SMART SENSORS UNIT 3

By Disha Sharma

MEMS Sensor

- MEMS- Micro Electro-Mechanical Systems. Also called Microsystems Technology (MST).
- Electro-mechanical systems with miniaturized mechanical & electrical elements manufactured using microfabrication techniques.
- Range – few microns to cm.

Key features of MEMS sensor

- Miniaturization –
  - Small in size (few microns to cm)
  - Operational advantages like super sensitivity, low thermal reach, less intrusive (for example – in biomedical applications like probes)
- Micro electronics integration –
  - Embedded with computing, (sometimes networking & decision-making) capabilities.
  - Monolithic integration – fabrication of various components on a single substrate in an unbroken wafer level process flow.
  - Monolithic integration improves quality of signal by decreasing the length of signal path & noise.

Key features of MEMS sensor (Cntd…)

- Parallel fabrication with precision –
  - Can realize 2D or 3D features with small dimensions & precision which are difficult with traditional machining tools.
  - Mass production is possible.
- Low Power Consumption-
  - Energy-efficient, making them ideal for battery-powered devices such as IoT sensors, wearables, and portable medical devices.
- Cost effective

Components of MEMS sensor

- Micro Sensors –
  - Physical – force, acceleration, pressure, temp., flow etc.
  - Chemical/Biological – pH, concentration, binding strength etc.
  - Characteristics to be considered for sensor selection/design – linearity, sensitivity, accuracy, precision, resolution, range, interference/cross talk, cost, etc (**NOTE –** these characteristics are already discussed in detail earlier, hence no definition is provided here).

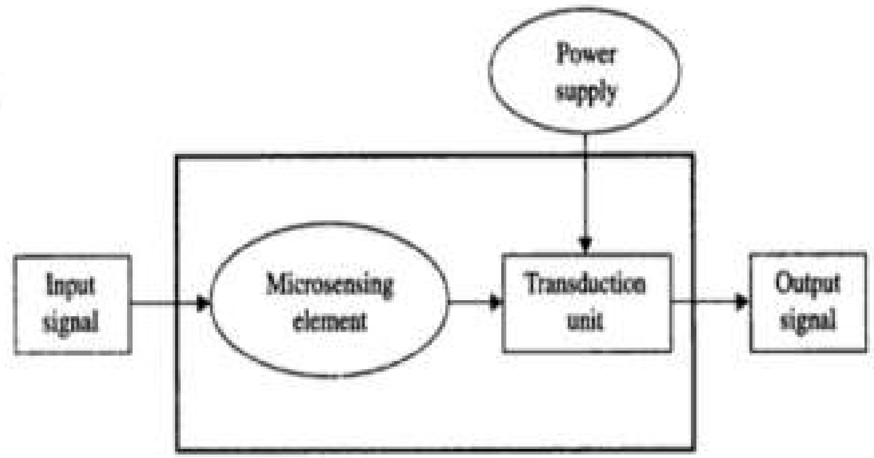


Figure 1. MEMS as a microsensor

Components of MEMS sensor (Cntd…)

- Micro Actuators –
  - Convert non-mechanical energy to mechanical energy like generating movements by using electrostatic force, piezoelectricity or thermal expansion.
  - Criteria when considering actuator selection/design-
    - Torque & force output capacity
    - Range of motion – linear or rotary
    - Dynamic response speed & bandwidth
    - Power consumption & efficiency
    - Linearity of displacement as a function of driving bias
    - Cross sensitivity & environmental stability
    - Footprint – total chip area actuator will occupy.

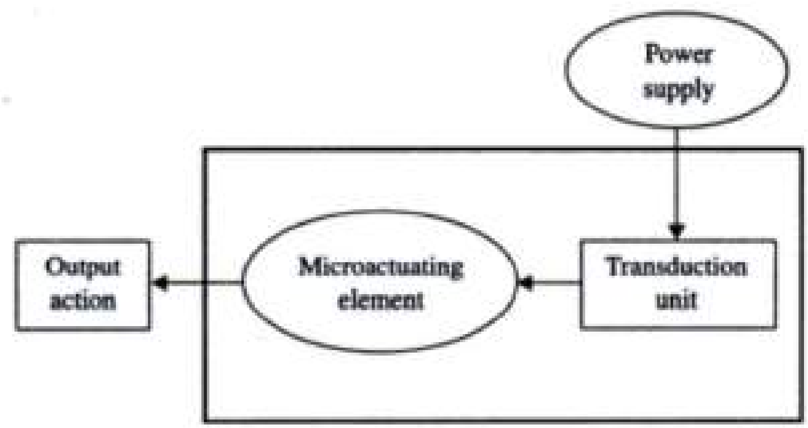


Figure.2 MEMS as a microactuator.

Components of MEMS sensor (Cntd…)

- Micro Electronics –
  - Processes the signals generated by the sensors & converts them into usable data
  - Can be filter, amplifier, clipper, clamper etc.
- Micro Structure –
  - Refers to the structure on which all the previously described components are placed.
  - Can be called a substrate or wafer.
  - Most commonly made of silicon.

Types/ Applications of MEMS sensor

- Accelerometers – measures acc. Forces. Used in smartphones screen rotation, airbags, fitness trackers, etc.
- Gyroscopes – measures rotational motion. Used in drone stabilization, game controllers, etc.
- IMU – Inertial Measuring Unit. Combination of Gyro & Accelerometer. Used in drones, robotics, & defence vehicles.
- Pressure Sensors – used in tire pressure monitoring, medical devices
- Microphones- used in mobile phones, hearing aids, etc.

