators:-





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

Measurands (Input Signal to the Sensor):-

Inputsignal to the sensor are as mentioned below.

→ Acoustic:- Waveamplitude, phase, polarization, spectrum
Wave velocity, etc.

→ Biological:- Biomass (identities, Concentrations, states)

→ chemical:- Components (identities, Concentrations, state)

→ Radiation:- Type, Energy, intensity.

→ Electric:- charge, current, potential difference,
electric field (amplitude, phase, spectrum)
conductivity, permittivity.

→ Mechanical:- Position (linear, angular), velocity, force
acceleration, Pressure, strain, mass,
moment, torque, speed of flow, etc.

→ Magnetic:- Magnetic field (amplitude, phase,
Polarization, spectrum), magnetic flux,
Permeability.

→ Optical:- Wave amplitude, phase, polarization,
spectrum, Wave velocity.

→ Thermal:- Temperature, flux, specific heat,
thermal Conductivity.

Forms of Energy Converted by a Sensor:-

Atomic Energy:- Related to the force b/w nuclei and electrons.

Electrical Energy:- Pertains to electric field, current, voltage etc

Gravitational Energy:- Related to gravitational attraction between mass and the earth.

Magnetic Energy:- deals with Magnetic field, etc.

Mass Energy:- described by Einstein $E=mc^2$

Mechanical Energy:- Pertains to motion, displacement, force, etc.

Molecular Energy:- The binding energy in molecules.

Nuclear Energy:- The binding energy between nuclei

Thermal:- Related to kinetic energy of atoms and molecules

Radiant Energy:- Related to electromagnetic radio-waves, microwaves, infrared, visible light, ultraviolet, X-rays and gamma rays.

Characteristics of Sensors:-

1.) Range:-

It is the minimum and maximum value of physical variable that the sensor can sense or measure.

For Ex:- Resistance temperature Detector (RTD) for the measurement of temperature has a range of -200 to 800°c.

2.) Span :-

It is the difference between the maximum and minimum values of input. Ex:- the span of RTD is 800 - (-200) = 1000°c.

3.) Accuracy:-

The error in measurement is specified in terms of accuracy.

Difference b/w measured value and true value.

Absolute Error = |Measured value - True value|

$$E_a = |X_m - X_t|$$

X_t is calculated by taking mean of infinite number of measurements.

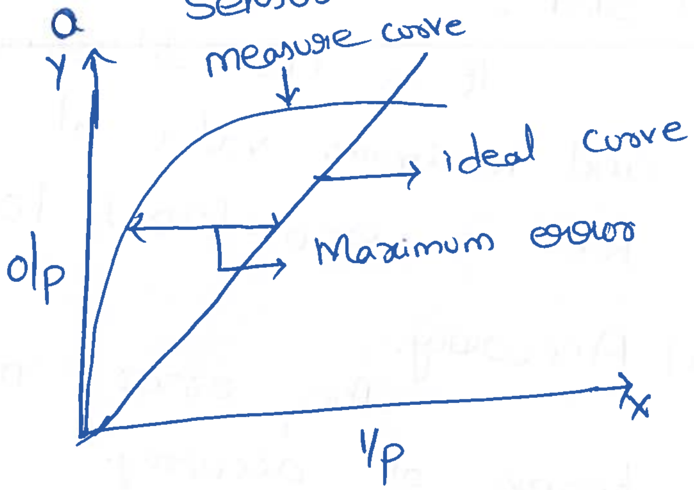
$$\text{Relative Error} = \frac{\text{Absolute Error}}{\text{True Value}}$$

$$E_r = \frac{|X_m - X_t|}{X_t}$$

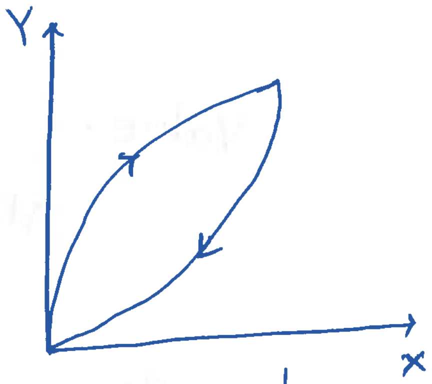
Sensitivity:- It is the ratio of change in output to change in input. If Y be the o/p quantity to input X the sensitivity S is

$$S = \frac{dY}{dx} = \frac{\Delta Y}{\Delta x}.$$

Linearity:- It is the maximum deviation between the measured values of a sensor from ideal curve.



Hysteresis:- It is the difference in output when input is varied in two ways increasing and decreasing



~~Resolution:-~~ It is the difference in output ~~When input~~ is varied.

Resolution:- It is the minimum change in input that can be sensed by the sensor.

Reproducibility:-

It is defined as the ability of sensor to produce the Same output When Same input is applied.

Repeatability:-

It is defined as the ability of sensor to Produce the Same output every time When the same input is applied When all the physical and measurement Conditions kept the Same including the operator, instrument, ambient Conditions etc.

Response time:-

It is generally expressed as the time at Which the output reaches a certain percentage of it's final Value. in response to a step change of the input.

