

Module-1 Functional Materials for Memory and Display Systems

Memory Devices: Introduction, organic semiconductors; types of organic semiconductors used in memory devices, p-type semiconductor-pentacene and n-type semiconductor-perfluoropentacene. Differences between organic and inorganic memory devices. Construction, working, and advantages of the pentacene semiconductor chip.

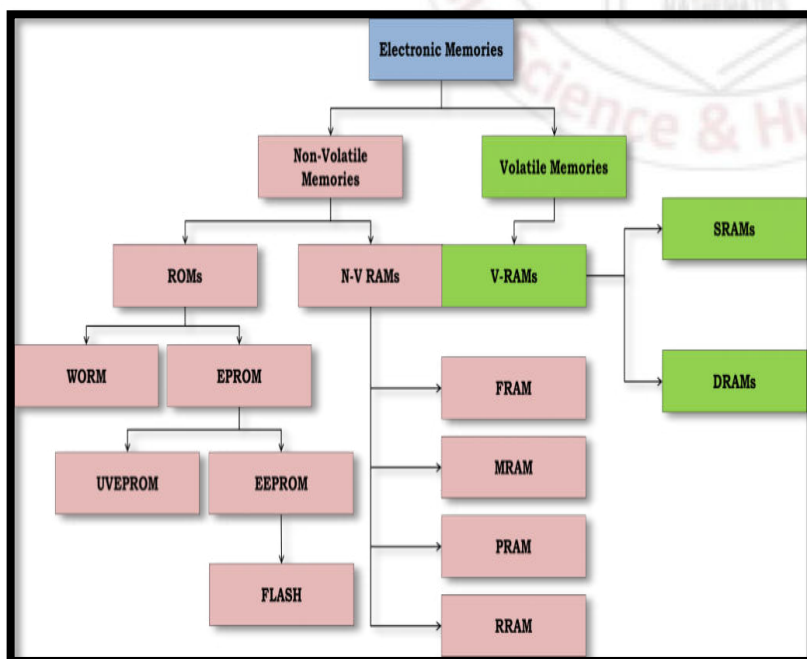
Resistive RAM (ReRAM) Materials: Introduction, synthesis of TiO_2 -RAM nanomaterial by sol-gel method, properties and applications.

Display Systems: Introduction, liquid crystals (LCs)-classification, properties, and their applications. Construction, working principle, and applications of Light Emitting Diodes (LEDs), Organic Light Emitting Diodes (OLEDs), Active-Matrix Organic Light Emitting Diodes (AMOLEDs), and Quantum Light Emitting Diodes (QLEDs).

MEMORY DEVICES

An **electronic memory** is a component, device, or recording medium used to store data for retrieval on a temporary or permanent basis for use in a computer or other digital electronic devices. It is a fundamental component of all modern computers and electronic systems.

- The basic goal of a memory device is to provide a storing and accessing **binary digital data sequences of “1’s” and “0’s”**.



Electronic memories can be divided into two primary memory categories:

- Volatile memory**, which requires a constant power supply to retain the stored information, it loses written data as soon as the system is turned off.
Ex: RAM
- Non-volatile memory**, which retains stored information even when the electrical power supply is turned off.
Ex: ROM

- Currently, DRAM and Flash memories constitute the biggest part of the semiconductor memory market.
- DRAM (dynamic random-access memory) is volatile, high-speed, short-term memory that loses data when power is off, while Flash memory is non-volatile, slower, long-term storage that retains data even without power, like on SSDs and USB drives.
- DRAM acts as a computer's working memory for running programs, whereas Flash is used for permanent data storage.
- Secondary memory or External storage includes HDD, SSD, CD, DVD, USB flash drives and SD cards.

Organic semiconductors:

- Organic semiconductors are carbon-based materials with conductivity between that of metals and insulators, characterized by pi-conjugated structures that allow for electrical charge transport.
- Organic semiconductors are organic materials, typically polymers or small molecules containing carbon and hydrogen atoms, that possess properties of both organic compounds and semiconductors.
- They conduct electricity by allowing charges (electrons or holes) to move along their pi-conjugated systems.
- While they are insulators under normal conditions, their conductivity can be increased by external factors like voltage, light, or heat.

Importance:

- Organic semiconductors are crucial for the development of the next generation of electronic devices.
- They enable the creation of flexible electronic devices, such as wearable health monitors, foldable displays, and flexible solar cells, which are not possible with traditional rigid inorganic semiconductors.
- Their compatibility with various biological systems opens doors for applications in biomedical engineering.

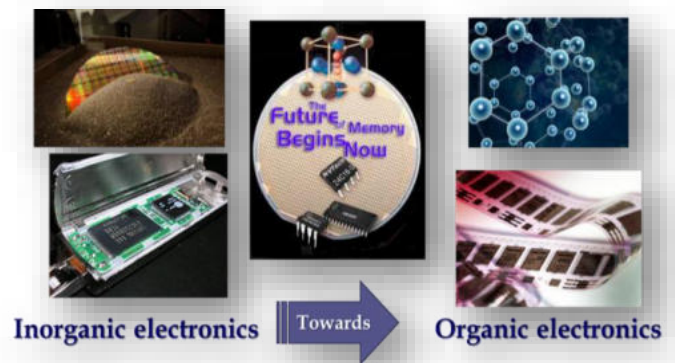
Advantages:

- **Mechanical Flexibility:** Their inherent polymer structure allows for the creation of flexible and even stretchable electronics.
- **Chemical Versatility & Tunability:** Molecular design allows for precise control over the material's electronic and optical properties, such as its band gap.
- **Low-Cost Fabrication:** Organic semiconductors can be processed using low-temperature and printing techniques, which are simpler and less expensive than that of silicon.
- **Lightweight:** These materials are lighter than their inorganic counterparts.
- **Compatibility with Flexible Substrates:** They can be deposited on various substrates, including plastics, textiles, and paper, integrating electronics into everyday objects.
- **Environmentally Friendly:** The materials and processing methods often have a lower environmental impact and can be more energy-efficient.

Why an Organic Memory Device?

- The focus of research is on obtaining non-volatile, fast, high-density, low-power consumption, high data transfer rate and reliable memories.

- Numerous types of memories have been proposed to overcome the shortcomings of conventional memories. Among the emerging candidates for non-volatile memories, organic materials are promising candidates for future molecular-scale device applications.
- Organic electronics is going to offer the mechanical flexibility, stretchability, as well as low-cost manufacturability, complementing the computing power of silicon electronics.
- Moreover, the low-temperature fabrication process of organic memory also offers benefits for integrating memory devices into stretchable electronic systems on an elastic polymeric substrate.



TYPES OF ORGANIC SEMICONDUCTOR:

Organic semiconductors are classified into three types, such as, Small-Molecule, Polymeric and Organic Inorganic semiconductors.

Small-Molecule Organic Semiconductor:

Definition: Small-molecule organic semiconductors are low molecular weight organic compounds with well-defined structures and conjugated π -electron systems.

Ex: Pentacene, Anthracene & Rubrene.

Properties:

1. High crystallinity and planarity enable strong π - π stacking between molecules.
2. Typically exhibit high charge carrier mobility (especially hole mobility in p-type materials).
3. Narrow and tunable HOMO–LUMO gaps allow for efficient charge injection and transport.
4. Sensitive to processing conditions for crystal quality and film morphology.



Advantages:

- **Flexibility and Light Weight:** They allow for the creation of bendable and lightweight electronic devices.
- **Tunable Properties:** Their electronic and optical properties can be precisely adjusted through molecular design, allowing for optimized performance in specific applications.
- **Cost-Effectiveness:** They offer the potential for low-cost, solution-based fabrication, which can reduce manufacturing expenses.

- **Biocompatibility:** Their ability to interface with biological systems makes them ideal for bioelectronic and wearable health applications.