NOTE – refer book shared to study various MEMS sensors & their working

Difference between MEMS & Macro sensor

Parameter	MEMS sensor	Macro sensor
Size & scale	Extremely small	Bulky, larger in size
Fabrication techniques	Photolithography, etching, deposition	Traditional mechanical machining & assembly
Mass production	Possible	Micro-scale production
Cost per unit	Low	Comparatively higher
Power consumption	Low	Comparatively higher
Signal processing	Integrated/In-built	External signal conditioning required
Environmental sensitivity	Can be sensitive to temp., humidity, stress	Robust

Microfabrication

- Process to crate miniature structures.
- Made on single crystal silicon wafers.
- Bulk Si with a crystalline structure doesn’t exist so it has to be made.
- Single Si seed is dipped in molten Si & drawn out forming Si crystals in atmosphere. Rods of Si crystals with various dia & longitudinal orientation can be formed.
- Rods are sawed into thin circular slices & polished to form wafers.
- Process used- photolithography, etching, deposition.

Crystal seed → Molten Silicon (drawing) → Crystal rod → Sawing operation → Polishing → Wafer → Packaging

Photolithography

- Objective – to produce fine features (patterns on the substrate) on wafers.
- Involves deposition of photo-sensitive chemicals called photo-resists or resists, on Si wafer, exposing it with light (UV) through a mask & removing photoresist material modified by light.
- Components of Photo-resist
  - Base material – polymer that forms pattern
  - Sensitizer – photosensitive agent
  - Solvent – to keep photo resist liquid then evaporate on baking
- Types of photo resist –
  - Positive – becomes soluble in wet chemical developer
  - Negative - becomes insoluble in developer.

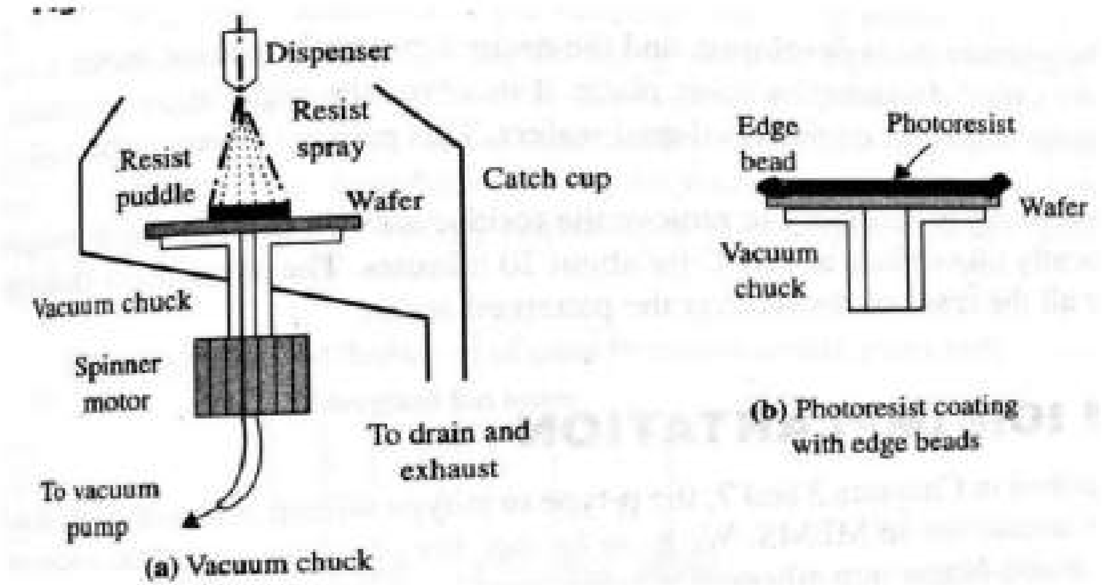
Photolithography (Cntd…)

Steps involved -

Deposition of photoresist → Soft baking (to harden the resist) → Etching pattern on substrate → Dissolving photoresist

Photolithography (Cntd…)

- Photo resist coating is done via spin coating. Then, the substrate is soft-baked to harden the photoresist layer.
- A resist puddle is applied to the center portion of the wafer from a dispenser. The wafer is then subjected to high-speed spinning at a rotational speed that varies from 1500 to 8000 rpm for 10 to 60 seconds.

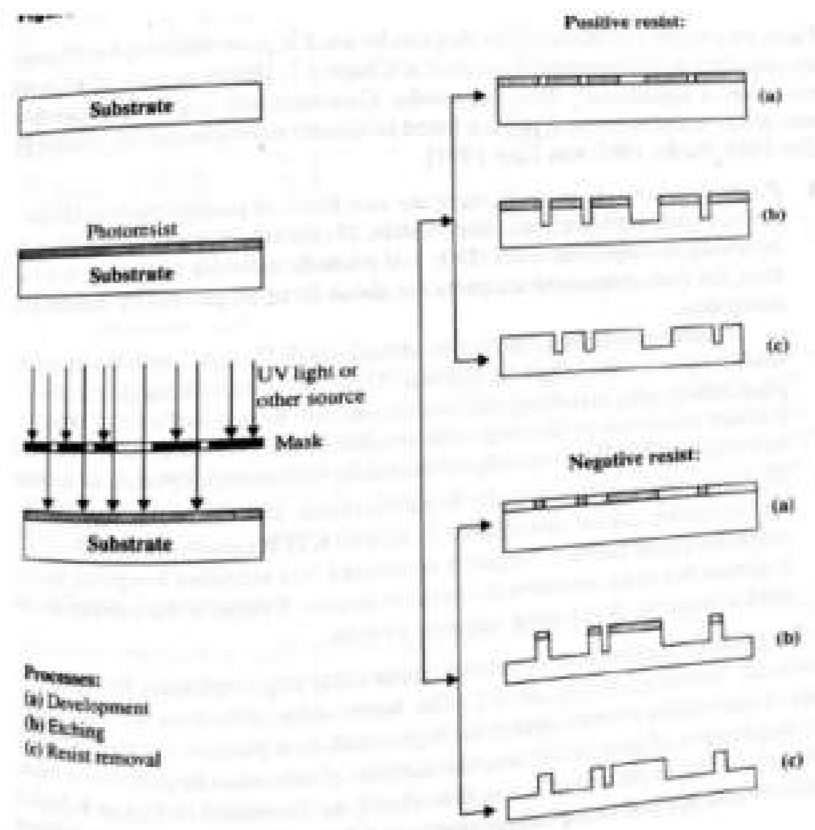


Photolithography (Cntd…)