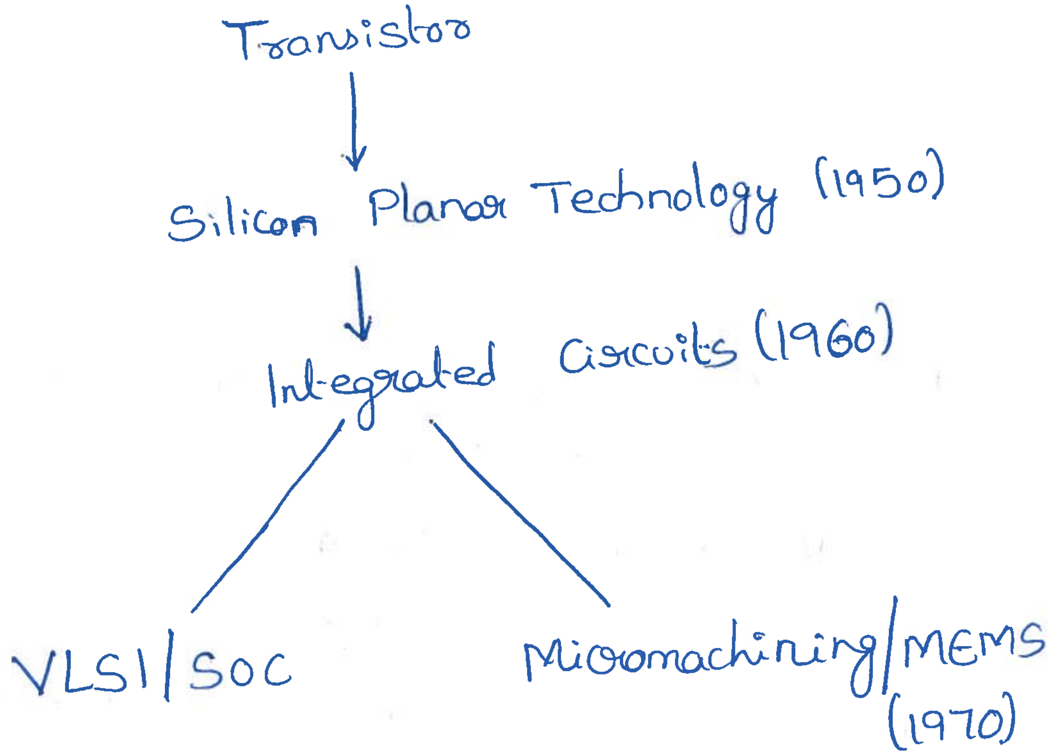
Drift:-

This is low frequency change in a sensor with time. It is often associated with electronic aging of Components or reference standards in the sensor.

Evolution of MEMS MicroSensors:-

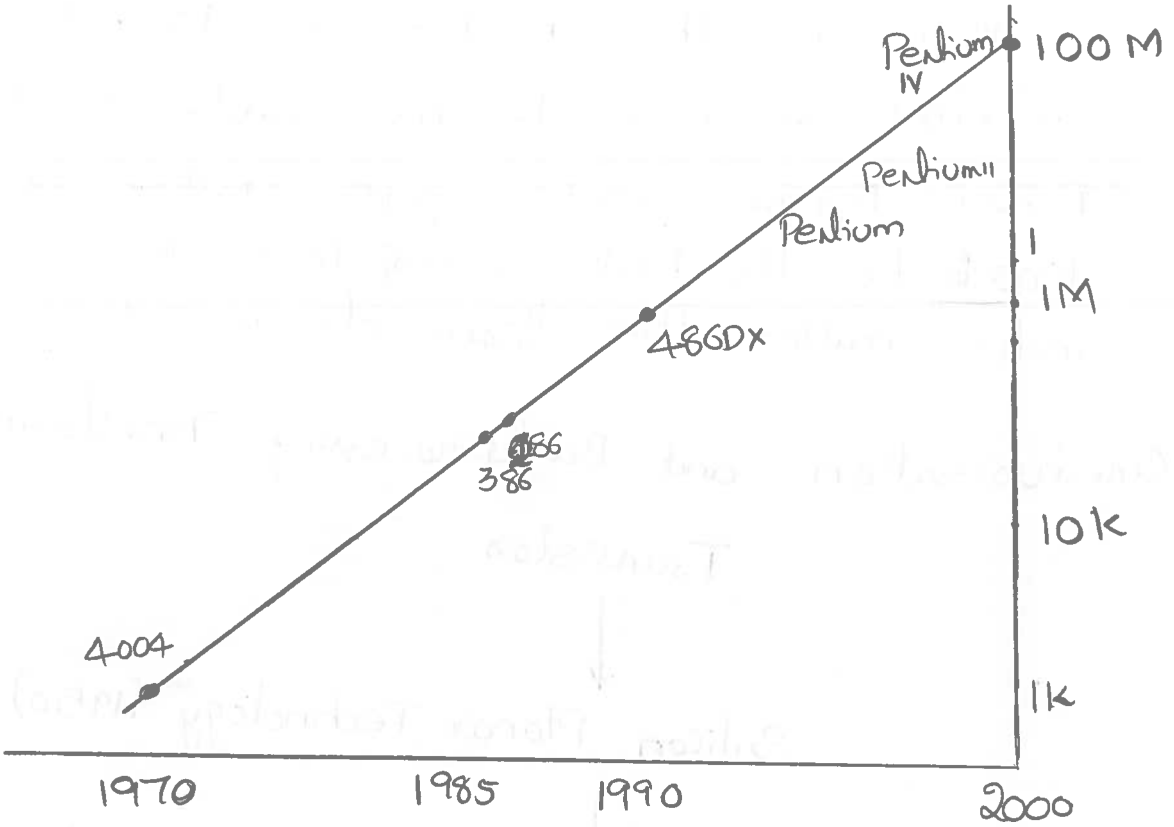
→ "There is plenty of room at the bottom" by Feynmans in 1959 at the Same time he Predicted "The entire encyclopedia could be written on the head of a Pin". His vision in 1959 is close to the reality in 2004. Richard Feynman issued a public challeng by offering 1000$ to the first person to create an electrical motor smaller than 1/64th of an inch.

Miniaturisation and Batchprocessing Transformations:-



Transistor discovered in 1947, later Integrated Circuits in 1960 from there on We have two areas.
One is Silicon VLSI / System on Chip and another are is Micromachining / MEMS.

It got importance in 1970 from there in 1982 when peterson published a paper people thought extensively how to improve and how to progress with that particular area i.e MEMS or micro machining.



