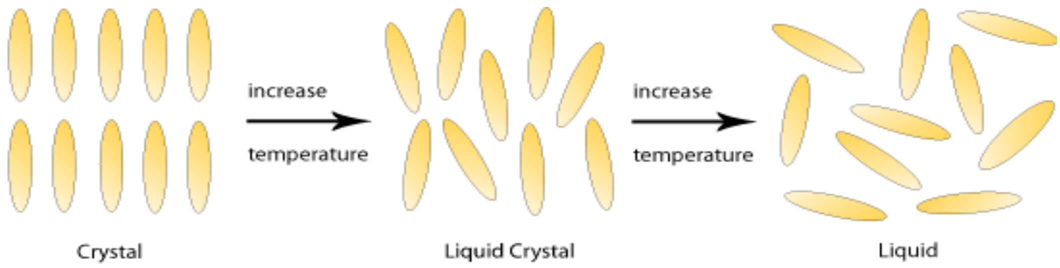
Materials for Display Systems

Liquid crystals

Definition: Liquid crystal is a state of matter whose properties are between those of conventional liquids and those of solid crystals. Materials having the properties between like conventional liquid and crystalline solid.

Example: p-Azoxyanisole (PAA), p-Azoxyphenetole (PAP) molecules exhibits liquid crystalline behavior.



Properties:

- Materials having the properties between like conventional liquid and crystalline solid are liquid crystals.
- The molecules possess characteristic order in orientation like traditional solid but randomness in their position like conventional liquids.
- They are able to flow like liquids.
- They are anisotropic (high temperatures they become isotropic).
- They possess a rod-like molecular structure and rigidity of the long axis.
- They possess strong dipoles and easily polarizable substituents.

Criterion for a molecule to behave as Liquid Crystal:

- Molecule should be rod shaped - long and elongated.
- Length of the molecule should be greater than its width.
- Center of the molecule should be rigid.
- Two ends of the molecule should be flexible.
- Molecule should have polarity with polarizable substituents.
- Molecule should have conjugation.

Classification:

Thermotropic Liquid Crystals: Thermotropic LCs are those substances that exhibit liquid crystalline state on change of temperature alone.

PAA (crystal) $\xrightarrow{118^0C}$ Liquid crystal $\xrightarrow{135^0C}$ Isotropic liquid

Lyotropic liquid crystals: Lyotropic LCs exhibit phase transitions as a function of both temperature and concentration of molecules in a solvent (typically water).
Example: a mixture of soap and water.

Metallotropic liquid crystals: They are composed of both organic and inorganic molecules. Their LC transition additionally depends on the inorganic-organic composition ratio and of temperature.

Mesophases: Most liquid crystal compounds exhibit more than one phase, these **“subphases”** of liquid crystal are called mesophases. They exist due to different degree of ordering in the sample.

Nematic Liquid Crystals:

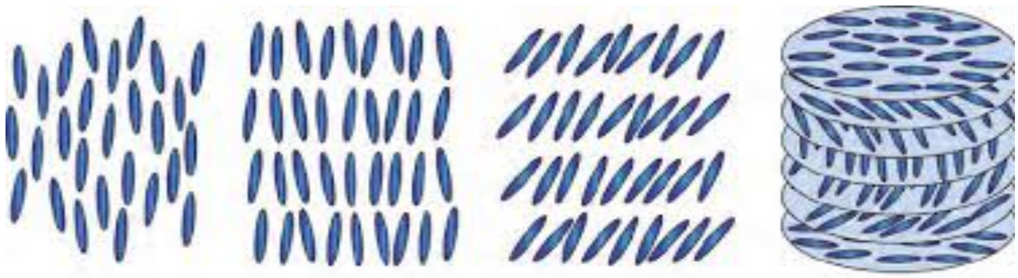
- Nematic is derived from Greek word Nematos meaning thread like structures.
- The molecules are not layered but are pointed in the same direction.
- Least ordered phase with simple structure.
- Molecules align parallel to each other and each molecule can roll or slide over another molecule.
- Flow like normal liquids, having low viscosity.
- They are formed from optically inactive compounds.
- Affected by strong magnetic and electric field.
- Used mainly in LCDs.