- Due to the centrifugal force/spin the resist spreads uniformly forming a layer on the substrate.
- The speed depends on the type of resist, desired thickness and uniformity of the resist coating. The thickness is between 0.5 and 2μm with ±5 nm variation
- A common problem is the bead of resist that occurs at the edge of the wafer as shown in Figure (b) These beads can be bigger than the size of the resist. The uniformity of the coating can be increased and the thickness of the edge beads can be reduced by controlling the spin speed.

Photolithography (Cntd…)

- A photo resist is first coated onto the flat surface of the substrate.
- The substrate with photoresist is then exposed to a set of lights(high energy, collimated light rays) through a transparent mask with the desired patterns. Masks used for this purpose are often made of quartz .

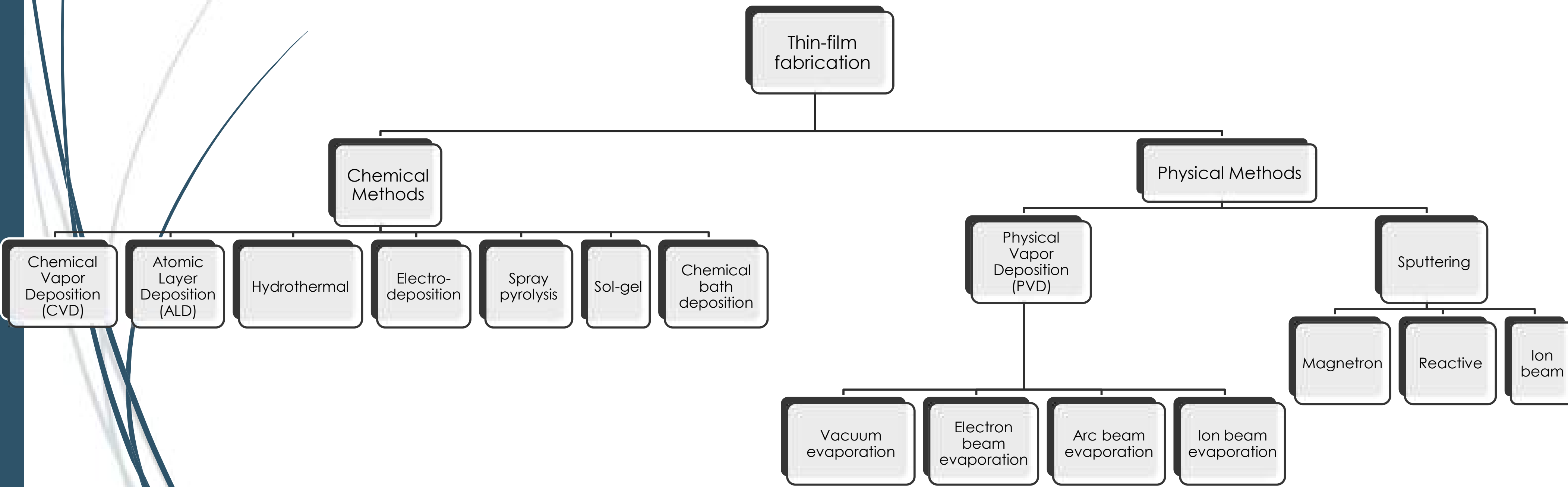


Photolithography (Cntd…)

- Photoresist materials change their solubility when they are exposed to light, they become soluble and called as positive photoresists. The retained photoresist materials create the imprinted patterns after the development.
- Now substrate with the photoresist is dipped in a developing solution where +ve resist will become soluble & leave a permanent pattern.

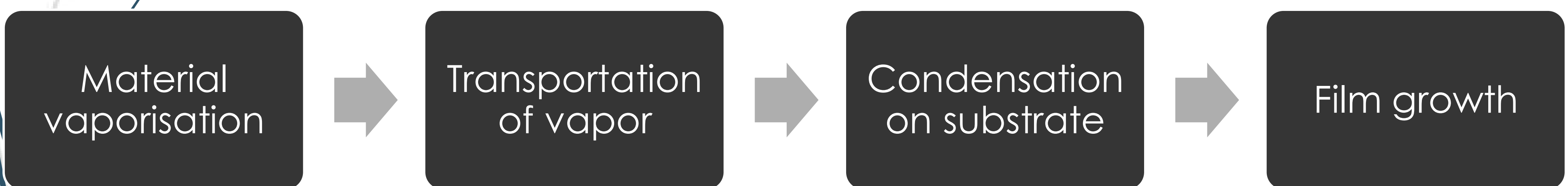
Thin-film fabrication techniques

- Thin film is a layer of material with thickness in the range of nm to μm.
- Importance – improves surface properties like higher conductivity, corrosion resistance, reflection, hardness, etc.



PVD

- Deposition – Process used to create thin or thick layers of substance atom-by-atom or molecule-by-molecule.
- Material to be deposited is vaporized and then condensed on substrate at the atomic or molecular level.