Here Moore's law shows the evolution of the Computers with Miniaturization of the Components.

In Microprocessor 4004 have a transistor count of 1000 in the year 1970

In 286 and 386 processor nearly in 1985 whose transistor count is 100. thousand in a chip.

The next generation processor 486DX which has nearly 1 million transistors i.e 10^6 in the year 1990.

Pentium 4 in the year 2000 have a transistor count of 100 million transistors

Evolution of VLSI depends on Moore's law as shown above.

But MEMS evolution does not exactly depends or follows the Moore's law.

The Evolution of MEMS started in 1954 With discovery of strong piezoresistive effects in silicon and Germanium by C.S. Smith.

Silicon in Compatible with integrated Circuits and VLSI.

In 1980 the micromachining technology evolved as photolithography, etching ~~reg~~ recognised as a tool for micromachining.

Micromachining Came into limelight and the lot of research has been taking place in micromachining. One Can foresee various kinds of sensors using micromachining which in basically ~~of~~ Photolithography and etching technique employed in Case of VLSI fabrication.

In 1982 a paper published by K. Peterson as silicon established as an Excellent Mechanical Material.

Silicon has excellent mechanical properties as silicon can be used for sensor which will sense mechanical behaviour of any body or any system.

Evolution of semiconductor Sensors:-

1947 to 1960:- Discovery phase.

1960 to 1970:- Basic Technology Development phase.

1970 to 1980:- Batch Process Phase in Case of semiconductor sensor.

1980 - tilldate - Micromachining ~~Sensors~~ phase.

From Moore's law last ten years is of decade of microprocessors. as lots of improvement and development came into existence. The Next ten years known as the decade of MEMS and microsensors.

Chronology of MEMS:-

1957 - 89:- Micromachining, silicon MEMS/Microsystems.

1979 - first MEMS accelerometer by stanford University. it has been commercialized in the year 1993.

1990 - Surfacing/Surface micromachining advance MEMS technology compatible with CMOS Process which has lot of applications in automotive, Medical IT and industry military.

Market Survey :-

The commulative annual growth rate of the MEMS market is nearly 25 percent. Present markets are primarily in pressure and inertial sensors.

Ex:- Inkjet print heads dominated by the HP- Hewlett - Packard.

High-resolution digital displays with Texas Instruments.

Today large volume applications of MEMS device are in the area of inkjet head in case of pressure and acceleration sensors for automobile application and pressure sensors for medical application. These three have the bigger market at present.

MEMS Market Growth:- (Millions of US Dollars)

	Automotive	Medical	IT & Industries	Militarys Aerospace	Total
1996	355	165	492	62	1074
2000	646	291	733	111	1781
2004	1172	716	1514	202	3604

The Market Comparision of 2000 and 2004 with 1996 that in every 4 years the market has almost doubled.

The total growth in 1996 is 1074 and 3604 million US dollars in 2004 so that the market is picking up

The expected growth stems from technical innovations and acceptance of the technology by an increasing number of end users and customers.

Analysis of Markets Forecast of World Wide MEMS:-
(in Million US Dollars)

	2002	2007
Microfluidics:	1404	2241
Optical MEMS:	702	1826
RF MEMS:-	39	249
Other Actuators:-	117	415
Inertial Sensors:-	819	1826
Pressure "	546	913
Other Sensors	273	830
Total	3900	8300

→ In 1997 automotive applications accounted for 35% of the total $1.2 billion MEMS market dropping to 26% in 2002 and to 18% in 2007. The Automotive market in 2007 is of $1.5 billion.

→ As of geographical Distribution USA and Europe lead the world in the manufacture of MEMS-based Products, with Japan trailing

	No. of fabs
North America	139
Germany	34
France	20
United kingdom	14
Benelux	17
Scandinavia	20
Switzerland	14
Rest of Europe	10
Japan	41
Rest of Asia	31

→ Important action when sizing market for MEMS is to distinguish between Components and systems.

Ex: For disposable blood pressure sensors in 2000 was approximately 25 million units totaling $30 million at Component level but $200 million at the system level.

→ Emerging automotive application for MEMS initiated by the U.S. Congress when it passed the Transportation Recall Enhancement, Accountability and Documentation (TREAD) Act in 2000 requiring warning systems in new vehicles to alert operators when their tires are underinflated. With 16 million new vehicles sold in North America each year, there is a new market nearly of $100 million per year for 70 million pressure sensors.

The cost of total system ranges from $65 to $200, making the market size at the system level well over $1 billion per year.

Application of MEMS:-

Today high volumes of MEMS can be found in a diversity of applications across multiple markets.

Automotive:- Internal Navigation sensors,
Air Conditioning Compressor sensor,
Brake force sensors & suspension control accelerometers.
Fuel level and Vapour pressure sensors
Airbag Sensors
Intelligent tyres.

Electronics:- Disk drive heads, Inkjet printer heads. Projection screentelevisions, Earthquake sensors, Avionics pressure sensors, Mass data storage systems.

Medical :- Blood Pressure Sensor,
Muscle Stimulators & drug delivery systems
Implanted pressure sensors.
Prosthetics, Miniature analytical instruments.
Pacemakers.

Communications:- Voltage Controlled Oscillators, Tuneable lasers, RF Relays switches and filters,
Fibre-optic network components.

Defence :- Munitions Guidance, Surveillance, Arming systems, Data Storage, Aircraft Control.
Embedded Sensors and actuators for Condition based maintenance.
Weapons safing, arming and fusing.