Applications:

- **Organic Light-Emitting Diodes (OLEDs):** These are used in various displays, known for their excellent emission properties and flexibility.
- **Organic Photovoltaics (OPVs):** Also known as solar cells, these convert light into electricity, with small molecules offering advantages for building-integrated photovoltaics due to their lightweight nature.
- **Organic Field-Effect Transistors (OFETs):** Used in flexible displays and smart cards, OFETs are a key component in the development of flexible electronics.
- **Sensors:** Small-molecule organic semiconductors are integral to sensors for detecting gases and biological parameters, such as glucose, making them useful for both environmental monitoring and healthcare.
- **Thermoelectrics:** These can convert heat energy into electricity, with applications in small devices like wearable sensors and watches.
- **Bioelectronics:** Organic semiconductors' biocompatibility and flexibility enable their use in wearable health monitoring devices, facilitating personalized medicine.

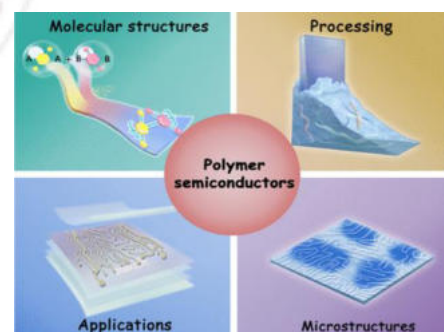
Polymeric Organic Semiconductor:

Definition: Polymeric organic semiconductors are long-chain macromolecules composed of repeating units with conjugated backbones.

Ex: Polythiophene derivatives and Poly(p-phenylene vinylene).

Properties:

1. Long-chain conjugated polymers with repeat units allow flexible film formation.
2. Solution is processable and compatible with low-cost printing techniques.
3. Moderate charge carrier mobility, often lower than small molecules but improving with design.
4. Tunable optical and electronic properties through chemical modification of side groups.



Advantages:

- **Flexibility:** Their inherent flexibility makes them ideal for flexible and stretchable electronic devices.
- **Low Cost:** Compared to traditional inorganic semiconductors like silicon, organic semiconductors offer lower manufacturing costs.
- **Tunable Properties:** Synthetic chemists can tune the electronic and optical properties of these materials by changing their molecular structure, allowing for tailored performance in specific applications.
- **Solution Processability:** Many organic semiconductors can be processed from solutions, enabling large-area fabrication techniques like inkjet printing for cost-effective device manufacturing.

Applications:

- **Organic Light-Emitting Diodes (OLEDs):** These are used in displays and lighting, benefiting from the semiconductor's ability to emit light through electron-hole recombination.
- **Organic Photovoltaic Cells (Organic Solar Cells):** These devices convert solar energy into electricity, utilizing the semiconductor's tuned band gap and light absorption properties.
- **Organic Field-Effect Transistors (OFETs):** Used in flexible electronics, smart cards, and integrated circuits, OFETs are a prime example of organic semiconductors in electronic devices.
- **Sensors:** Organic semiconductors are increasingly used in various types of sensors, including gas sensors and biosensors, due to their sensitivity and ability to be functionalized for specific targets.
- **Bioelectronics:** Their biocompatibility and flexibility make organic semiconductors promising for implantable medical devices, wearable technology, and interfaces with biological systems.
- **Thermoelectrics:** These materials can convert heat energy into electrical energy, finding applications in waste heat recovery and small-scale power generation.

Organic-Inorganic Hybrid Semiconductor

Definition: Organic–inorganic hybrid semiconductors are composite materials combining organic small molecules or polymers with inorganic substances such as nanoparticles, quantum dots, or metal halide perovskites(CaTiO_3).

Ex: Organic–inorganic perovskites and Hybrid nanostructures.

Properties:

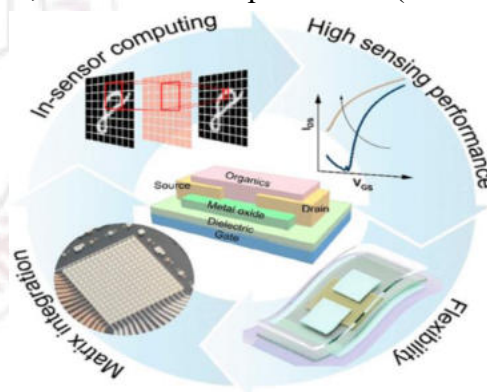
1. Enhanced charge transport through inorganic frameworks paired with organic tunability.
2. Improved stability and vigorous due to inorganic content.
3. Often exhibit superior light absorption and emission efficiency.

Advantages:

- **Tunable Properties:** The electronic and optical properties can be rationally designed by adjusting the molecular structures and material compositions.
- **Solution-Processability:** Many hybrid materials, particularly perovskites, can be processed at low temperatures from solutions, simplifying fabrication and enabling low-cost production.
- **High Performance:** They offer properties similar to conventional inorganic semiconductors, such as high charge carrier mobility and long diffusion lengths.
- **Flexibility:** Blending inorganic components with flexible organic materials offers advantages for optoelectronic devices requiring mechanical flexibility.

Applications:

- **Solar Cells (Photovoltaics):** Halide perovskites are a leading candidate for high-performance solar cells due to their excellent light absorption and carrier mobility.
- **Light-Emitting Diodes (LEDs):** Their ability to emit light with tunable properties makes them suitable for energy-saving LED lighting.

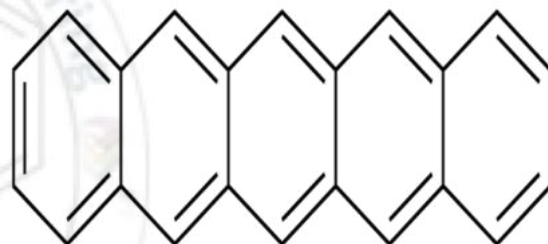


- **Photodetectors:** Hybrid semiconductors are used to create sensitive detectors for light, including broad-spectrum and UV-Vis-IR detection.
- **Lasers:** Their strong light-matter interaction properties allow for their use in laser applications.
- **Field-Effect Transistors (FETs):** High-performance organic and hybrid transistors can be fabricated at low temperatures and are used to build logic circuits, amplifiers, and displays.
- **Memory Devices:** They can be designed for charge storage layers and ferroelectric materials in memory applications.
- **Chemical and Biological Sensors:** Biocompatible organic-inorganic hybrid materials can be engineered to be sensitive to specific chemical, biological, or medical signals for diverse applications.

p- Type Semiconductor

Pentacene is an **organic semiconductor** made up of five linearly fused benzene rings (a polycyclic aromatic hydrocarbon). It is commonly used in **Organic Thin Film Transistors (OTFTs)** and **Organic Field Effect Transistors (OFETs)**.

Pentacene acts as a p-type organic semiconductor due to its large, planar conjugated structure of five linearly fused benzene rings, which promotes strong π - π stacking and high hole mobility in thin films.



Chemical Formula: $C_{22}H_{14}$

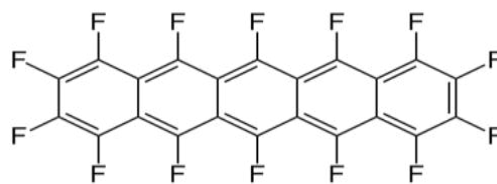
Properties:

1. **Charge Transport** – Hole-dominated conduction (p-type) via hopping between HOMO levels; mobility up to $\sim 1 \text{ cm}^2/\text{V}\cdot\text{s}$ in thin films.
2. **Energy Levels** – HOMO $\approx -5.0 \text{ eV}$, LUMO $\approx -3.0 \text{ eV}$, band gap $\approx 2.2 \text{ eV}$ $\rightarrow$ favorable for hole injection.
3. **Structural Property** -Planar conjugated molecule with strong π - π stacking, enabling efficient hole transport.
4. **Optical Property**-Strong absorption in the visible range (around 660 nm); excitons are Frenkel-type.
5. **Stability** – Sensitive to oxygen, moisture, and light, requiring encapsulation for device applications.

n - Type Semiconductor

Perfluoropentacene (PFP) is a **fluorinated derivative of pentacene**, where all hydrogen atoms are substituted by fluorine atoms. It is one of the most well-known **n-type (electron-transporting)** organic semiconductors.

- **Molecular Structure:** Similar to pentacene, but with complete fluorination $\rightarrow$ electron-withdrawing fluorine atoms lower LUMO energy $\rightarrow$ easier electron injection.
- **Semiconducting Nature:** **n-type** (electrons are the majority carriers)



Chemical Formula: $C_{22}F_{14}$

- **Key Feature:** High electron mobility, good ambient stability (due to strong C–F bonds).
- Perfluoropentacene (PFP), a perfluorinated derivative of pentacene, is an n-type organic semiconductor where all hydrogens are replaced with fluorine atoms.
- Which substantially lowers its lowest unoccupied molecular orbital (LUMO) energy (~ -4.5 to -4.8 eV) and increases its electron affinity.