PVD (Cntd…)

- Types of PVD –
  - Thermal Evaporation –
    - Material is heated in a vacuum until it vaporizes. Heating can be done via resistive heating or laser heating.
  - Arc Ion evaporation –
    - Impurities such as vapor in air are reduced to create a vacuum.
    - Substrate is heated to remove its moisture.
    - Etching is done where Argon (Ar) ions are generated from plasma source & impacted on the substrate with force.
    - Coating – arc discharge is conducted by vaporizing the metal material into a plasma state & ionizing the film forming elements.
    - -ve voltage is applied to substrate to be coated & ionized elements (Ar^+) impacted with force are deposited

Vacuum exhaust → Heating → Etching → Coating

PVD (Cntd…)

- Types of PVD –
  - Arc Ion evaporation –
    - Advantages – High deposition rates, can deposit hard coatings like titanium nitride (TiN) or diamond-like carbon.
    - Applications – coating cutting tools
  - Electron beam evaporation –
    - Electron beam is focused on target material providing enough energy to vaporize it.
    - Advantages – high precision
    - Applications – optical coatings, semiconductor manufacturing

PVD (Cntd…)

- Advantages of PVD –
  - Thin & uniform films
  - Versatility
  - Environmental friendliness
  - Strong adhesion
  - Improved surface properties like hardness, wear resistance, low contamination.
- Disadvantages of PVD –
  - Complex equipment
  - Line-of-sight deposition i.e., surface not directly exposed to vapor may not receive even coating
  - May require high temperature

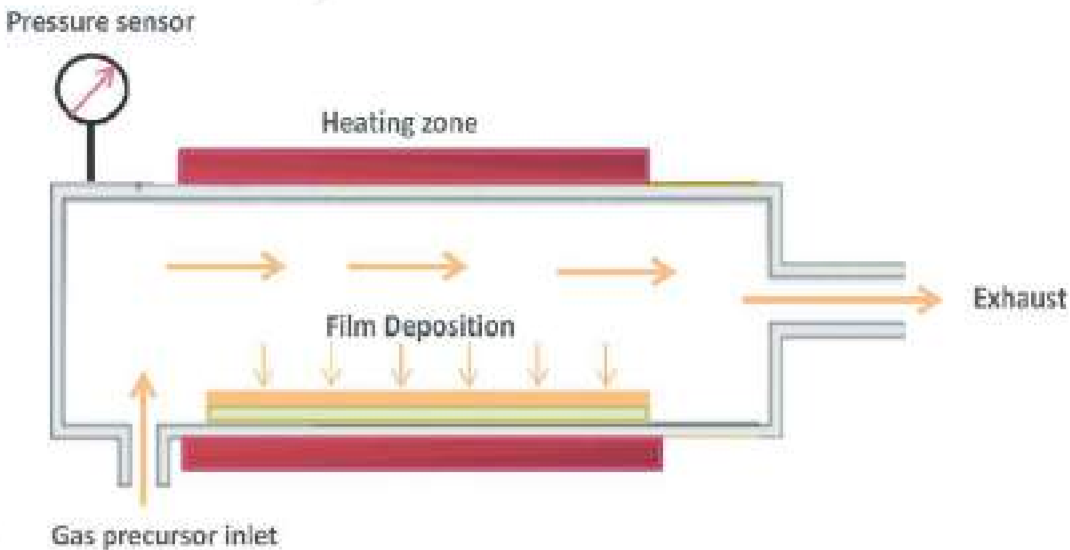
Sputtering

- Process in which atoms in solid state are released & passed into the gas phase by bombardment with energetic ions (mainly noble gas).
- Ion Bombardment - Ejecting atoms or molecules from target material through bombardment by energetic ions. Inert gas like Ar is introduced in a vacuum chamber. High voltage electric field is applied to ionize the gas creating a plasma.
- Ejection of atoms – When energetic ions strike the surface of target material they transfer energy. The energy dislodges or ‘sputters’ the atos by ejecting them into gas phase.
- Transport - These ejected atoms travel through vacuum.
- Film deposition – after enetering the chamber the deposit on the substrate.

Sputtering (Cntd…)

- Types of sputtering –
  - Magnetron - magnetic field is used to trap electron near target material increasing the ionization of plasma. The electron spiral around magnetic field lines creating more collisions with the gas atoms generating dense plasma near target.
  - Reactive – reactive gas like oxygen or nitrogen is introduced along with Ar. Sputtered material reacts with reactive gas to form oxidied, nitrides etc & deposit on substrate.
  - Ion-beam – instead of creating a plasma, focused beam is directed at target material to sputter.
- Advantages of sputtering – similar to PVD
- Disadvantages of sputtering –
  - Low deposition rates
  - High cost

CVD

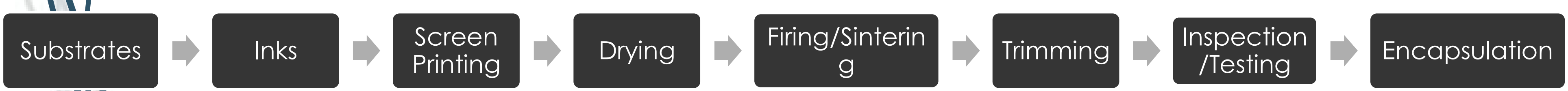


- 2 or more active species arrive at the vicinity of the wafer surface & react under favourable condition.
- Involves flow of gas with diffused reactants over a hot surface. The gas that carries the reactants is called 'carrier gas'.
- The energy supplied by the surface temp. provokes chemical reaction of the reactant forming a film
- The by-products are vented out
- Conditions for Low Pressure CVD –
  - Pressure – 0.2-2 torr
  - Gas flow – 1-10 cm^3/s
  - Temp. – 300 ° -900°C

Carrier gas in chamber → Chemical reaction on contact → Film formation → Film growth