Established MEMS Applications:-

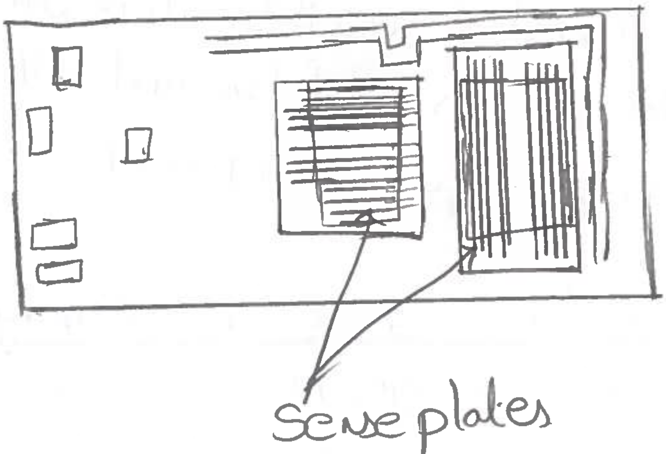
→ Automotive Airbag Sensor:-

Automotive airbag sensors were one of the first commercial devices using MEMS. They are in widespread today in the form of a single chip Containing a smart sensor or accelerometer.

Initial Airbag 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 front of the vehicle with seperate electronics near the bag.

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 ~~and~~ which costs only a few dollars.

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 Plate sense a change in acceleration from deflection of the plates

The airbag sensor is fundamental to the success of MEMS and micromachining technology.

→ **InkJet Printer head:-**

It is one of the most succesful MEMS applications in the inkJet printer head. InkJet uses a series of nozzles to spray drops of ink directly on to a printing medium.

Invented in 1979 by Hewlett-packard Within a printer head there is an array of resistors known as heaters. These tiny resistors can be fired Under microprocessor with electronic pulses of a few milli seconds.

Ink flows over each resistor Which when fired, heat up at 100 ~~million~~ °C per second, Vaporizing the ink to form a bubble. When a bubble Collapses a Vaccum. is created Which pulls more ink into the print head from the reservoir in the Cartridge.

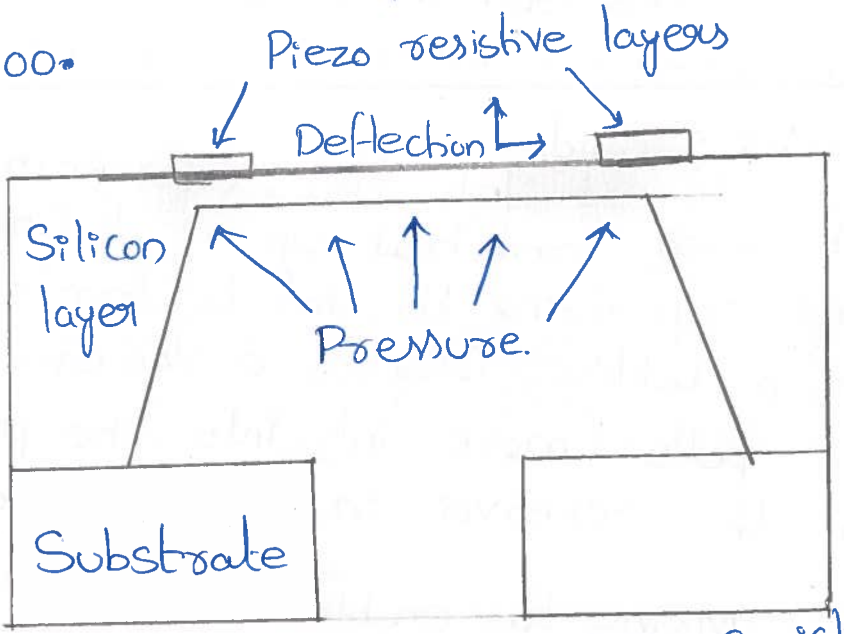
MEMS has enabled more and more heating elements and piezoelectric crystals to be incorporated into a printer head.

Early Printers had 12 nozzles with resolution of upto 92dpi possible.

Today modern printers have upto 600 nozzles which can all fire a droplet simultaneously enabling 1200dpi. Over 350 million units were sold in 2000

→ Medical Pressure Sensor:-

Miniature disposable pressure sensor used to monitor blood pressure in hospitals. These sensors connect to a patient intravenous line and monitor the blood pressure through the IV solution. For a fraction of their cost $10 they replace the blood pressure sensors that cost over $ 600.



The disposable sensor consists of a silicon layer ~~substrate~~ which is etched to 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. the pressure corresponds to deflection of the membrane.

The sensing element is mounted on a plastic or ceramic base with a plastic cap over it.

Pressure sensors are the biggest medical MEMS application to date with the accelerometer MEMS a distant second.

MEMS Materials:-

Micromachining technology as a set of generic tools, then there is no reason to limit its use to one material.

Major material families are.

→ Semiconductors (mainly silicon).
→ Metals and metal alloys.
→ Ceramics.
→ Polymers, glass.

Silicon - Compatible Material System:-

Silicon - Compatible material system encompasses in addition to silicon itself a host of materials commonly used in the semiconductor integrated circuit Industry.

Normally deposited as thin films, they include silicon oxides, silicon nitride and silicon carbides.

Silicon:-

Silicon is one of very few materials that is economically manufactured in single crystal substrates. This crystalline nature provides significant electrical and mechanical advantages.

Mechanically silicon is an elastic and robust material.

Silicon as an element exists with three different microstructures. crystalline, polycrystalline, Amorphous.

Polysilicon and Amorphous silicon are usually deposited as thin films with typical thickness below $5\mu m$.

Crystalline silicon substrates are commercially available as circular wafers with 100mm (4-in) and 150-mm (6-in) diameters. larger diameter (200mm and 300mm) Wafers used by Integrated Circuit industry are currently economically unjustified for MEMS.

Silicon has a diamond-cubic crystal structure that can be as if it were simple cube.

The three major co-ordinate axes of the cube are called the principal axes.

Specific directions and planes within the crystal are designated in reference to the principal axes.

Directions are specified by brackets for example [100] which is a vector in the $+x$ direction referred to three principal axes (x y z) of the cube.