Effect of Fluorination:

- Electron-Withdrawing Nature of Fluorine lowers both HOMO and LUMO levels.
- Makes LUMO closer to electrode work function which favors electron injection and transport.
- Improves air stability by lowering susceptibility to oxidation.

Advantages:

- **High Electron Mobility** – enables faster switching OFETs.
- **Good Air Stability** – better than many other n-type organic semiconductors.
- **Complementary Circuit Integration** – can be combined with pentacene for low-power logic.
- **Lower Operating Voltage** – beneficial for portable and wearable electronics.

Construction, working and advantages of pentacene semiconductor chip:

Pentacene semiconductor chip: A pentacene semiconductor chip is an organic electronic device using pentacene as the semiconducting layer.

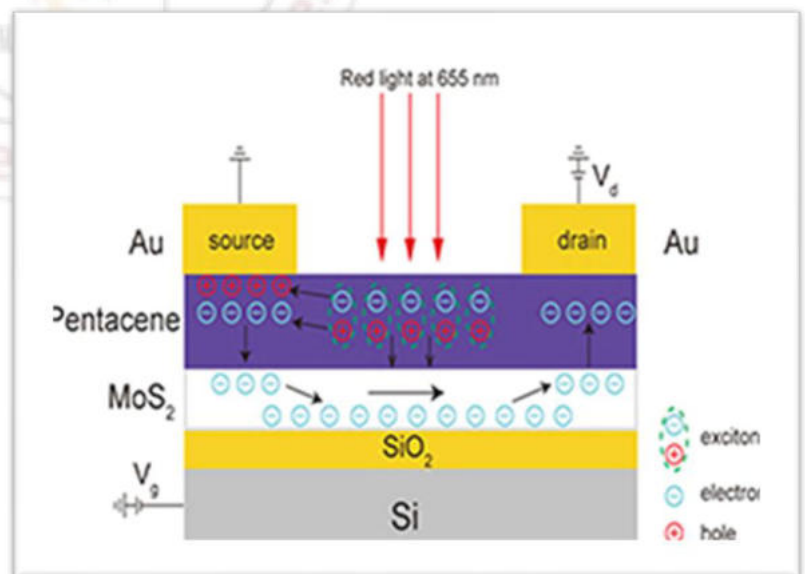
Construction:

1. Substrate: A material that provides mechanical support, often glass, silicon wafer (Si/SiO₂), or a flexible plastic foil (for flexible electronics).

2. Gate Electrode (G): A metal layer (e.g., gold or aluminum) that controls the electric field. In the bottom-gate structure, it's deposited directly onto the substrate.

3. Gate Dielectric Layer: An insulating layer (e.g., silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), or an organic polymer) that separates the gate from the semiconductor. This layer stores charge and allows the gate voltage (V_G) to modulate the charge carriers in the pentacene layer.

4. Pentacene Semiconductor Layer (Active Layer): A thin film of pentacene (the p-type organic semiconductor) is deposited onto the dielectric. Its thickness is typically tens of nanometers.



5. Source (S) and Drain (D) Electrodes: Metal electrodes (often gold) deposited on top of the pentacene layer to inject and collect the charge carriers (holes). A channel is defined between the source and drain.

6. Encapsulation: Parylene C is a polymer used for encapsulating electronic and medical devices due to its biocompatibility, flexibility, and excellent barrier properties, protecting them from moisture and chemicals in harsh environments.

Working Principle:

As a p-type semiconductor, the pentacene OFET operates by controlling the flow of holes (positive charge carriers) through the channel.

1. Gate Voltage OFF ($V_G \approx 0$): When no or a small gate voltage is applied, the pentacene film is highly resistive. The current flow between the source and drain (I_{DS}) is very low (I_{OFF} state).

2. Accumulation (Turning ON the Transistor):

- A negative voltage (V_G) is applied to the gate electrode.
- This negative voltage creates an electric field that attracts the majority carriers, which are holes, to the interface between the dielectric and the pentacene film.
- This accumulation of holes forms a thin, highly conductive channel at the interface.

3. Current Flow:

- A negative voltage is then applied to the drain electrode (V_D is negative, e.g., -20 V) relative to the source (which is typically grounded).
- The accumulated holes are pulled from the source, travel through the conductive channel in the pentacene layer, and exit at the drain, resulting in a measurable drain-source current (I_{DS}). This is the I_{ON} state.

4. Modulation: By controlling the magnitude of V_G , the density of the hole accumulation layer is varied, which in turn precisely controls the magnitude of the I_{DS} .

Pentacene-based semiconductor chips offer several benefits compared to traditional silicon chips:

- **Low-Cost Fabrication:** Can be processed at low temperatures, often using solution or vacuum deposition techniques.
- **Lightweight:** Suitable for portable and wearable electronics.
- **Flexibility:** Can be fabricated on flexible substrates (plastic), useful in wearable electronics and bendable displays.
- **Transparency (optional):** When used with transparent electrodes (like ITO), pentacene devices can be made semi-transparent.
- **Large-Area Applications:** Easy to manufacture over large surfaces (e.g., roll-to-roll printing).
- **Compatibility with Printing Techniques:** Enables low-cost mass production compared to silicon IC fabrication.
- **Good Mobility (for organic materials):** Among the highest mobilities for organic semiconductors (~ 0.1 – 3 $\text{cm}^2/\text{V}\cdot\text{s}$).

Applications of Pentacene:

- Organic Thin-Film Transistors (OTFTs) - Active semiconducting channel (p-type)
- Organic Memory Devices - Charge storage layer in OFET memories or active layer in RRAM.
- Organic Photovoltaics (OPVs) - Donor material in bulk heterojunction solar cells.
- Flexible & Wearable Electronics - Used due to its mechanical flexibility.
- Sensors - Organic semiconductor-based chemical and biosensors.

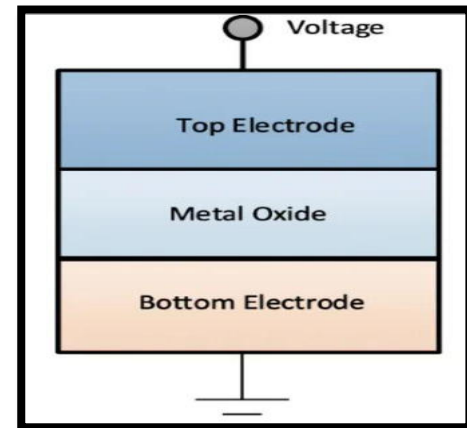
Organic & Inorganic Semiconductor

Organic Semiconductor	Inorganic Semiconductor
Composition: Made of carbon-based molecules, polymers, or pi-bonded structures, often including heteroatoms like hydrogen, nitrogen, and oxygen.	Composition: Consist of non-carbon-based materials such as silicon, germanium, and gallium arsenide.
Structure & Bonding: Molecules are held together by weak van der Waals forces, forming amorphous or polycrystalline thin films rather than highly ordered crystals.	Structure & Bonding: Typically have crystalline structures with strong covalent bonds, forming well-defined energy bands.
Processing & Cost: Can be processed using low-cost, solution-based wet chemistry methods and offer high yields.	Processing & Cost: Require more complex manufacturing processes, often involving single-crystal forms.
Flexibility: Inherently flexible and can conform to various shapes.	Flexibility: Generally rigid and brittle.
Mobility: Lower electron mobility compared to inorganic semiconductors.	Mobility: Exhibit high electron mobility due to their optimal crystalline structure.
Stability: More sensitive to humidity, oxygen, and high temperatures.	Stability: More stable and durable in various environmental conditions.
Applications: Used in flexible displays (OLEDs), solar cells, and sensors.	Applications: Widely used in transistors, diodes, and integrated circuits for traditional electronics.