Thick-film fabrication technique

- Substrates –
  - Most commonly used ceramics usually alumina (Al_2O_3) due to its high mechanical strength, chemical resistance & thermal stability.
  - Other substrates like porcelainized steel, organic materials like epoxies, flexible substrates even synthetic diamond.
- Inks –
  - Prepared by mixing powder with solvent/polymer paste.
  - Different formulation of pastes are used to produce- conductors, resistor, dielectrics, binder (a glassy frit).
  - Functional material – metal powder. Ex – Ag, Au, Pt for conducters. Metal oxides for resistors or ceramic powders for dielectrics



Thick-film fabrication technique (Cntd…)

- Inks –
  - Binder – an organic polymer or resin that helps the paste maintain its form.
  - Solvent – a liquid carrier that dissolves the binder ensuring right viscosity for printing.
- Screen printing –
  - A stencil/mesh screen is often made of steel/polyester and is placed over the substrate & the paste is spread using a squeegee.
  - Layer thickness depends on mesh size, viscosity of paste & pressure applied during printing.
  - This way allows precise control over pattern, suitable for crating intricate circuit layouts & sensors.

Thick-film fabrication technique (Cntd…)

- Drying -
  - After screen printing, the paste contains solvent & binder which need to be removed.
  - So printed substrate is placed in an oven & dried at moderate temp (80 ° -150°C) for few mins.
- Firing/Sintering –
  - Done at high temp. 500 ° -900°C.
  - Removes organic binders & causes metllic/ceramic particles in the paste to bond together stronger.
  - Mechanism – at high temp., particles in the paste fuse forming a continuous conductive or resistive film. This process enhances mechanical strength, electric conductivity & adhesion of fim substrate.
  - May require controlled atmosphere to prevent oxidation.

Thick-film fabrication technique (Cntd…)

- Trimming -
  - After sintering, the resistance or performance of resistive or capacitive components may need fine tuning.
  - This is done via trimming where laser removes small portion of material.
  - Can be done in open loop i.e., estimating the material to be removed or in closed loop i.e., real time monitoring.
- Inspection & testing –
  - Tested to ensure proper functionality including correct resistance, capacitance, or inductance.
- Encapsulation –
  - Optional
  - To protect from moisture, dust or mechanical wear.
  - Done via protective coating or sealing compound.

Thick-film fabrication technique (Cntd…)

- Types of thick film techniques –
  - Screen printing – patterned mesh screen used for printing
  - Stencil printing – metal stencil used for printing
  - Plasma spray coating –
    - Material in powder form is injected at high temperatures plasma jet where it melts & is sprayed onto the surface. Particles cool & solidify forming a thick, dense coating.
    - Used in protective coating industries where corrosion & wear resistance are critical
    - Advantages – high deposition rates & ability to deposit thick , durable films
  - Electroplating –
    - Conductive substrate is submerged in solution of metal ions, By applying current, metal ions are reduced (gain of electrons) & deposit on surface.
    - Used for metals like Au, Cu, and Ni in PCBs.
    - Advantages – excellent control over film thickness & is capable of producing thick, high quality films.

Thick-film fabrication technique (Cntd…)

- Types of thick film techniques –
  - Dip coating –
    - Substrate is dipped into solution containing desired film material & withdrawn at controlled speed. Thickness of film depends in viscosity of solution & withdrawal speed.
    - Advantages – simple, can coat complex shapes.

Sensors for robotics

- Proximity sensors -
  - IR sensor
  - Ultrasonic sensor
  - Capacitive/Inductive sensor
- Vision sensors -
  - 2D camera
  - 3D camera
  - LIDAR – Light Detection And Ranging
- Touch/Tactile sensors -
  - Force sensitive sensors
  - Piezoelectric sensor
  - Capacitive touch sensor

Sensors for robotics (Cntd…)

- Position & motion sensor -
  - Encoders
  - Gyroscopes
  - Accelerometers
  - IMU – Inertial Measuring Unit
- Force & torque sensor -
  - 6-axis force/torque sensor
  - Strain gauges
- Temperature sensor
- Sound sensor/microphone
- Gas sensors

Sensors for robotics (Cntd…)

- Light sensor -
  - LDR
  - Photodiode
  - Phototransistor
- Biosensors
- Magnetic sensors

Wireless Sensors - devices that detect physical change & transmit the measured physical quantity wirelessly to a hub or control system.

Transmission of data without physical connections.
Used where traditional wiring is costly.

Wireless sensor network -

Network of distributed sensors that wirelessly transmit data.
Collection of sensing devices working together
Transfer can be done @ RF or using electromagnetic (EM) or acoustic waves over atmosphere. EM waves travel at speed of light in free space & inside medium with a delay time = length of cable / c
Node - sensor capable of communication.

Architecture of WSN -

Layered Network architecture -

Uses 100s of sensor nodes as well as base station.
Arrangement of network nodes can be done into concentric layers.
5 layers - Application, Transport, Network, Data Link & Physical
3 cross layers - Power management, Mobility management, Task management plane
Cross layers mainly used for controlling network as well as to make sensors func. as one in order to enhance efficiency.

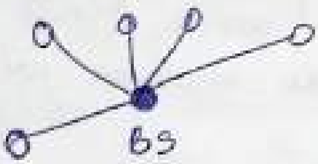
↗ application specific
Application Layer - traffic management. offers software for numerous applications that convert data in clear form to find +ve info.

Transport Layer - to deliver congestion avoidance & reliability where lot of protocols intend to offer this func. are either practical on the upstream.

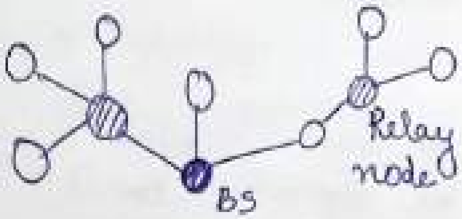
This layer is needed when system is planned to contact other networks.
Provides end-to-end data transmission reliability.
Protocols used - TCP, UDP

Network Layer - responsible for routing data from sensor nodes to base station or neighbouring nodes using multi-hop or single-hop communication.