Ex:- $[1\,0\,0] = +x$ $[\bar{1}\,0\,0] = -x,$

$[0\,1\,0] = +y$ $[0\,\bar{1}\,0] = -y,$

$[0\,0\,1] = +z$ $[0\,0\,\bar{1}] = -z$ directions.

Directions are specified by brackets Ex:- [100] which is vector in the $+x$ direction.

Parantheses specifies a plane that is perpendicular to a direction with the same numbers. Ex:- (111) is a plane perpendicular to the [111] vector.

Braces specify all equivalent planes for Example {111} represents the four equivalent crystallographic planes (111), $(\bar{1}11)$ $(11\bar{1})$ and $(1\bar{1}1)$

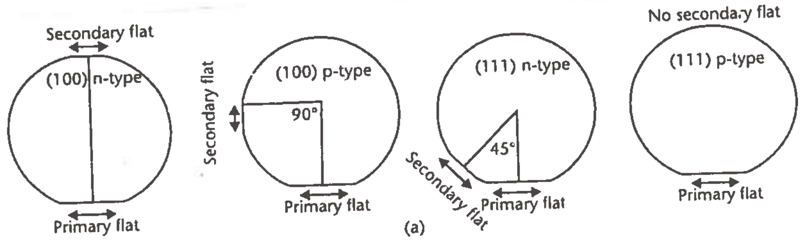
The (100) and (111) Wafers with n and p-type doing are Produced with a minor flat at a specific location relative to a wider major flat.

If the primary flat is 180° to the secondary flat with primary flat is bigger than secondary flat then it is known as 100 n-type silicon wafer.

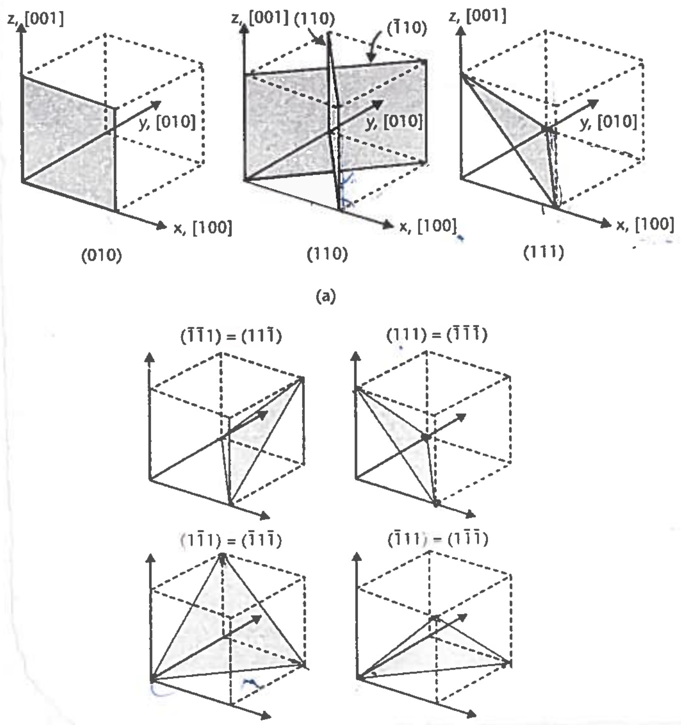
If there is a 90° orientation of the primary flat and the secondary flat then it is known as 100 p-type silicon wafer.

If there is a 45° orientation of the primary flat to the secondary flat then it is known as 111 n-type silicon wafer.

If there is only primary flat and there is no secondary flat then it is known as 111 P-type silicon wafer.



Poly silicon is an important material in the integrated circuit industry and has been extensively studied.



The angles b/w {1 0 0} and {1 1 0} planes are 45° or 90°.

The angles b/w {1 0 0} and {1 1 1} planes are 54.7° or 125.3°

The angle between {100} and {111} planes is particular importance in micromachining because many alkaline aqueous solutions such as potassium hydroxide(KOH) selectively etch the {100} planes of the silicon but not {111} planes.

Material Manufacturers cut thin ~~large~~ circular Wafers from large silicon boules along specific crystalplanes. The (100) Wafers dominate both MEMS and CMOS technology.

Polysilicon is an equally important and attractive Material for MEMS.

It is used to make micromechanical structures and to integrate electrical interconnects, thermocouples, P-n jonction diodes.

Mechanical properties of polycrystalline and amorphous silicon vary with deposition conditions but they are similar to that of single crystal silicon.

silicon is a very good thermal conductor with a thermal conductivity greater than that of many metals and approximately 100 times larger than that of glass.

silicon is not an active optical material as silicon based lasers doesnot exist. silicon is effective only while detecting lights. emission of light is very difficult to achieve.

silicon is also well known to retain its mechanical integrity at temperature upto about 700°c.

At higher temperatures silicon starts to soften and plastic deformation can occur under load.

Silicon oxide and Nitride:-

Silicon has a stable oxide that is electrically insulating - unlike germanium whose oxide is soluble in water or gallium arsenide, whose oxide cannot grow appreciably.

Various forms of silicon oxides (SiO_2, SiO_x, silicate glass) are widely used in micromachining due to their excellent electrical and thermal insulating Properties.

SiO_2 is thermally grown by oxidizing silicon at temperatures above 800°c. Where as other oxides and glass are deposited by chemical vapor deposition, sputtering or even spin o

Silicon oxides and glass ~~are deposited~~ layers are known to soften and flow when subjected to temperature above 700°c.

Disadvantages ~~are~~ of SiO_2 large intrinsic stress Which are difficult to Control. This limited their use of materials for large suspended beams, membranes

Silicon Nitride (Si_xN_y) is also widely used insulating thin film and is effective as a barrier against mobile ion diffusion. (Sodium and potassium found in biological environments).