Resistive RAM (ReRAM) Materials:

Resistive RAM (ReRAM) is a next-generation non-volatile memory that stores information by switching a material between high and low resistance states, most commonly utilizing transition metal oxides such as TiO_2

- Resistive RAM (ReRAM), also known as **RRAM** or **memristors**, is a type of non-volatile memory that stores data by changing the electrical resistance of a material.
- It has a metal-insulator-metal structure, generally referred to as MIM structure.
- An insulating layer(I) is sandwiched with the two metal(M) electrodes.



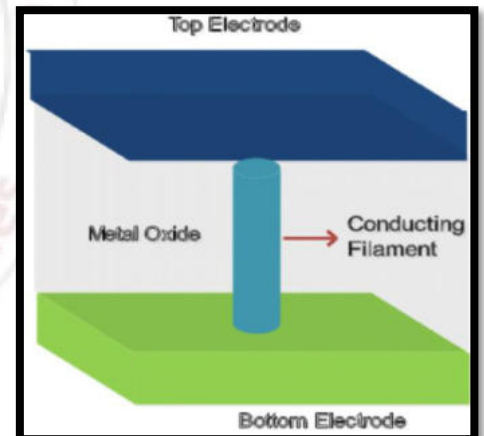
ReRAM is renowned for:

1. Non-volatility (retains information without power)
2. High switching speed and scalability (down to a few nanometers)
3. Simple device architecture, power efficiency, and 3D stacking capability.

Fundamental Operating Mechanism:

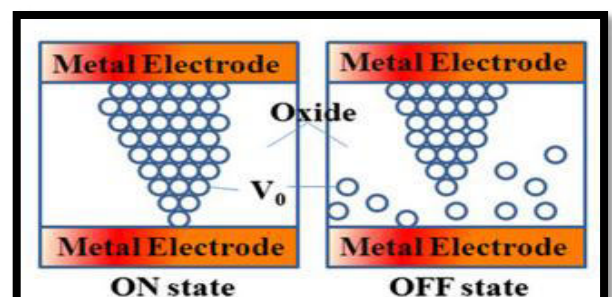
The change in resistance is due to the formation and rupture of a **conductive filament (CF)** within the active switching material.

- ❑ **Forming/SET Process (Low Resistance State - LRS):** A voltage is applied, causing the drift of mobile species (e.g., oxygen vacancies, metal ions) to form a conductive path through the material, resulting in a low resistance state (LRS), which is typically read as '1'.
- ❑ **RESET Process (High Resistance State - HRS):** Applying a reverse or opposite polarity voltage, or sometimes a large current, ruptures the conductive filament, returning the device to a high resistance state (HRS), read as '0'.



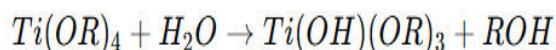
Resistive Switching:

- The memory cell switches between two resistance states:
Low-Resistance State (LRS) → represents logical “1”
High-Resistance State (HRS) → represents logical “0”
- Switching is induced by applying a voltage pulse.
- Set Process: Switching from HRS → LRS (conductive filament forms).
- Reset Process: Switching from LRS → HRS (filament ruptures).
- Binary Transition Metal Oxides: They are compounds formed by one transition metal + oxygen. They are simple oxides.
Examples: TiO_2 , HfO_2 , Ta_2O_5 , NiO , Al_2O_3
- Resistive switching occurs due to migration of oxygen vacancies in metal oxide layer.
- The conductive filament formation/rupture enables high/low resistance states (HRS/LRS).

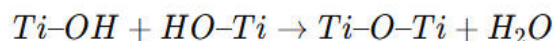


Synthesis of TiO₂-RAM nanomaterial by the sol-gel method:

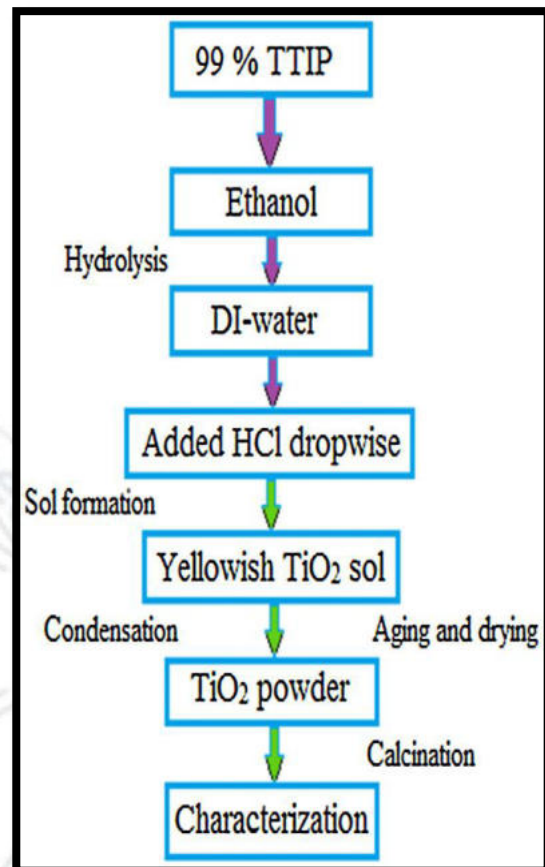
- The synthesis begins with 99% pure titanium tetraisopropoxide (TTIP) as the titanium source.
- TTIP is first mixed with ethanol, which serves as the solvent and helps in evenly dispersing the precursor.
- Deionized water is then slowly added to this mixture to initiate the hydrolysis reaction, where TTIP reacts with water, leading to the formation of titanium hydroxide intermediates.
- During this step, hydrochloric acid (HCl) is added dropwise as a catalyst, which helps control the pH and facilitates uniform sol formation.



- As the reaction continues, a yellowish TiO₂ sol appears, indicating the initial formation of titanium dioxide nanoparticles suspended in the solution.
- This sol is then left undisturbed to undergo the condensation process, where the titanium hydroxide species undergo further reactions to form more extensive Ti–O–Ti networks.



- Following condensation, the mixture is subjected to an aging and drying step, allowing the nanoparticles to aggregate and form a dry TiO₂ powder.
- The obtained powder is subsequently subjected to calcination—a heating process at elevated temperatures to remove any remaining organic components and improve crystallinity, resulting in well-formed TiO₂ nanomaterials.
- Finally, the synthesized TiO₂ powder is characterized using techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) to analyze its structural, morphological, and chemical properties, ensuring its suitability for applications like ReRAM devices.



Properties of TiO₂-RAM Nanomaterial:

- 1. Resistive Switching Ability:** TiO₂ shows bipolar and unipolar resistive switching due to formation/rupture of conductive filaments created by oxygen vacancies.
- 2. High Dielectric Constant:** With a dielectric constant up to ~100 (rutile phase), TiO₂ supports strong field-induced effects at low operating voltages.
- 3. Fast Switching Speed:** Resistive switching occurs within nanoseconds, supporting high-speed data writing/erasing.

4. Non-volatility: Memory states (HRS/LRS) remain stable without power due to oxygen vacancy stabilization, ensuring long-term data retention (up to 10 years).

5. Material Advantages: Abundant, low-cost, chemically stable, and non-toxic, making TiO_2 ideal for large-scale memory production.

Applications of TiO_2 -RAM Nanomaterials:

1. Next-Generation Non-Volatile Memory

- Used in RRAM devices as an alternative to Flash memory.
- Offers fast switching, low power, high density and long retention.

2. Neuromorphic Computing

- Useful for artificial intelligence hardware and brain-inspired computing.

3. High-Density Data Storage

- Enables 3D memory stacking with nanoscale TiO_2 layers.
- Supports ultra-large storage capacity in compact devices.

4. Reconfigurable Logic Circuits

- Can be used as programmable resistors in logic-in-memory circuits.
- Helps reduce data transfer between memory and processors.