Example: Cyanobiphenyls

Smectic liquid crystal:

- Smectic is derived from Latin word Smectius means soap alike.
- They are found at lower temperatures than the nematic, form well defined layers that can slide over another. Thus, they flow like layers instead of flowing like normal liquid.
- In the Smectic A phase, the molecules are oriented along the layer normal, while in the Smectic C phase they are tilted away from the layer normal.
- They show x-ray diffraction.
- They are not affected by magnetic and electric field.
- Used in LCDs

Example: Ethyl p-azoxy benzoate, soap, p,p’-dinonylazobenzoate.



nematic smectic A smectic C cholesteric

Discotic Nematic Discotic Columnar

Cholesteric liquid crystal:

- First discovered in cholesterol derivatives.
- A cholesteric liquid-crystal display (ChLCD) is a display containing a liquid crystal with a helical structure and which is therefore chiral.
- These are made up of rod like molecules that are arranged in layers, with the long axis of the molecules parallel to the layer planes.
- These layers are rotated at a certain angle with respect to each other.
- Used in thermometers, display devices, sensors, textile industries etc,

Example: hydroxypropyl cellulose, cholesteryl benzoate

Discotic liquid crystal:

Discotic liquid crystals are mesophases formed from disc-shaped molecules known as "discotic mesogens". Molecules are stacked on top of each other thereby they self-organise into columns. Discotic mesogens are typically composed of an aromatic core surrounded by flexible alkyl chains.

Used in LEDs
Example: triphenylene, perylene

Applications of Liquid Crystals in LCDs

LCDs are used in wide range of consumer and commercial electronics like:

TVs, computers, laptops, mobile phones and touch sensitive integrated Smart phones, tablets, ATMs, alphanumeric displays like calculators, digital clocks, and watches, Automobile Applications like in car dashboards and navigation systems etc.

LCDs offer several advantages over other display technologies and finds it applications in all these applications, because:

- Liquid crystals **control light to create images** in devices like TVs, laptops, and phones.
- **Require minimal energy**, making them ideal for battery-operated devices.
- Ideal for compact and sleek electronic gadgets due to their **lightweight, flexible and thin structure.**
- Provide **adjustable brightness levels**, making them easy to view in various lighting conditions.
- **Enable sharp, clear visuals** with vibrant colors for detailed viewing experiences.
- Brightness can be adjusted, ensuring visibility in bright sunlight or dim environments.
- Reliable and efficient for showing numbers and letters in calculators, digital clocks, and watches.
- Integrates display and touch screen functionalty for smartphones, tablets, and ATMs.

Differences between Liquid Crystal and Solid/Liquid

SOLIDS	LIQUIDS	LIQUID CRYSTALS
Strong intermolecular force of attraction	Weak intermolecular force of attraction	Moderate intermolecular force of attraction
Fixed shape and volume	Fixed volume but no fixed shape	Molecules are arranged in some order but flow like liquid
Anisotropic	Isotropic	Anisotropic
Molecules possess both positional order & orientational order	Molecules do not possess both positional order & orientational order	Molecules possess some positional order & orientational order
Definite melting and boiling points	Definite boiling points and no fixed melting points	Transition temperature
Restricted flow	Ease to flow	Moderate flow
Ice, metals, rocks etc.,	Water, oil, mercury, etc.,	Used in Display screens, optical devices etc.,

Properties and Applications of OLEDs, QLEDs, and LECs

Light Emitting Diodes (LEDs)

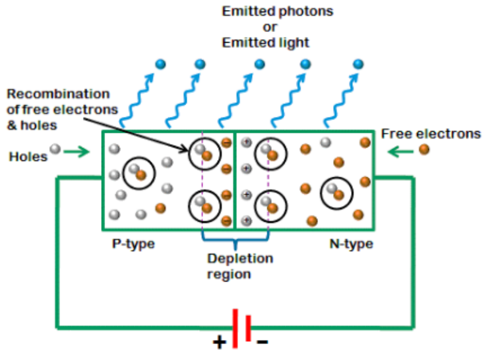
Definition:

A Light Emitting Diode (LED) is a semiconductor device that emits light when an electric current flows through it. The light is produced as electrons recombine with holes in the semiconductor material, releasing energy in the form of photons.