Its Young's modulus is higher than that of silicon and it's intrinsic stress can be Controlled by the specifies of the deposition process.

Silicon Nitride is an effective masking material in many alkaline etch solutions.

For higher temperatures and harsher environments. gold titanium and tungsten are substitutes.

Aluminium tends to anneal over time with temperature causing changes in it's intrinsic stresses.

Aluminium is good light reflector in the visible. gold excels in the infrared.

Gold, Platinum and iridium are good choices for microelectrodes used in electrochemistry.

chromium, titanium and titanium-tungsten are frequently used as very thin (5-20nm) adhesion layers for metals that have poor adhesion to silicon, SiO_2 and silicon-nitride.

Permalloy has been explored as a material for thin magnetic cores.

Polymers:-

Polymers in the form of polymides or photoresist can be deposited with varying thickness from few nanometers to hundreds of microns.

Standard photoresist is spin coated to the thickness of 1µm to 10µm. but special photoresists such as epoxy based SU-8 can form layers upto 100µm thick.

Spin-on organic polymers are generally limited in their application as a permanent part of MEMS devices because they shrink substantially as the solvent evaporates and because they cannot sustain temperatures above 200°C. Unique absorption and adsorption properties polymer gained acceptance of sensing chemical gases and humidity.

Thin Metal Films:-

The choice of a thin metal film depends greatly on the nature of the final application.

Thin Metal films are normally deposited either by sputtering, evaporation or chemical vapor deposition. Gold, Nickel and permalloy (Nix Fey) and a few other metals can also be electroplated.

Electrical Resistivity :- Property that quantifies how strongly a given material opposes flow of electric current.

Metal	ρ (μΩ·cm)	Typical Areas of Applications
Ag	1.58	Electrochemistry.
Al	2.7	Electrical interconnects, optical reflection in the visible and the infrared.
AU	2.4	High-temperature electrical interconnects, electrochemistry.
Ni	6.8	Magnetic transducing, Solderable layer.
Permalloy (NixFey)	-	Magnetic transducing.
Cr	12.9	Intermediate adhesion layer.
CU	1.7	Transparent conductive layer for liquid crystal displays
Ir	5.1	Electrochemistry: microelectrode for sensing dipotentials

For basic electrical connections, aluminium is most common and is relatively easy to deposit by sputtering but it's operation is related to Noncorrosive environments and to temperatures below 300°C.

Ceramic Materials:-

Ceramics are inorganic materials that Consist of metallic and nonmetallic elements chemically bonded together.

Ex:- Al_2O_3, SiO_2, Si_3N_4, NaCl, CaF_2, $YBa_2Cu_3O_6$

$YBa_2Cu_3O_6$ is a new ceramic material started using MEMS devices.

Ex:- Ceramic pressure sensor for high temperatures

Ceramic materials are promising mainly in two areas → 1.) High temperature.
2.) Harsh Environment.

In high temperature and harsh environments you Cannot use the metallic MEMS because metal at high temperature soften and loose it's property. Where as semiconductor properties are highly dependent on temperature.

Ex:- Piezoresistance where resistance change occurs due to mechanical strain and as well as temperature.

Piezoelectrive property too as electricity (AC voltage) changes at high temperature.

Normal metal, Polymers or Semiconductors are not Promising so we have to go for Ceramic material which Can with stand very high temperature and other is in a harsh environment.

→ Polymer strain gauges and Capacitors serve as a sensing element of piezoresistive and capacitive microsensors.

→ Polymide is one class of polymer it has electrostatic Properties and it is used for making microactuators.

→ Polymers Can be used as a electronic material because now a days polymer transistor has com and win Succesfuly in fabrication.

→ Polymer Names:- Polymide, Parylene, Polyester, PolyCarbonate, PMMA (Poly methylmethacrylate).

Fabrication process of various polymers.

Polymide → Coating technique
Parylene C → Coating "
PMMA → LIGA
Polyester → Casting technique.
PolyCarbonate → Hot Embossing

Functional properties are piezoelectricity, conductivity and electrostriction. These functional properties and its main applications are either Sensor or actuators. Some of the polymermaterials used for sensors and actuators are used as employing the functional Properties are PVDF, Polypyrrole and Fluorosilicone.

Fabrication process of MEMS Ceramics are

→ Screen Printing
→ Tape lamination
→ Micromoulding
→ MSL → Microstereolithography.

Microstereolithography is not used in VLSI.

Microstereolithography used to get 3D structures in polymers, ceramics and sometimes silicon.

Applications of CeramicMEMS:-

Silicon Carbide → Optical devices

PZT and Zinc oxide → functional material for MEMS

Material Properties of MEMS:-

Most Commonly used Physical effects are Piezoresistivity, Piezoelectricity and thermoelectricity.

Piezoresistivity:-

It is derived from greek word piezein meaning to apply pressure. Discovered first by Lord kelvin in 1856. Electrical resistance changes in response to mechanical stress

First application of piezoresistive effect was metal strain gauges to measure strain, from which other Parameters such as force, weight and pressure were inferred. Resistance change in metals is due to dimensional changes: under stress the resistor gets narrower longer and thinner.

C.S. Smith discovered that the effect of Piezoresistance is greater in silicon and germanium than in other materials.

Majority of today's commercial pressure sensors use silicon piezoresistors.

Physics of piezoresistivity:-

It arises from the deformation of the energy bands as the result of an applied stress. Deformed bands affect the effective mass and the mobility of electrons and holes therefore modifying resistivity.

Piezoresistivity for the Engineer:-

The fractional change in resistivity $\Delta\rho/\rho$ is to a 1st order linearly dependent on $\sigma_\parallel$ & $\sigma_\perp$ the two stress Components parallel & orthogonal to the direction of the resistor respectively.

Direction of the resistor is here defined as that of the current flow.