5. Flexible and Wearable Electronics

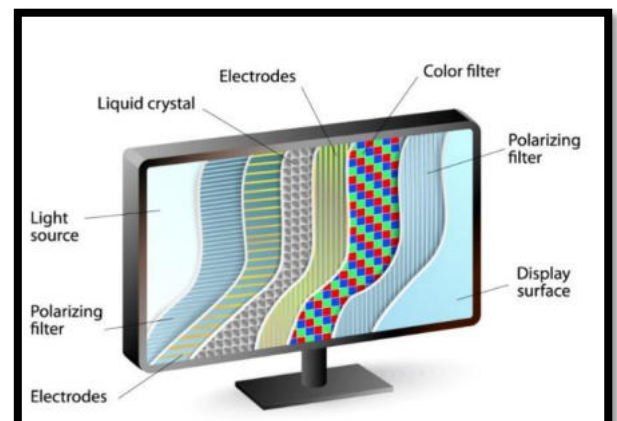
- TiO_2 nanomaterials can be deposited on flexible substrates.
- Applications include wearable memory devices, bendable displays and e-textiles.

DISPLAY SYSTEMS

- A **display system** is an electronic arrangement that converts electrical signals into a **visual form** that humans can perceive.
- It acts as the **interface between a machine and the user**, presenting data, images, or video in a way that is easy to understand.
- Display systems are widely used in **computers, televisions, mobile devices, control panels, medical instruments, and industrial equipment**.

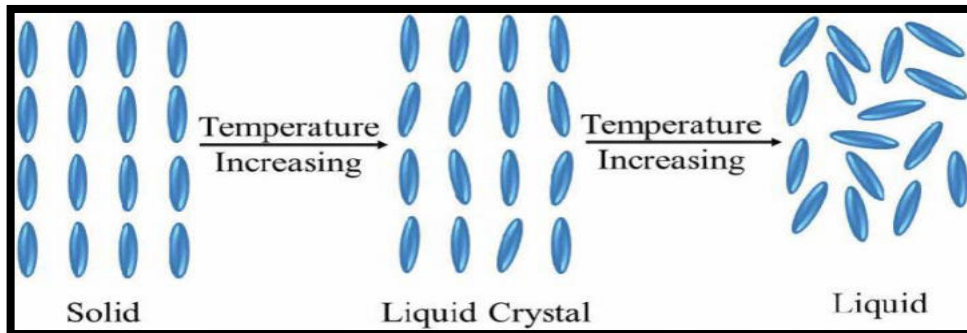
BASIC CONCEPT:

- A **display system** takes input from a source (computer, camera, sensor, or storage).
- It processes this information.
- Then it **projects or renders** it onto a screen or surface for human observation.



Liquid Crystals:

- Liquid Crystals (LCs) are a state of matter that has properties between those of a solid crystal and a liquid.
- They flow like liquids, but their molecules are arranged in an orderly (partially crystalline) structure like solids.
- This unique dual behavior makes liquid crystals very useful in display technology (LCDs), optical devices, sensors, and biological applications.



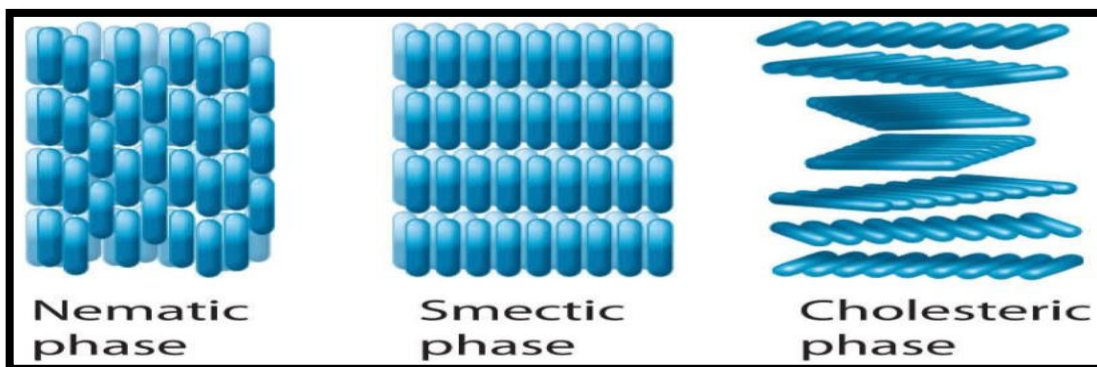
- In solid crystals, molecules are tightly ordered and fixed.
- In liquids, molecules are randomly arranged and can move freely.
- In liquid crystals, molecules can move like in a liquid but still maintain a degree of order or orientation as in a crystal.
- Thus, LCs represent a mesophase (intermediate phase) between solid and liquid.

Types of Liquid Crystals: Liquid crystals are mainly classified into two categories:

1. Thermotropic Liquid Crystals: Their phase depends on temperature. As temperature changes, they can transition between solid, liquid crystal, and isotropic liquid phases.

Subtypes:

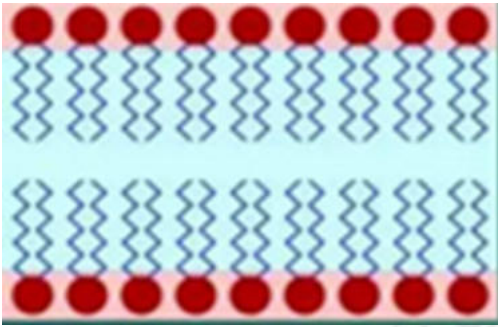
- a) Nematic Phase: Molecules are parallel but not arranged in layers. (Used in LCDs)
- b) Smectic Phase: Molecules are parallel and arranged in distinct layers.
- c) Cholesteric (Chiral Nematic) Phase: Molecules form a helical structure; reflect selective wavelengths of light (used in color displays).



2. Lyotropic Liquid Crystals:

- Formed by mixing an amphiphilic compound (like soap or detergent) with a solvent such as water.
- Structure depends on the concentration of the solute and temperature.
- Commonly found in biological systems (cell membranes, surfactant layers).

Micelle

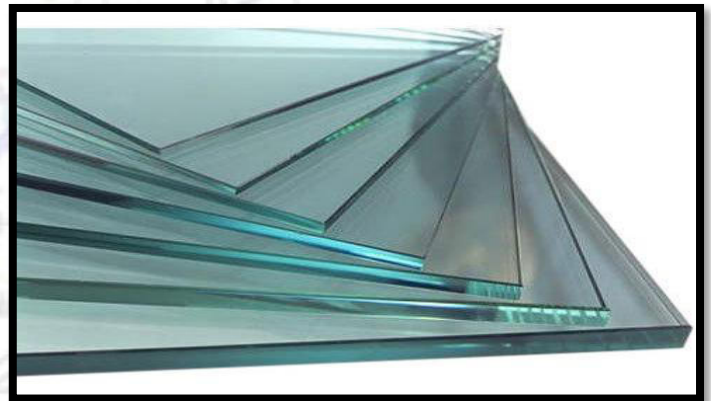


Ex: Soap and Water



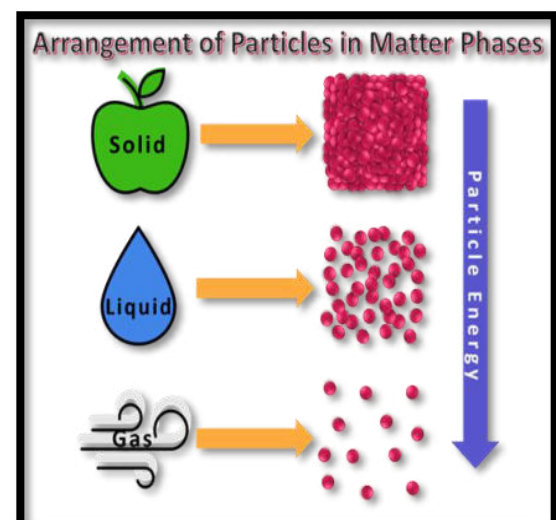
3. Metallotropic Liquid Crystals:

- A "metallotropic liquid crystal glass" refers to a type of glass material that exhibits liquid crystal properties due to the presence of metal ions within the glass structure.
- These materials are formed by incorporating metal compounds, often halides, into a liquid crystal system.
- The resulting material displays characteristics of both liquid crystals (like orientational order) and glasses (like a disordered network).



Properties of Liquid crystal:

- Liquid crystal can flow like a liquid, due to loss of positional order.
- Liquid crystal is optically birefringent, due to its orientation order.
- Transition from crystalline solids to liquid crystals caused by the change in temperature gives rise to thermotropic liquid crystals.
- Anisotropy: Liquid crystal exhibits anisotropy, which refers to the property of a material where its physical characteristics vary depending on the direction in which they are measured.
- Reversible Phase Transitions: Phase changes (e.g., solid $\rightarrow$ LC $\rightarrow$ liquid) are typically reversible.