Single hop - sensor node directly connected to B.S. & takes command from BS

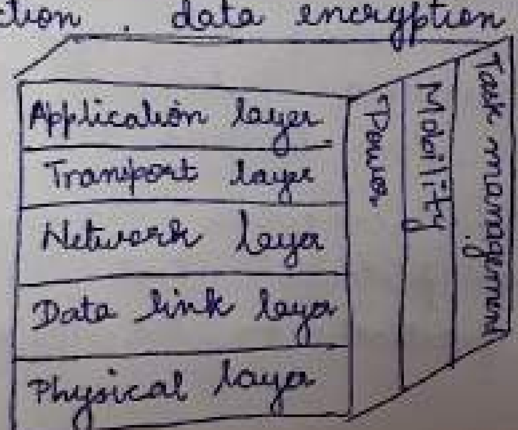


Multi-hop - instead of single link b/w node & BS, data is transmitted through one or more intermediate node

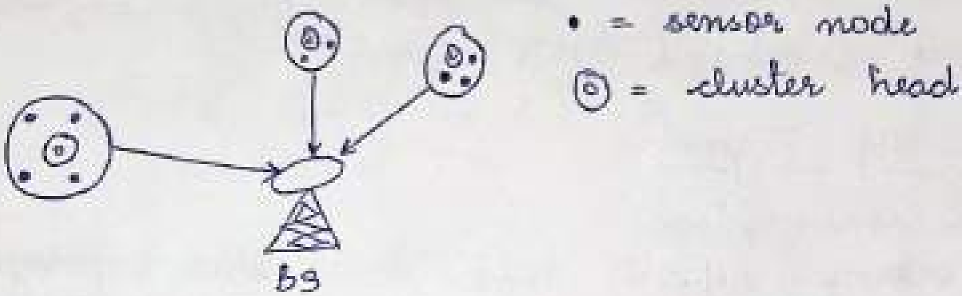


Data Link Layer - ensures reliable data transmission between sensor nodes by handling error, managing access to communication medium & maintaining link control.

Physical Layer - deals with actual transmission & reception of data via wireless comm. channels.
Handles modulation, transmission freq., signal detection, data encryption / decryption.

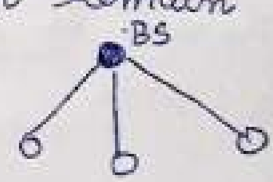


Clustered Network Architecture - seperately sensor nodes add into groups known as clusters which depend on LEACH protocol (Low Energy Adaptive Clustering Hierarchy). Each cluster has cluster head which exchanges message with their respective ~~cluster~~ head sensor nodes & sends message to BS

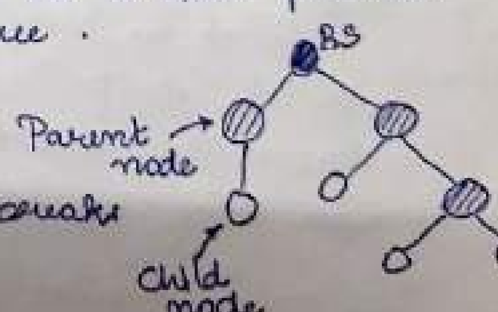


Structure of WSN -
Comprises of various topologies -

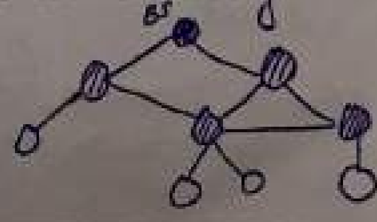
Star Topology - each node connected to gateway. Gateway can send or receive message to several nodes but nodes are not permitted to send message to each other. This allows low latency. Due to its dependency, gateway must remain in radio transmission range.
Minimum power consumption
Under control



Tree topology - also called cascaded star. Each node connected to a node placed ~~two~~ higher in tree.
Easy expansion
Easy error detection
Relies heavily on bus cable so if it breaks network will collapse.



Mesh topology - every node can communicate with each other either directly or via multi-hop routing



Zigbee - wireless comm. protocol intended primarily for wireless personal area network (WPAN).

WPAN - wireless network designed to cover a small area typically within the range of individual's surrounding.

Can establish comm. b/w laptop, mobile, wearables etc.

Common WPAN Technologies - Bluetooth, Zigbee, Infrared (IrDA), Ultra-wideband (UWB) etc.

Key features of Zigbee -

1. Low power consumption
2. Mesh networking - supports mesh, tree, star topologies ↑ coverage area & enhances network reliability
3. Low data rate - optimized for low data rate applications (250 kbps at 2.4 GHz) where bandwidth is not a priority, such as transmitting sensor data or controlling devices.
4. Scalability - can scale from few nodes to 1000s with hierarchical structure
5. Optimised or long battery life
6. Affordable

Components - For smart home system

Zigbee Coordinator - smart home controller can be referred as hub, gateway or bridge. Establish network itself, setup & maintain security, add devices to network & manage comm. Act as root. Can only be 1 ZC & needs to be powered ON always