LEDs are heavily doped p-n junction. Based on the semiconducting material and the amount of doping an LED will emit light at a particular spectral wavelength.

When the LED is forward biased, and a voltage is applied, electricity flows in the right direction, i.e., electrons move from the n-type side to the p-type side, where they recombine with holes and release energy in the form of light.

The LED only allows current to flow in one direction. If the current is reversed (reverse bias), the LED won't light up because the electrons and holes won't meet.

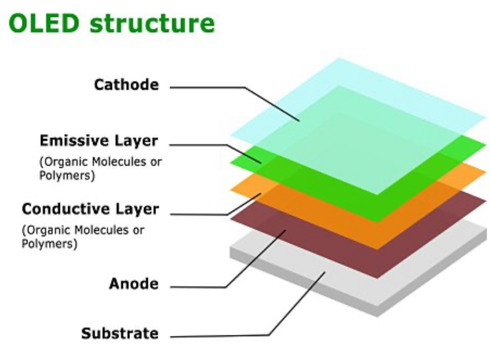


Organic Light Emitting Diodes (OLEDs)

Definition:

OLEDs are a type of light-emitting diode (LED) where the light is emitted by organic (carbon-based) compounds. When an electric current passes through the organic layer, it emits light.

An OLED consists of:



1. Substrate. Regarded as the base of an OLED, it is made up of a thin translucent glass.

2. Anode. It is also called as emitter. Its function is to injects holes (i.e., absence of electrons) into the organic layers when electric current flows through the device.

3. Conductive layer. This layer is made of organic molecules and helps to move holes from anode.

5. Emissive layer. This layer is made of organic materials that are different from those used in the conductive layer. It helps to transport electrons from cathode. The heart of the device and where light is made.

6. Cathode. Cathode is the topmost part of OLED displays. It injects electrons into the organic layers when electric current flows through the device.

Properties:

1. Self-Emitting:

Each pixel generates its own light, eliminating the need for a separate backlight.

2. Thin, lighter, and Flexible:

OLED displays are thin and flexible, making them ideal for curved, foldable, light weight and even stretchable screens.

3. Fast Response Time:

OLEDs have very fast response times, which makes them perfect for high-definition video playback and fast-moving images without motion blur.

4. Wide Viewing Angles:

Maintain color accuracy and brightness from various angles, offering consistent image quality.

5. Vibrant Color Reproduction:

OLEDs are capable of reproducing a wide color gamut, providing rich, vibrant, and accurate colors with high saturation.

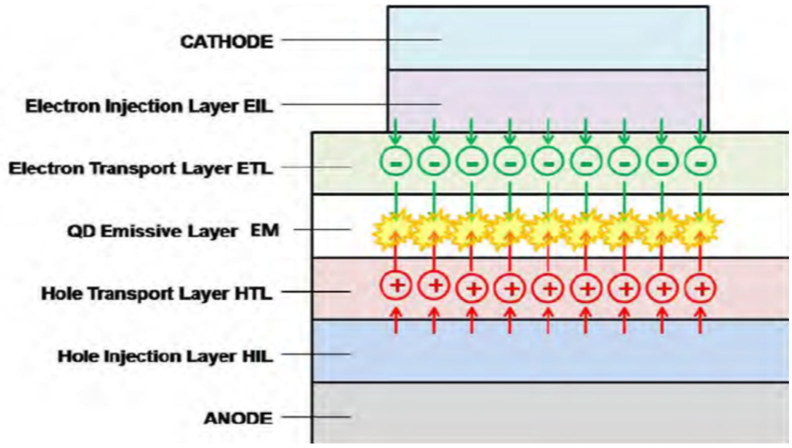
Applications:

Displays: Used in smartphones, TVs, monitors, and wearables,
Flexible Electronics: Foldable screens in phones and rollable TVs.
Automotive: Instrument panels and interior lighting.