Advantages of Liquid Crystals:

- ✓ Low power consumption.
- ✓ High optical efficiency.
- ✓ Thin, lightweight, and flexible materials.
- ✓ Can be controlled precisely with low voltage.

Limitations of Liquid Crystals:

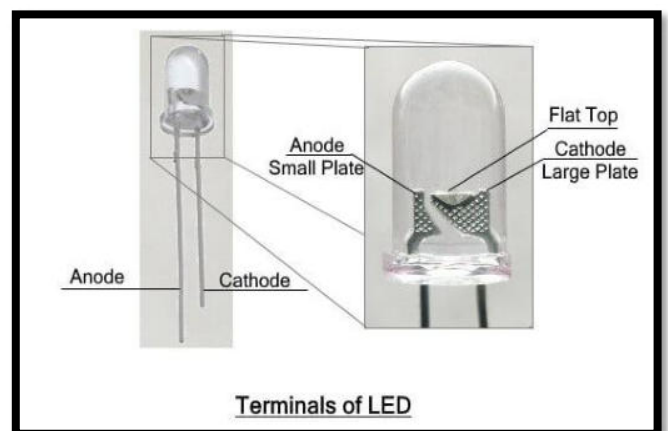
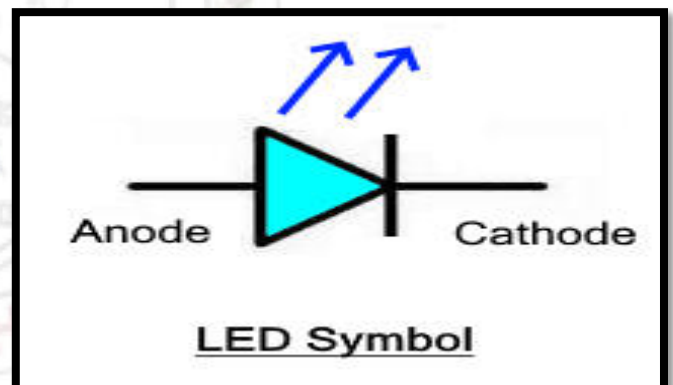
- ✓ Sensitive to temperature.
- ✓ Slow response time compared to modern OLEDs.
- ✓ Narrow viewing angles (in traditional LCDs).

Applications:

- Liquid Crystal Displays (LCDs): The LC molecules control light passage based on electric fields.
- Temperature Sensors: LCs change color with temperature (used in thermometers and thermal imaging).
- Optical Devices: LCs used in modulators, shutters, and tunable filters.
- Biomedical Devices: LCs used to detect biological molecules or structural changes in membranes.
- Smart Windows: It is used to control transparency with applied voltage.

LIGHT EMITTING DIODE (LED):

- LED is a short form of Light Emitting Diode. It is a type of diode that emits light when a current passes through it. It is a special type of p-n junction diode that emits light when forward biased.
- The junction is covered in transparent epoxy to direct the light emitted from the junction in all directions.
- Light energy is generated when an electron from a higher energy band falls into the lower energy band and releases energy. In other words, when charge carriers, electrons and holes, combine, they release light energy. This property of a material to convert electrical energy into light energy is called Electroluminescence.
- Instead of Silicon and germanium, gallium arsenide, gallium phosphide, and indium phosphide compounds are used, depending on the color of the emitting light.
- LED is a diode, therefore it has two terminals: anode (+) and cathode (-). The longer leg is the anode, while the shorter leg is the cathode.
- In the case of a transparent LED, the inner smaller plate is the anode while the larger plate is the cathode. The cathode has a flat spot on it.



Construction:

- LED is made of three layers, i.e., P-type semiconductor layer, N-type semiconductor layer, and Active region.
- The N-layer had the majority of electrons. It is doped with donor atoms → provides electrons.

Materials: Gallium Arsenide (GaAs) – infrared LEDs.

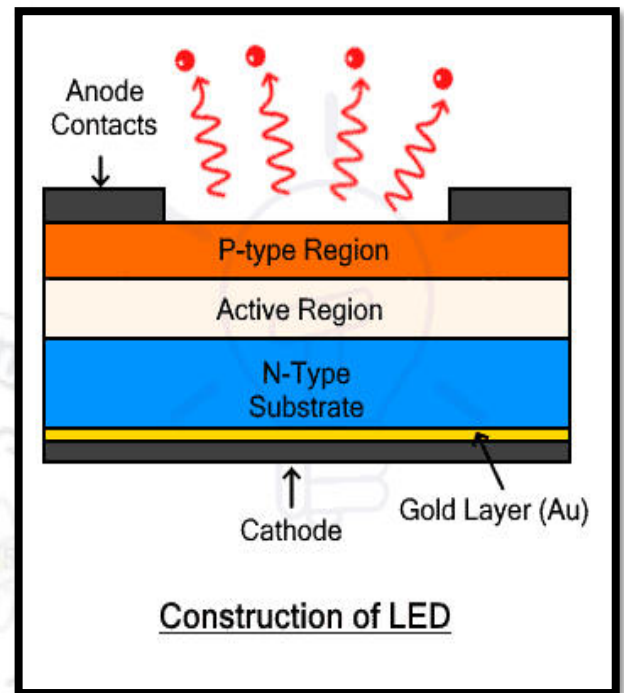
Gallium Phosphide (GaP) – red, green LEDs.

Gallium Nitride (GaN) – blue/white LEDs.

- While the P-layer had a majority of holes. It is doped with acceptor atoms → provides holes.

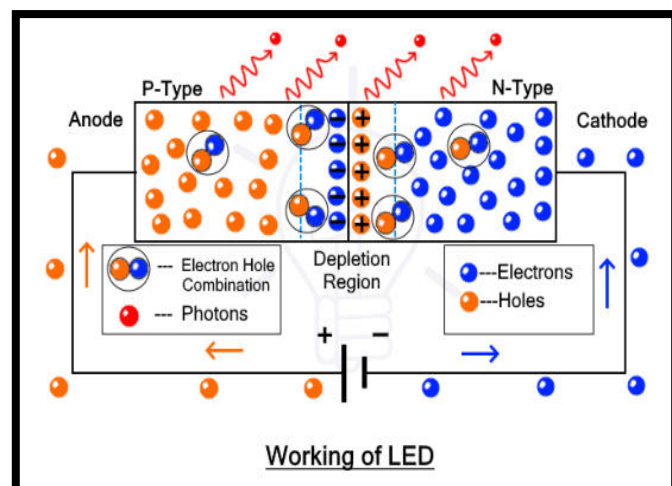
Materials: Mg doping in GaN

- The active region has an equal amount of electrons and holes. Therefore, there are no majority charge carriers. Active Region (P–N Junction): It is made up of Gallium Arsenide (GaAs).
- The active region is also known as the depletion region. The electrons and holes recombine in this region.
- As we know, light is emitted when an electron and a hole combine. The holes are the absence of electrons. They do not move.
- The electrons move and combine with holes in the p-layer. Therefore, the p-layer is designed to be kept at the top of the LED.
- The layer of P-type material and N-type material is combined on top of each other with an active region between them.
- As the electron-hole recombination occurs in the p region, the p layer is kept at the top.
- The anode is deposited at the edge of the p layer to have maximum light emission.
- While for the cathode, a gold film is deposited at the bottom of the N-type layer.
- Electrodes: 1. Indium Tin Oxide (ITO) – Anode & 2. Gold (Au)-Cathode



Working principle:

- Just like any normal diode, an LED only operates in forward bias, i.e., the anode is kept at a higher voltage as compared to the cathode, or the anode is connected with the positive terminal and the cathode is connected with the negative terminal of the battery.
- The n region has electrons in the majority, while the p region has holes in the majority.
- Apart from that, the n-type layer is heavily doped as compared to the p-type layer.



