5. Computer Displays

- Liquid Crystal Displays
- Organic LED Displays
- Electronic Paper Displays
- Quantum Dot Displays

Organic LED Displays

- Organic LED Displays
  - Types of Organic LEDs
  - Structure and Operation
  - Passive-Matrix Displays
  - Active-Matrix Displays
  - Color Generation Techniques
  - Transparent and Flexible Displays
  - Sub-Pixel Layouts
  - Advantages and Disadvantages

Types of Organic LEDs (1)

- OLED – *Organic Light Emitting Diode*
  - Composed of layers of organic materials
  - Based on electroluminescence
  - In the 1970s, OLEDs based on conductive polymers were developed
  - The first practical OLED was developed at Eastman Kodak (1987)
  - In 1990, a material based on polyphenylene vinylene was developed → layer of 100 nm

Types of Organic LEDs (2)

- Depending on the size of molecules, there are two types of OLEDs:
  - With small molecules: SM-OLED (*Small-Molecule OLED*)
  - With polymers: P-OLED (*Polymer OLED*), LEP (*Light Emitting Polymer*)
- Both types generate light by forming electrons and holes, and then by their recombination

Types of Organic LEDs (3)

- Small-Molecule OLEDs (SM-OLED)
  - Used for most of OLED displays
  - An evaporation process under vacuum is used
    - Advantages: homogeneous films and complex multi-layer structures can be formed
    - Disadvantage: expensive process
  - Materials: fluorescent dyes
    - Absorb light and re-emit it at different wavelengths
  - Research to develop soluble SM-OLED materials
    - Enable to use inexpensive technologies

Types of Organic LEDs (4)

- Polymer OLEDs (P-OLED)
  - Require lower voltages
  - Can be processed from solutions
    - Technologies: inkjet printing; spin-coating
    - Advantage: lower cost than evaporation in vacuum
  - Materials: polyphenylene vinylene (PPV), polyfluorene (PF)

Printable P-OLED materials (Image credit Sumitomo Chemical)

Types of Organic LEDs (5)

- Based on the type of emission, there are fluorescent and phosphorescent OLEDs
- Fluorescent OLEDs
  - Fluorescence: emission of visible light by a material due to absorption of energy
  - The energy is re-emitted when the electrons return to the original energy level
  - The return occurs almost immediately (10^{-8} s)
  - Stops as soon as the energy source is removed

Types of Organic LEDs (6)

- Phosphorescent OLEDs
  - Phosphorescence: emission of light by a material exposed to a form of radiation
  - The emission persists after the radiation has been removed
- Concepts related to particle physics
  - Spin
    - Angular momentum carried by elementary and composite particles
    - Measured in multiples of a unit called Dirac (ħ) → usually, the unit ħ is omitted
    - Vector quantity: it has direction and magnitude

Types of Organic LEDs (7)

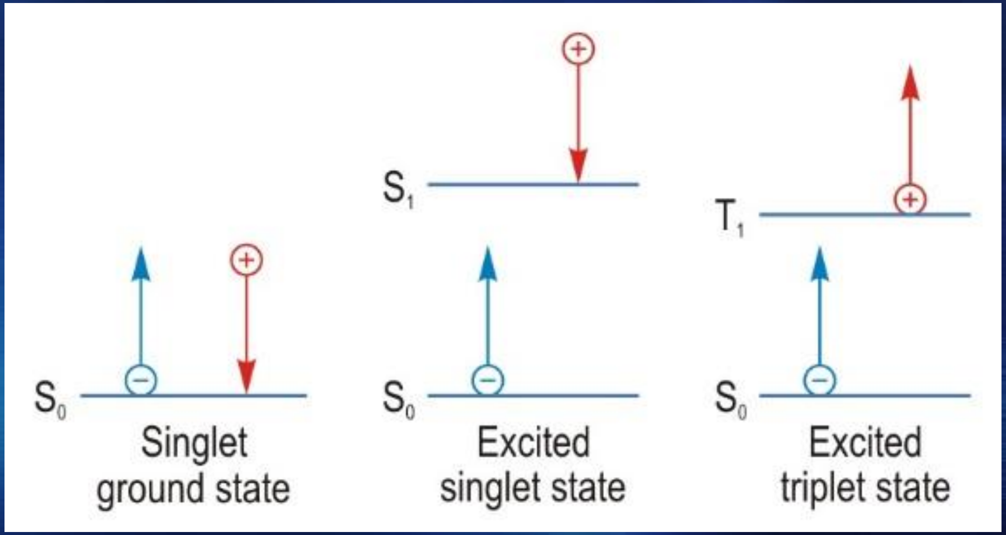
- Spin direction: direction the spin vector is pointing to
- Spin magnitude: specified by the spin quantum number (s)
- For fermions, particles that make all known matter: s is 1/2, 3/2
- Spin-½ particles: one of two orientations in a magnetic field, with the spin pointing in the $+z$ or $-z$ direction
- When two fermions reside on a single orbital, they must have different quantum states (the Pauli exclusion principle) $\rightarrow$ s = 0

Types of Organic LEDs (8)

- Singlet state
  - Obtained when two spin-½ particles are combined
  - If the particles have opposite spins, the total spin is $s = 0 \rightarrow$ only one quantum state
- Triplet state
  - Set of three quantum states of an elementary particle or combination of particles
  - Each state has a total spin of $s = 1$
  - Combination of two spin-½ particles: the spin directions are the same