Quantum Dot Light Emitting Diodes (QLEDs)

Definition:
QLEDs are displays that use quantum dots, which are tiny semiconductor particles, to produce brighter and more vibrant colors. QLEDs typically use an LED backlight along with quantum dots to improve color and brightness.

The structure of QLED is similar to the fundamental design of OLED, but the difference is that the light emits from the QDs, such as cadmium selenide (CdSe) nanocrystals. A QLED (QD-LED) device consist of two electrodes an anode and a cathode and QD layer placed between two layers. When a voltage is applied to an QLED device through anode and cathode, charge carriers are injected from the electrodes to the QD layer. Anode injects the holes (+ve charges) and cathode injects electrons (-ve charges) to the system. The holes and electrons are transported to an emission site and recombined. QD material in the emission site is exhibited by recombination of holes and electrons. When the exited QD returns to its ground state emits the energy in the form of photons.



Properties:

Quantum Dot Technology: Quantum dots emit pure, saturated colors when illuminated by a backlight.
High Brightness: Achieves brighter displays compared to OLEDs, making them ideal for bright environments.
Improved Color Accuracy: Offers a wider color gamut and more accurate colors.
Longer Lifespan: More durable and longer-lasting than OLEDs.
Requires Backlight: Unlike OLEDs, QLEDs need a backlight for the display to function.

Applications:

Displays: Found in high-end TVs, monitors, and large displays.
Medical Imaging: High-contrast screens for precise imaging in medical devices.
Photovoltaics: Emerging use in solar cells for efficient energy conversion.

Light Emitting Electrochemical Cells (LECs)

Definition:
LECs are a type of light-emitting device where light is produced through electrochemical reactions. They consist of an electrolyte and electrodes, with the light emission occurring when the ions move across the device.

Properties:

Low Voltage Operation: Can operate at lower voltages compared to other light-emitting technologies.
Simple Structure: Made from just one active layer, making them easier and cheaper to manufacture.
Efficient and Flexible: Suitable for flexible and large-area applications.
Color Tuning: Can produce a wide range of colors depending on the materials used.

Applications:

Displays: Used in low-cost, flexible display technologies.
Lighting: Thin, flexible light panels for various applications.
Signage: Flexible, colorful displays for advertising and public signs.
Wearables: Integrated light sources in smart textiles and fabrics.

Introduction to Photoactive and Electroactive Materials

Photoactive Materials

Photoactive materials are materials that interact with light by absorbing, emitting, or converting it into electrical energy.

There are various photoactive semiconductors like silicon, Quantum dots like CdTe (cadmium telluride) and CdSe (Cadmium Selenide); bulk material like GaAs (Gallium arsenide), metal oxides like TiO_2 and ZnO, etc.

Key application:

- **OLEDs**: Organic molecules or polymers, emit light when electrically stimulated.
- **QLEDs**: Quantum dots (photoactive materials) are excited by light or electricity to emit vibrant colors.

Electroactive Materials

Definition: Electroactive materials are materials that can change their physical properties, such as shape, color, or molecular arrangement, when exposed to an electric field.

Liquid crystals, PEDOT:PSS, E-Ink particles are various examples.

Key application:

They are integral to the operation of devices like LCDs, OLEDs, and E-ink displays.