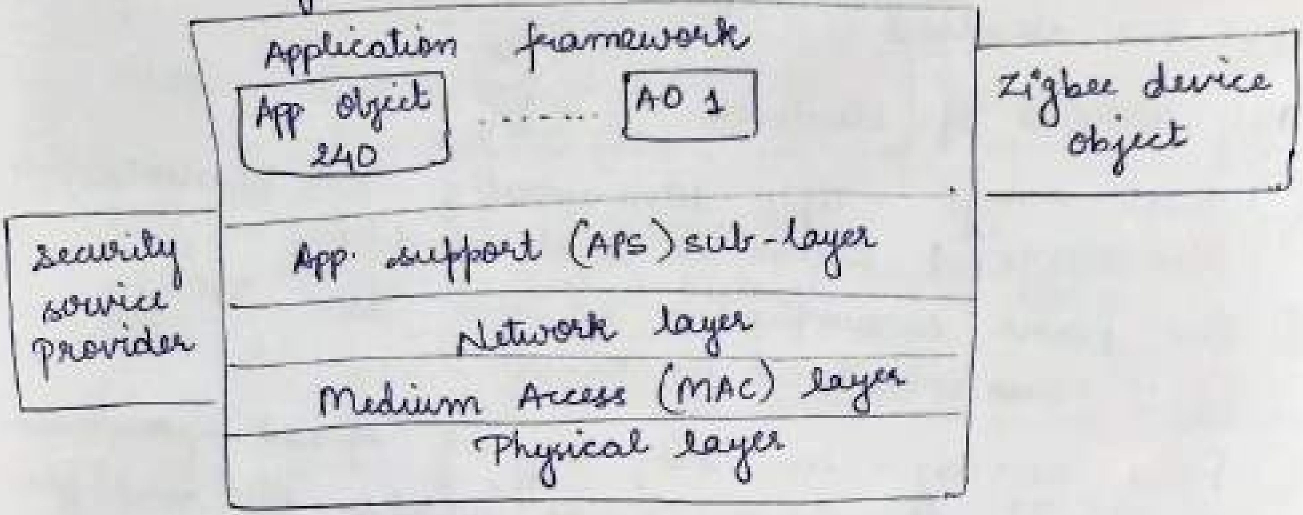
Zigbee Router (ZR) - extend comm. range by relaying data b/w devices. Can be many routers within network

Zigbee End Devices (ZED) - most basic device on network generally sensor or actuator. Perform specific func. like sensing, collecting or transmitting data

Can't relay data, depend on ZC or ZR to send info.

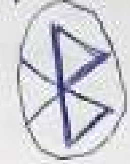
Zigbee protocol architecture -

Based on IEEE 802.15.4 standard defined by physical & MAC layers while complimented by accumulating its own network & application layers.



- Physical layer - does modulation & demodulation operations & defines how data is transmitted & received on radio freq. spectrum. Channel selection. Data to MAC layer.
- Data link / Medium Access (MAC) layer - handles access control & collision avoidance using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Manage access to physical medium & provides reliable data transmission b/w devices.
- Network layer - responsible for establishing, maintaining & routing data. Ensures messages reach their destination.
- Application support (APS) sub-layer - provides data transfer b/w application objects & zigbee device objects (ZDO). Basically, matches 2 devices according to service & needs.
- Application framework - defines app. profile & device role. Ex- ON/OFF of light.
- ZDO - manages device roles, discovery, security setup, controls network formation, device joining & binding

Bluetooth - WPAN technology. Use to exchange data over smaller distances. Invented by Ericson in 1994. Operates in the Unlicensed, Industrial, scientific & Medical (ISM) band at 2.4GHz to 2.485 GHz. Max devices that can be connected at same time are 7-8. with each device having unique 48 bit address from IEEE 802 standard.



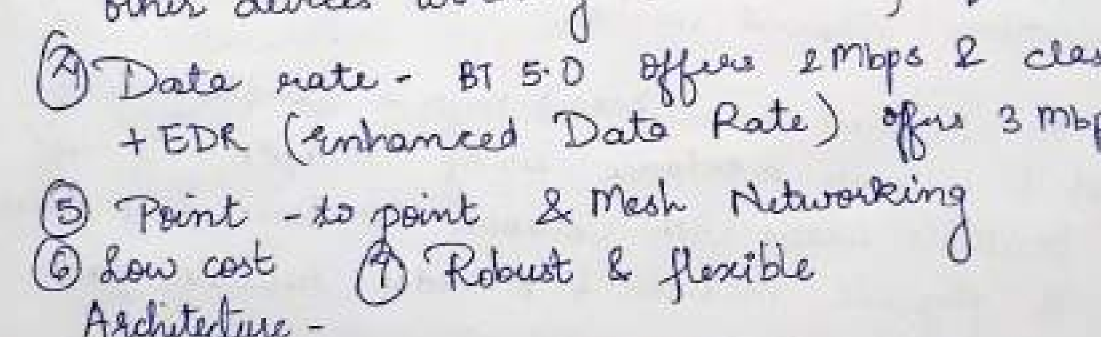
Key features of bluetooth -

1. Short range - upto 10m usually. But Bluetooth 5.0 the range ↑ 240m in ideal conditions.
2. Low power consumption - Bluetooth Low energy (BLE) was introduced in BT 4.0
3. Freq. hopping - uses freq. hopping spread spectrum (FHSS) to ↓ interference. It switches b/w multiple freq. during transmission to avoid interference from other devices working at same freq.
4. Data rate - BT 5.0 offers 2Mbps & classic bluetooth + EDR (Enhanced Data Rate) offers 3 Mbps.
5. Point - to point & Mesh Networking
6. Low cost
7. Robust & flexible