Relationship Can be expressed as

$$\Delta\rho/\rho = \pi_\parallel \sigma_\parallel + \pi_\perp \sigma_\perp$$

$\pi_\parallel$ and $\pi_\perp$ are Called the parallel and perpendicular Piezoresistive coefficients.

The piezoresistive coefficients depends on crystal orientation and change significantly from one direction to the other.

They also depend upon dopant type (n-type & p-type) and Concentration.

Piezoresistive Coefficients for n and p-Type {100} Wafers and Doping levels Below 10^{18} cm^{-3}

	$\pi_\parallel$ $(10^{-11} m^2/N)$	$\pi_\perp$ $(10^{-11} m^2/N)$	
P-type	7	-1	In <100> direction
	-72	-66	In <110> direction
N-type	-102	53	In <100> "
	-31	-18	In <110> "

The Values decrease precipitously at higher doping Concentrations.

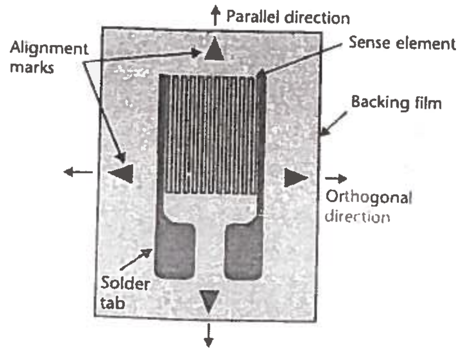
Piezoresistivity is a strong function of temperature. For lightly doped silicon the temperature coefficient of $\pi_{\parallel}$ and $\pi_{\perp}$ is approximately −0.3% per degree celsius. It decreases with dopant concentration to about −0.1% per °C at $8 \times 10^{19} cm^{-3}$.

Polysilicon and amorphous silicon exhibit a strong piezoresistive effect. Coefficients loose their sensitivity to direction.

Gauge factor k relating the fractional change in resistance to strain. Gauge factors in polysilicon and amorphous silicon range typically between −30 to +40 which is 1/3rd of crystalline silicon.

Gauge factor of poly silicon & amorphous silicon quickly decreases as doping increases above $10^{19} cm^{-3}$.

The advantage of polysilicon over crystalline silicon is it's reduced TCR. Doping levels approaching $10^{20} cm^{-3}$ the TCR for polysilicon is approx 0.04% per °C compared to 0.14% per °C for crystalline silicon.



Thin Metal foil strain gauge. (stretching of sense element causes a change in it's resistance).

Piezoelectricity:-

Some Crystals produce an electric field when subjected to an external force. Conversely they can expand or contract in response to an externally applied voltage.

The effect was discovered in quartz by the brothers Pierre and Jacques Curie in 1880.

It's first application was in 1920's when Langevin developed a quartz transmitter and receiver for underwater sound - the first Sonar.

Piezoelectric attractive for MEMS acts as both sensors and actuators and they can be deposited as thin films over standard silicon substrates.

Adding up the individual dipoles over the entire crystal gives a net polarization and an effective effective electric field with in the material.

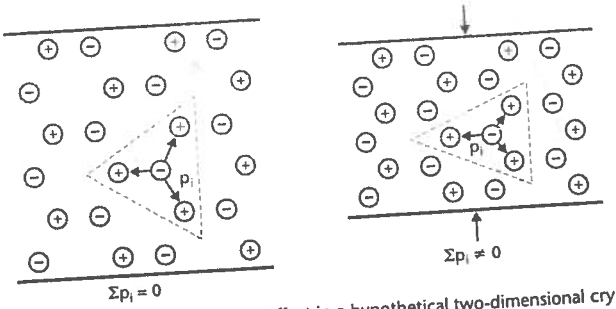
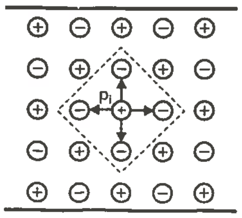
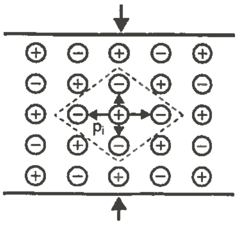


Figure 2.5 Illustration of the piezoelectric effect in a hypothetical two-dimensional crystal. The net electric dipole within the primitive unit of an ionic crystal lacking a center of symmetry does not vanish when external stress is applied. This is the physical origin of piezoelectricity. (*After:* [21].)

Silicon is not piezoelectric because it is cubic and further the atoms are held together by Covalent bonding.



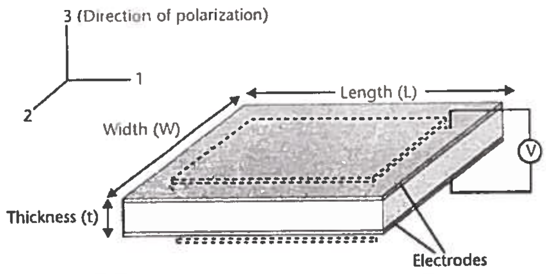
$\Sigma p_i = 0$



$\Sigma p_i = 0$

A Crystal possessing a centre of symmetry is not piezoelectric because the dipoles P_i, with in the primitive unit always Cancel each other out. Hence there is no net polarization with in Crystal. An externally applied stress doesnot alter the center of symmetry.

When temperature exceeds a critical Value called the Curie temperature, the material loses it's Piezoelectric characteristics.



Piezoelectric effect on a Crystalline plate. An applied voltage across the electrodes results in dimensional changes in all three axes (if d_{31} and 33 are non zero). Conversely an applied force in any of three directions gives to a measurable voltage across the electrodes.

d_{ij} in direction of i = Static voltage, electric field or surface charge.

in direction of j = applied force, displacement or stress.

un constrained displacements $\left\{ \begin{array}{l} \Delta L = d_{31} \cdot V_a \cdot L/t \quad \Delta W = d_{31} \cdot V_a \cdot W/t \\ \Delta t = d_{33} \cdot V_a . \end{array} \right.$ & if Voltage V_a is applied across the thickness of piezoelectric Crystal.