- When the LED is forward-biased, the applied potential starts pushing on the P-layer and the N-layer. As a result, the depletion region or the active layer starts to shrink.
- Therefore, electrons from the n region and holes from the p region start passing through the junction. It starts to recombine in the active region or depletion region.
- During its recombination, the electrons from the higher band (conduction band) fall into the lower energy band (valence band) by recombining with the holes (absence of an electron in the valence band) and release the energy in the form of light. During recombination, energy is released in the form of photons (light) is called as electroluminescence.
- After a few recombination events, the width of the depletion region further decreases, and the intensity of the light increases.
- The wavelength (color) of light depends on the band gap of the semiconductor material:
GaAs → Infrared, GaP → Red/Green, GaAsP → Yellow/Red

Application:

1. Display Devices

- Digital watches, calculators, and clocks.
- TV screens, computer monitors, smartphones.
- Advertising billboards and signboards.

2. Indicator Lights

- Power ON/OFF indicators in electronic gadgets.
- Charging status lights in devices.
- Automobile dashboards and instrument panels

3. Lighting

- Household and industrial LED lamps.
- Streetlights and traffic signals.
- Automobile headlights, brake lights, and interior lights.
- Decorative and stage lighting.

4. Communication

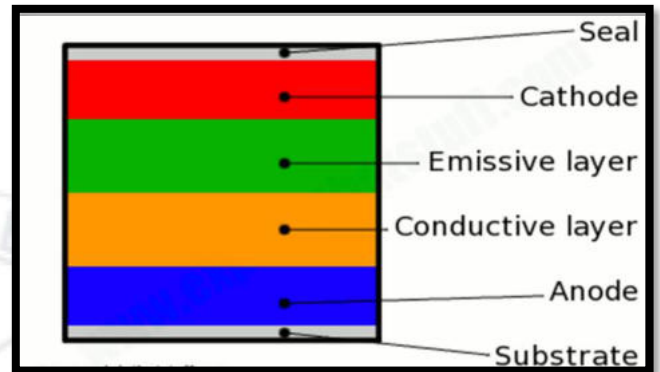
- Optical fiber communication (LEDs used as light sources).
- Infrared LEDs in TV/remotes and wireless devices.

ORGANIC LIGHT EMITTING DIODES (OLEDs):

An organic light-emitting diode (OLED), also known as an organic electroluminescent (organic EL) diode. It is a light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current.

Construction:

- OLEDs has 6 Layers in it as shown in the figure.
- SEAL and SUBSTRATE are the two protective layers of OLEDs
- OLEDs has two electrode system Cathode and Anode.
- In-between cathode and anode, two organic layers are present, they are Emissive layer and Conductive layer.



Working:

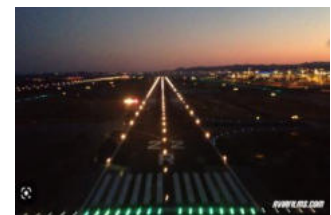
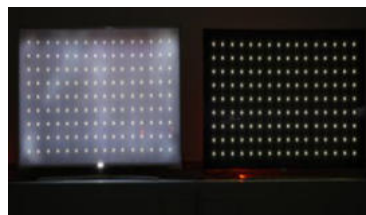
- OLED lights up by attaching a voltage across the anode and cathode.
- When electricity flows, the cathode receives electrons, and the anode loses electrons to form holes.
- Electrons move towards the emissive layer, creating a negatively charged (n-type).
- The conductive layer becomes positively charged due to holes (p-type).
- Positive holes are much more mobile than negative holes. Thus, they jump across the boundary from the conductive layer to the emissive layer.
- When a hole meets an electron, it releases energy in the form of a particle of light (photon).
- Thus, OLED produces continuous light for as long as the current keeps flowing.

Properties:

- OLED displays have many outstanding characteristics:
- Very saturated, vivid colors
- Deepest black, highest contrast ratio
- A wide viewing angle (180°)
- Low power consumption
- Extremely thin form factor, flexible
- Response time in microseconds for very crisp motion picture quality and 3D applications

Applications of OLED

- Back lighting
- Automotive lighting
- Airport runway
- Interior car lighting
- Smart card
- Advertisement boards
- Display systems

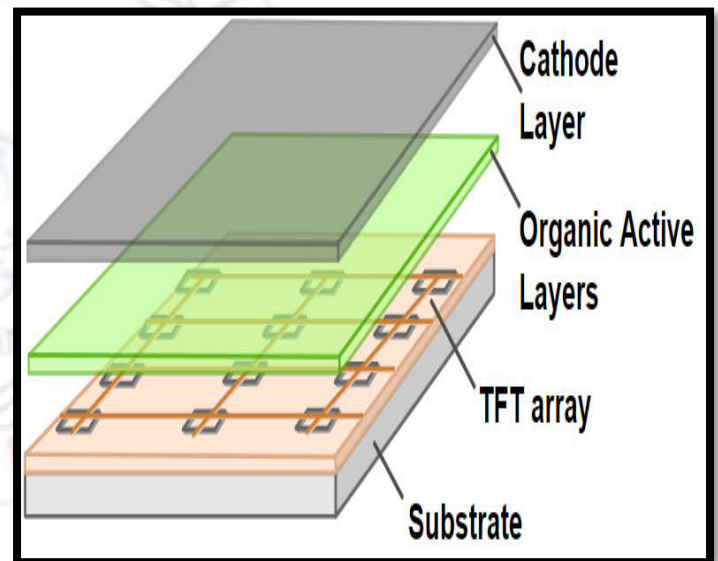


ACTIVE MATRIX ORGANIC LIGHT EMITTING DIODES (AMOLEDs):

- Active-Matrix Organic Light Emitting Diodes (AMOLEDs) are advanced display devices known for vibrant colors, flexibility, fast response, and energy efficiency, making them popular in high-end smartphones, televisions, wearables, and more.
- It is a type of OLED technology commonly used in large and advanced display systems.
- The term "active matrix" refers to the arrangement of light-emitting pixels, each controlled by its own dedicated thin-film transistor (TFT) and storage capacitor.
- This design ensures that each pixel is "actively" managed, resulting in high-quality displays with a long lifespan.

Construction:

- **Layered Structure:** An AMOLED consists of multiple layers: a glass or plastic substrate, a thin-film transistor (TFT) array, organic electroluminescent layers, top and bottom electrodes (anode/cathode), and encapsulation for protection against moisture and oxygen.
- **Pixel Circuit:** Each pixel includes a TFT and storage capacitor, which allows precise electrical control and maintains brightness between screen refresh cycles.
- **Organic Layer:** The organic layer (OLED) comprises various polymers or small molecules, sandwiched between a transparent anode and a metallic cathode. Light is emitted when current passes through this layer.
- **Encapsulation:** AMOLEDs are especially sensitive to water and oxygen, requiring careful encapsulation (protective layers/barriers) to ensure long operational life.



Working:

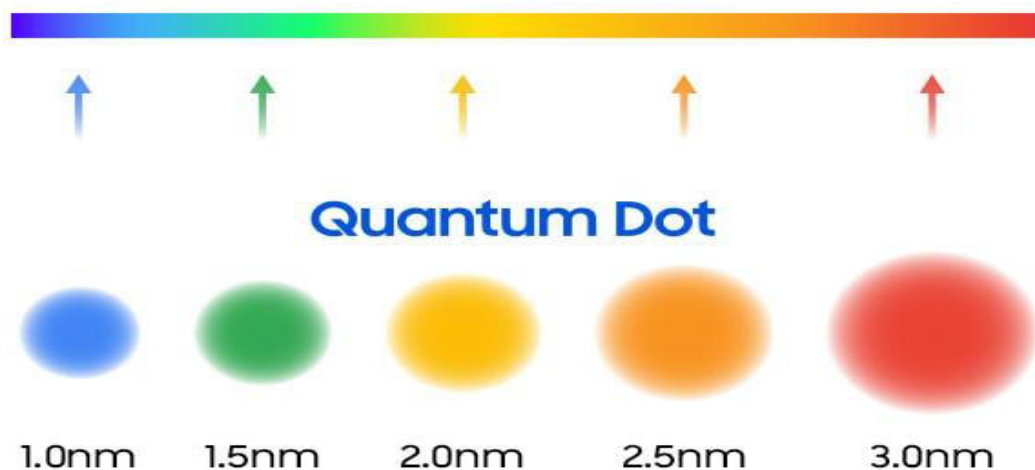
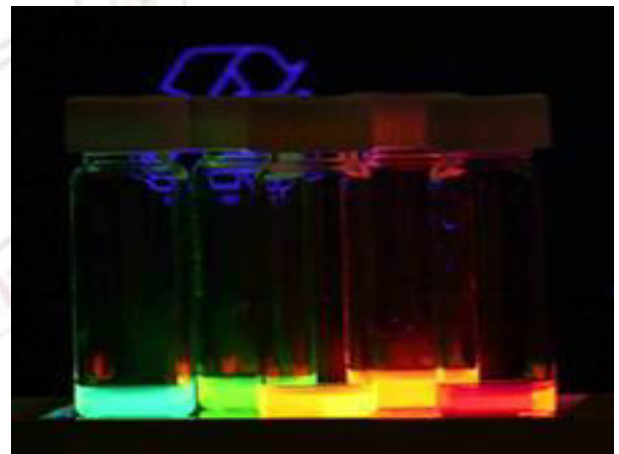
- AMOLEDs consist of a grid of OLED pixels, each controlled by dedicated circuitry that includes transistors and capacitors.
- Each OLED pixel is paired with at least one thin-film transistor and a corresponding capacitor, which precisely manage its on/off state and brightness.
- When a voltage is applied to the transistor, it charges the capacitor, maintaining the pixel's state until the next refresh cycle.
- When a voltage is applied across the AMOLED device, the control and signal electrodes determine which pixels light up, their brightness, and timing.
- Only selected pixels receive voltage at any given moment to produce the desired image or light output.
- Within each pixel, the organic light-emitting diode (OLED) component is composed of specific materials that emit light at the required wavelength.

Applications:

- **Smartphones & Tablets:** AMOLED screens are dominant in many flagship devices due to their thinness, deep blacks, wide viewing angles, and high-speed response.
- **Televisions:** Used in premium TVs, offering outstanding color, ultra-thin profiles, and fast refresh rates for sports and gaming.
- **Wearable Devices:** Employed in smartwatches and fitness bands for flexible, lightweight displays.
- **Digital Cameras:** Provide bright, vivid electronic viewfinders and displays.
- **Automotive Displays:** Used in instrument clusters and dashboard screens for curved, high-visibility panels.
- **VR/AR Devices:** Features in virtual and augmented reality headsets for immersive visuals due to quick pixel transition and high color fidelity.
- **Medical Equipment:** Utilized where real-time, high-contrast, flexible displays are necessary for diagnosis and wearable health monitoring.
- **Flexible & Transparent Displays:** Enable future applications in foldable phones, roll-up TVs, and heads-up displays due to their physical flexibility.

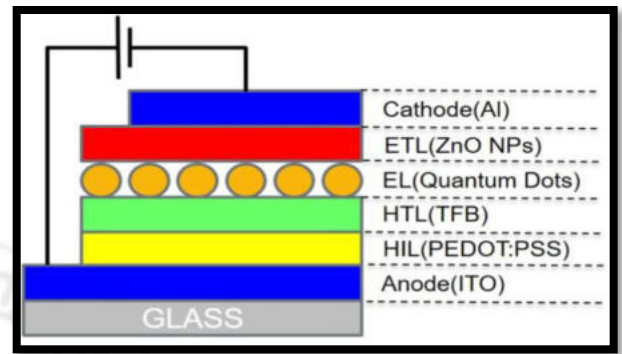
QUANTUM DOT LIGHT EMITTING DIODES (QLEDs):

- A quantum dot display is a device that uses quantum dots (QD) semiconductor nanocrystals, which can produce pure monochromatic red, orange, yellow, green, and blue light.
- The purpose of a quantum dot is to produce different colours of light depending on the size of the particle.
- A larger particle appears as a red colour, and the smaller the particle, the bluer it will appear.
- QDs are either photo-emissive (photoluminescent) or electro-emissive (electroluminescent).
- The incoming light from the LED backlight excites the quantum dots, causing them to emit light of a specific color.



Construction:

- **Substrate:** Typically made from glass or flexible plastic, providing a base for all other layers. It must be transparent to allow emitted light to pass through.
- **Anode:** Usually an indium tin oxide (ITO) layer that is transparent and conductive, allowing positive charges (holes) to be injected into the device.
- **Hole Injection Layer (HIL):** This layer facilitates the injection of holes from the anode into the hole transport layer. Materials like PEDOT: PSS are commonly used as the HIL.
- **Hole Transport Layer (HTL):** A polymer or organic compound such as TFB or poly-TPD that transports holes efficiently from the HIL into the quantum dot emissive layer. It helps lower the energy barrier for hole injection to the emissive layer.
- **Quantum Dot Emissive Layer (QDEL):** The core of the QLED, consisting of a thin film of semiconductor quantum dots (e.g., CdSe/ZnS, InP/ZnSe/ZnS). Quantum dots are nanoscale semiconductor crystals whose size controls the color of emitted light by quantum confinement effects. This layer emits light when electrons and holes recombine inside the dots.
- **Electron Transport Layer (ETL):** Commonly made from ZnO nanoparticles, this layer facilitates the injection and transport of electrons from the cathode to the quantum dots. ZnO nanoparticles provide high electron mobility and proper band alignment to confine holes in the emissive layer for efficient recombination.
- **Cathode:** Typically, a metal like aluminum or silver that injects electrons into the ETL. It must be reflective or transparent depending on the device architecture (top-emitting or bottom-emitting).
- **Encapsulation:** Protective barrier layers prevent oxygen and moisture from degrading the sensitive quantum dots and organic layers, improving device longevity.



Working:

- **Charge Injection:** When forward bias voltage is applied, holes are injected from the anode through the hole injection and transport layers into the quantum dot emissive layer. Simultaneously, electrons are injected from the cathode through the electron transport layer into the emissive layer.
- **Charge Transport and Confinement:** The HTL and ETL layers are designed with suitable band energy levels to efficiently transport charges and confine the electrons and holes within the quantum dot layer. This confinement maximizes the chances of electron-hole recombination inside quantum dots.
- **Radiative Recombination:** Electrons and holes recombine inside the quantum dots and release energy in the form of photons. The size-dependent quantum confinement effect determines the photon energy (color of light), producing pure and tunable colors.
- **Light Emission:** The generated photons exit through the transparent substrate or electrode, producing bright, highly saturated light with excellent color purity and luminescence efficiency thanks to the unique properties of quantum dots.

- **Bandgap Engineering:** The wide bandgap and high electron affinity of layers like ZnO ensure electrons are efficiently injected without leaking, while holes are confined, leading to enhanced recombination and low non-radiative losses.
- **Turn-On Voltage and Efficiency:** Due to the high mobility of materials like ZnO nanoparticles and well-engineered charge transport layers, QLEDs have low turn-on voltages (~2-3 V) and can achieve high luminance and efficiency

Properties:

- Very Accurate, vivid colors, which are more realistic
- High brightness.
- Deepest black, highest contrast ratio.
- A wide viewing angle (180°).
- Low power consumption
- Extremely thin, flexible, and lightweight.
- Low input lag: the amount of delay between user input and action on screen, which helps in gaming and other interactive applications.



Applications:

- **Televisions and Monitors:** QLED panels are prominent in TVs and computer monitors, offering superior brightness, sharper colors, and a better high dynamic range (HDR) viewing experience compared to standard LED and many OLED displays.
- **Digital Signage:** Their high brightness and durability make them ideal for indoor and outdoor advertising, information displays, airports, malls, and stadiums, where vivid visibility in bright environments is crucial.
- **Professional Content Creation:** Due to high color accuracy, QLED is preferred for photo/video editing, graphic design, and other tasks requiring precise color grading.
- **Gaming:** QLED gaming monitors provide fast refresh rates, low input lag, and rich visual detail, catering to a premium gaming experience.
- **Automotive Displays:** They are integrated into car systems, instrument clusters, and heads-up displays, valued for readability, aesthetic flexibility, and durability.
- **Medical Imaging:** QLED is utilized in diagnostic and surgical imaging displays for its high resolution, stability, and color accuracy, essential for detailed medical visualization.
- **Industrial and Control Rooms:** QLED's reliability and long operational life make it suitable for mission-critical process monitoring, surveillance, and collaborative industrial settings.