Architecture -

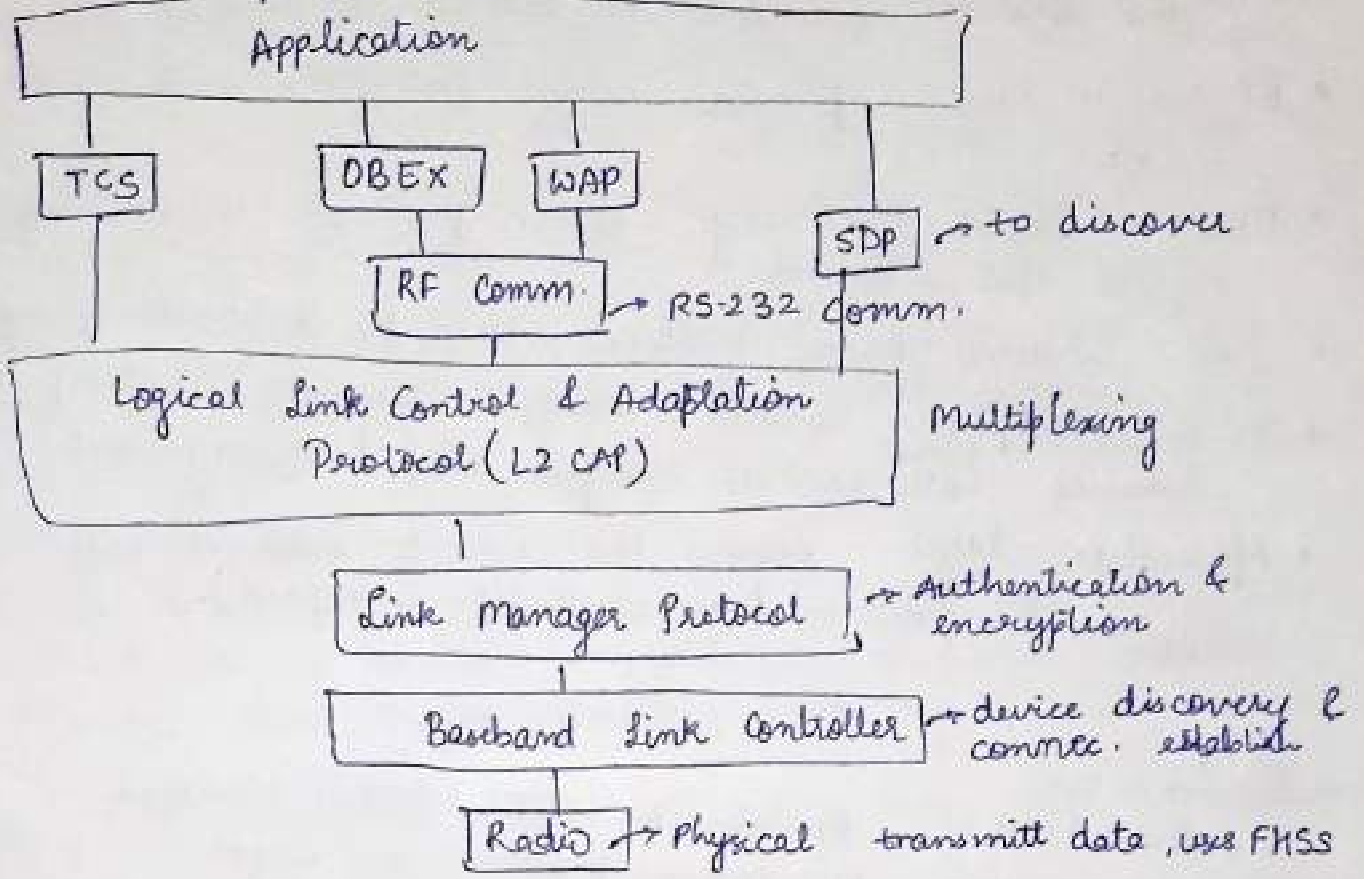
Piconet - type BT network that contains one master node & 7 active 2ndary nodes called slave nodes. Possible comm. master - slave. No slave - slave.

Scatternet - formed using multiple piconets. A slave in 1 piconet can act as master for another



Scatternet

Bluetooth protocol stack -



- Radio layer - It specifies details of air interference, including freq, uses FHSS, performs modulation / demodulation of data
- Baseband link controller / layer - digital engine of BT. Equivalent to MAC sublayer. Performs connection establishment within a piconet, addressing, packet format, timing & power control.
- Link manager protocol layer - performs management of already established links which includes authentication & encryption process. Responsible for creating links, monitoring health & terminating them on command or incase of failure.
- L2CAP - known as heart of BT. Allows comm. b/w upper & lower layers. Packages data packets received from upper layers into expected form by lower layers. Perform segmentation & multiplexing.

- SDP - Service Discovery Protocol. Allows discovering the services available on another BT enabled device.
- RF comm layer - provides serial interface with WAP & OBEX.
- OBEX - Object Exchange. Comm. protocol to exchange objects b/w 2 devices
- WAP - Wireless Access Protocol. Used for internet access.
- TCS - Telephony Control Protocol. Provides telephony service. Call control - ~~setput~~ setup & management
- Application layer - enables the user to interact with application (HCI - host controller interface).

Wi-Fi -

Wireless Fidelity. Operates on IEEE 802.11 standard which outlines the comm. protocol for WLAN

Key features -

① Wireless Connectivity - allows internet access within range
② High data rates - multi gigabits
③ Wide compatibility - phone, laptop, appliances
④ Multiple bands - 2 freq. bands - 2.4GHz broader coverage but slow speed. More susceptible to interference other devices
5GHz - fast speed, less interference but short range.
6Hz - newly introduced, more channels, faster speed & lower latency.
⑤ Multiple users
⑥ Encryption & security - uses WPA2/3 (Wifi Protected Access 3) to secure data & protect networks from unauthorised access.
⑦ Easy to set up ⑧ One time investment hence inexpensive

Working - uses RF to transmit data b/w devices

- Wireless Access Points (WAPs) - central device that creates wireless network. Broadcasts wi-fi signals to devices in its range & connects them to internet
- Devices & network interfaces - devices have built-in network interfaces that allows them receive & send radio signals
- Data transmission - data is divided into small packets & send through wifi network to dest. device. These packets are decoded by receiving device, allowing data exchange b/w device & router
- Router & internet access - Router connects the local wifi network to broader internet via a wired connection. Manages data traffic, directing incoming & outgoing packets

Encryption - WPA2 protects the data transmited over network