If Force F is applied along any length width or thickness directions a measured voltage Vm across the electrodes is $\left\{ V_m = d_{31} \cdot F/(\varepsilon \cdot W) \quad V_m = d_{31} \cdot F(\varepsilon \cdot L) \quad V_m = d_{33} \cdot F \cdot t(\varepsilon \cdot L \cdot W) \right\}$

Quartz is a widely used stand alone ~~piezoe~~ Piezoelectric material.

There are no available methods to deposit Crystalline Quartz as a thin film over silicon substrates.

Lithium niobate($LiNbO_3$) & Barium titanate($BaTiO_3$) are well known examples but they are also difficult to deposit as thin films.

Piezoelectric materials that Can be deposited as thin films with relative ease are lead zirconate titanate (PZT) - a Ceramic based on solid Solutions of lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$) - ZnO, and PVDF.

PZT → Sputtering or Sol-gel deposition

PVDF → Spun-on.

All the deposited films must be poled in order to exhibit piezoelectric behavior.

Poled:- Polarized by heating above the Curie temperatures then Cooling with a large electric field across them.

Material	(10^{-12}) C/N Piezoelectric Constant (d_{ij})	Relative Permittivity ($\mathcal{E}$)	Density (g/cm³)	Young's modulus GPas	Acoustic Impedence (10^6 kg/m²s)
Quartz	$d_{33} = 2.31$	4.5	2.65	107	15
PVDF	$d_{31} = 23$ $d_{33} = -33$	12	1.78	3	2.7
$LiNbO_3$	$d_{31} = -4$, $d_{33} = 23$	28	4.6	245	34
$BaTiO_3$	$d_{31} = 78$, $d_{33} = 190$	1700	5.7		30
PZT	$d_{31} = -171$, $d_{33} = 370$	1700	7.7	53	30
ZnO	$d_{31} = 5.2$, $d_{33} = 246$	1400	5.7	123	33

Thermo Electricity:-

Interactions between electricity and temperature are Common in 19th century underlying theory was not put in place until early 20th century by Boltzman.

In the absence of a magnetic field there are 3 distinct thermoelectric effects:-

Seebeck effect:- used in thermo Couples to measure temperature difference.

Peltier :- used to make make Thermoelectric Coolers & refrigerators.

Thomson effect:- less know and Uncommon in daily applications.

In Peltier effect current flow across a junction of 2 dissimilar materials causes heat flux, cooling one side and heating the other.

→ In 1950's large Scale appliances like the mobile wet bar which have poor energy Conversion efficiency

→ Today n-type & p-type bismuth telluride elements are used to cool microprocessors, laser diodes & IR Sensors.

→ Peltier devices have proven to be difficult to ~~implem~~ implement as micromachined thin film structures.

The seebeck effect named after the scientist who made the discovery in 1822.

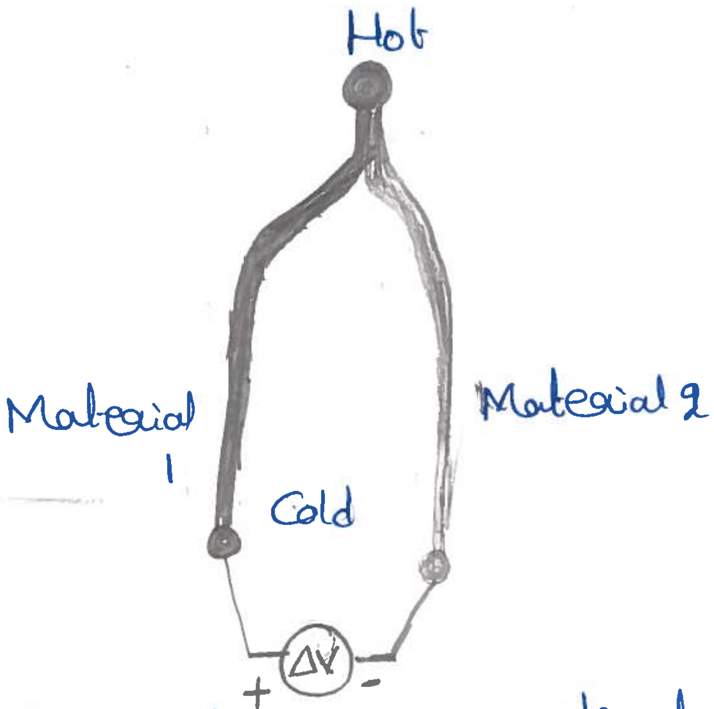
Temperature gradient across an element gives rise to a measurable E field that tends to oppose the charge flow resulting from the T imbalance

The measured Voltage is first order proportional to the temperature difference with the proportionality Constant known as seebeck effect.

$$\Delta V = \alpha_1 \cdot (T_{cold} - T_{hot}) + \alpha_2 (T_{hot} - T_{cold}) = (\alpha_2 - \alpha_1)(T_{hot} - T_{cold})$$

α_1 and α_2 are Seebeck Coefficients of materials 1 and 2.

T_{hot} and T_{cold} are the temperatures of the hot and Cold sides of thermocouple.



Measured Voltage is proportional to the difference in temperature.

ThermoCouples Can be readily implemented on silicon substrates using Combination of thin metal films or poly silicon.

→ Seebeck effect relative to Platinum for selected Metals and for n-and P-Type polysilicon are shown below

	µV/k		µV/k
Bi	-73.4	Ag	7.4
Ni	-14.8	Cu	7.6
Pa	-5.7	Zn	7.6
Pt	0	n-Poly ($30\Omega/\square$)	-100
Ta	3.3	n-Poly ($2600\Omega/\square$)	-450
		P-Poly ($400\Omega/\square$)	270