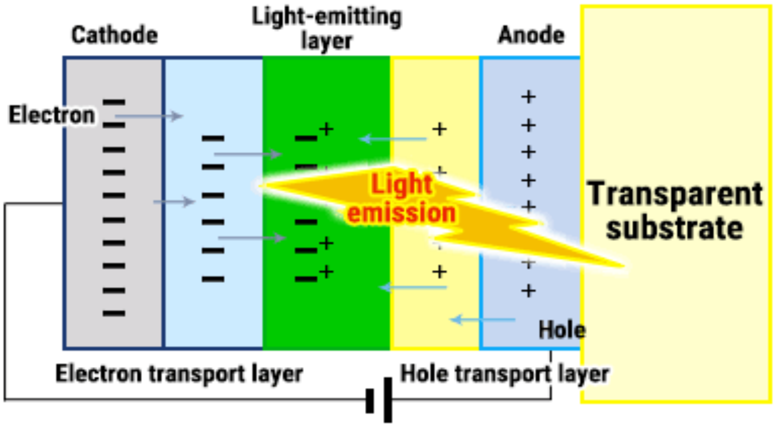
Working Principle of Photoactive and Electroactive materials in Display systems:

Photoactive and electroactive material absorb and emit light in the UV to IR region.

Display system (i.e., OLEDs) consisting of photoactive and electroactive material absorb light and allows an electron to jump from HOMO of a Donor to LUMO of an Acceptor.

This phenomenon generates and transport - charge carriers.

When electrons move from cathode, anode will allow the movement of holes - towards the light emitting layer under an applied field. Electrons and holes will combine and electron hole pairs are created at the Light-Emitting-Layer. Due to the recombination of electron hole pair, the energy is released. This released energy is enough to excite an electron from HOMO to LUMO in the light emitting layer. The light emitting layer which is made up of Photoactive and electroactive material will re emit back the light when returning back to the HOMO layer. This light is extracted by a transparent substrate which is placed adjacent to one of the electrode.



Example: Materials like organic compounds or quantum dots in OLED displays, emit vibrant colors when excited by light or an electric current.

Nanomaterials Used in Optoelectronic Devices

Definition:
Nanomaterials are materials with structural features at the nanometer scale (1–100 nm). At this size, materials exhibit unique optical, electrical, and mechanical properties, making them highly useful in optoelectronics.

Properties of Nanomaterials

1. Size-Dependent Properties:
   Optical properties like absorption and emission depend on the size of the material (e.g., smaller quantum dots emit blue light, larger ones emit red light).
2. High Surface Area:
   Increases interaction with light and other materials, improving device performance.
3. Quantum Effects:
   Confinement of electrons leads to discrete energy levels, enhancing electronic and optical behavior.
4. High Conductivity:
   Excellent charge transport properties in materials like graphene and carbon nanotubes.

Common Nanomaterials used in Optoelectronics:

1. Silicon Nano crystals (Si NCs)
   They have Optoelectronic properties like,
   - Wider bandgap energy due to quantum confinement.
   - Si NCs shows higher light emission property (Photoluminescence)
   - SiNCs exhibit quantum yield of more than 60%.
   - Si-NCs exhibit tunable electronic structure
   - Larger surface area-volume ratio.

   Applications in Optoelectronics:

   Light-emitting diodes (LEDs).
   Photodetectors and solar cells.
   Bio-imaging and sensors.

2. Quantum Dots (QDs)
   Examples: CdSe, CdTe etc.,.

   They have Optoelectronic properties like,
   - Size-Dependent Bandgap: The bandgap of quantum dots depends on their size, allowing tunable emission wavelengths (smaller QDs emit blue light; larger QDs emit red light).
   - High Photoluminescence Efficiency: Quantum dots efficiently convert absorbed light into emitted light with minimal energy loss.
   - Broad Absorption and Narrow Emission: They absorb a wide spectrum of light but emit specific colors, enhancing color purity.

Applications in Optoelectronics:

Displays: QDLEDs for vibrant and accurate color representation.
Solar Cells: Quantum dots enhance light absorption and energy conversion efficiency.
Photodetectors: High sensitivity due to efficient light absorption and emission.

3. Graphene
They have Optoelectronic Properties like,

- High Carrier Mobility: Graphene allows fast transport of electrons and holes, ideal for high-speed devices.
- Broad Light Absorption: Absorbs light from ultraviolet to infrared, enhancing device performance.
- Transparency: Nearly 98% transparent while being highly conductive, suitable for transparent electrodes.

Applications in Optoelectronics:

Transparent electrodes in displays and solar cells.
High-speed photodetectors for communication and imaging.
Flexible, lightweight optoelectronic devices.

Organic materials used in optoelectronic devices

Organic materials are carbon-based compounds, including polymers and small molecules, that exhibit semiconducting properties. These materials are lightweight, flexible, and exhibit unique optoelectronic properties due to their molecular structures, making them highly versatile for optoelectronic devices.

Properties of Organic materials for optoelectronic devices:

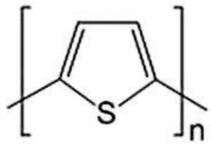
1. Bandgap Tunability: Organic materials have adjustable bandgaps for specific light absorption or emission.
2. Light Absorption: They absorb light efficiently in the UV-visible range due to π-electron transitions.
3. Photoluminescence: Organic materials emit light after absorbing it.
4. Charge Transport: Organic materials allow the movement of electrons (n-type) and holes (p-type) for current flow.
5. Electroluminescence: Light is emitted when electrons and holes recombine under an electric current.
6. Photoconductivity: Their conductivity increases when exposed to light.
7. Transparency: Thin organic layers are often transparent, making them ideal for see-through displays and electrodes.

Common Organic Materials in Optoelectronic Devices:

1. Conjugated Polymers

Conjugated polymers have alternating single and double bonds in their backbone, which allows delocalized π-electrons for optical and electronic properties.
Example of Light absorbing material:

P3HT (Poly(3-hexylthiophene)): Polythiophenes are an important class of conjugated polymers, environmentally and thermally stable material. Chemical structure of P3HTPoly(3-hexylthiophene) is a polymer with chemical formula (C10H14S) n. It is a polythiophene with a short alkyl group on each repeating unit.



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Properties:

- P3HT is a p type-semiconducting polymer, with high stability and exhibits conductivity due to transporting holes (positive charges)
- Absorbs visible light efficiently
- It has the structure that allows for the delocalization of π-electrons, facilitating efficient charge transport
- P3HT has a direct-allowed optical transition with a fundamental energy gap of 2.14eV.
- Fundamental bandgap of P3HT is 490nm visible region, corresponding to $\pi \rightarrow \pi^*$ transition, giving electron-hole pair

Applications:

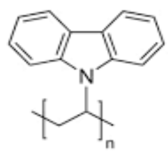
Organic solar cells, photovoltaic devices, memory devices, batteries, biosensors, Manufacture of smart windows, etc.

2. Organic Light-Emitting Materials

These materials emit light upon electrical excitation and are used in displays and lighting applications.

Examples:

- Poly (N-vinyl carbazole) (PVK) is one of the highly processable polymers as hole conducting material and therefore used as an efficient hole transport material to prepare highly efficient and stable planar hetero junction perovskite solar cells. It is a semiconducting polymer and an electron acceptor converts ultra-violet (UV) light into electricity. PVK has a band gap of 3.4 eV, optical absorption edge stating at 350 nm capable of absorbing Ultra-Violet light. The PVK film is hydrophobic, thermally stable with a relatively high glass transition temperature (Tg) of 200 °C. The PVK solution also showed good wettability, and provide uniform thin films on glass/ITO substrates.



- Iridium Complexes: Highly efficient phosphorescent materials for green and red OLEDs.
- Fluorescent Dyes (e.g., Coumarins): Used for color tuning in displays.

Applications:

OLEDs for displays, organic solar cells, lighting, light-emitting diodes and laser printers.