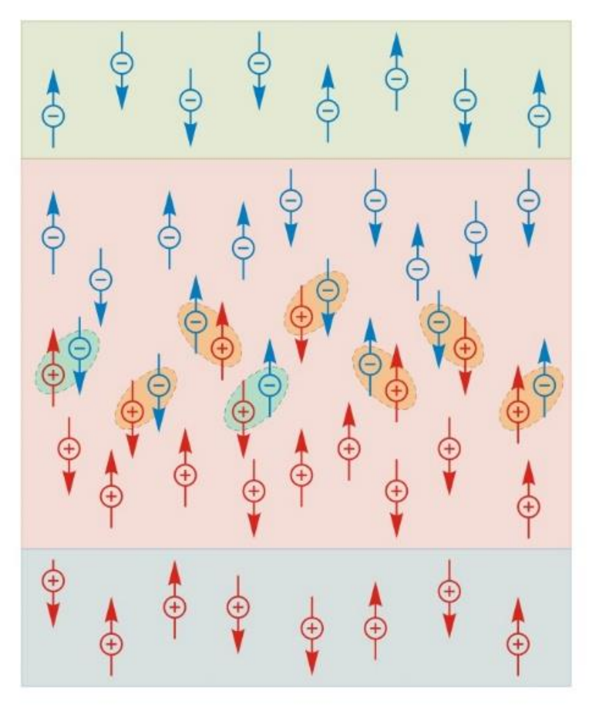
Types of Organic LEDs (9)

- Excitons
  - Formed when electrons and electron holes in a semiconductor absorb energy
  - Electron-hole pairs → excitons in singlet or triplet state



Types of Organic LEDs (10)

- Formation of a triplet state is more probable
- Triplet state: set of three quantum states → 75% of the excitons are in triplet state



Types of Organic LEDs (11)

- Fluorescent OLEDs:
  - Only singlet states contribute to light emission
  - Efficiency is limited to 25%
- Phosphorescent OLEDs:
  - Introduction of heavy-metal atoms into the emitting layer facilitates transition from the triplet to the singlet state → light emission
  - The singlet state also contributes to light emission
  - Efficiency approaches 100%

Organic LED Displays

- Organic LED Displays
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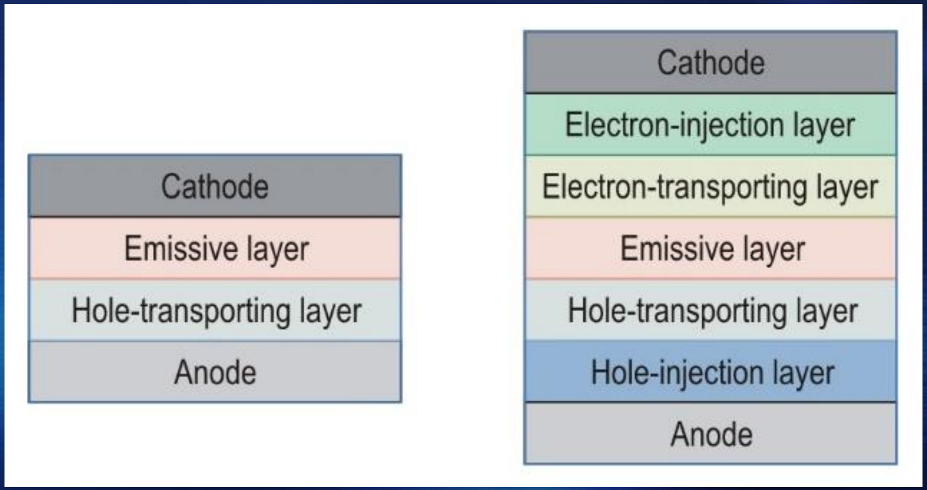
  - Active-Matrix Displays
  - Color Generation Techniques
  - Transparent and Flexible Displays
  - Sub-Pixel Layouts
  - Advantages and Disadvantages

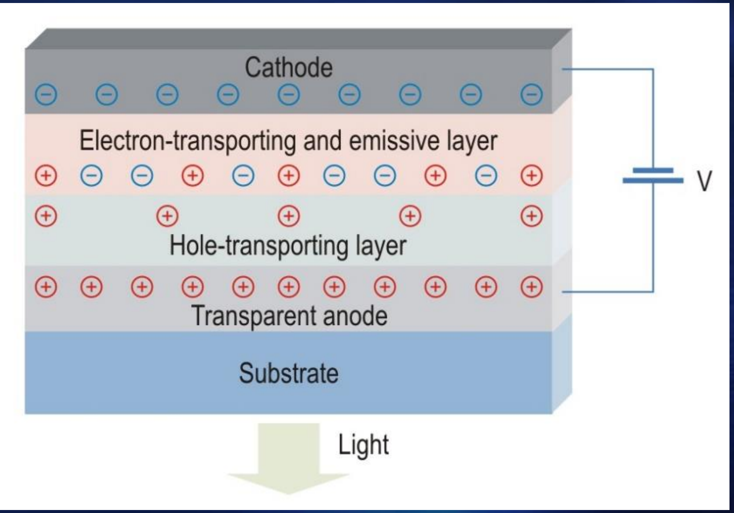
Structure and Operation (1)

- SM-OLED devices
  - First OLED devices: used a single organic layer inserted between an anode and a cathode
  - OLED devices developed at Kodak: two layers
  - Current OLED devices: multiple layers



Structure and Operation (2)

- P-OLED devices
  - Use simpler structures
  - May contain only two polymer layers
  - Cathode: metallic mirror (e.g., LiF)
  - Anode: transparent (ITO)



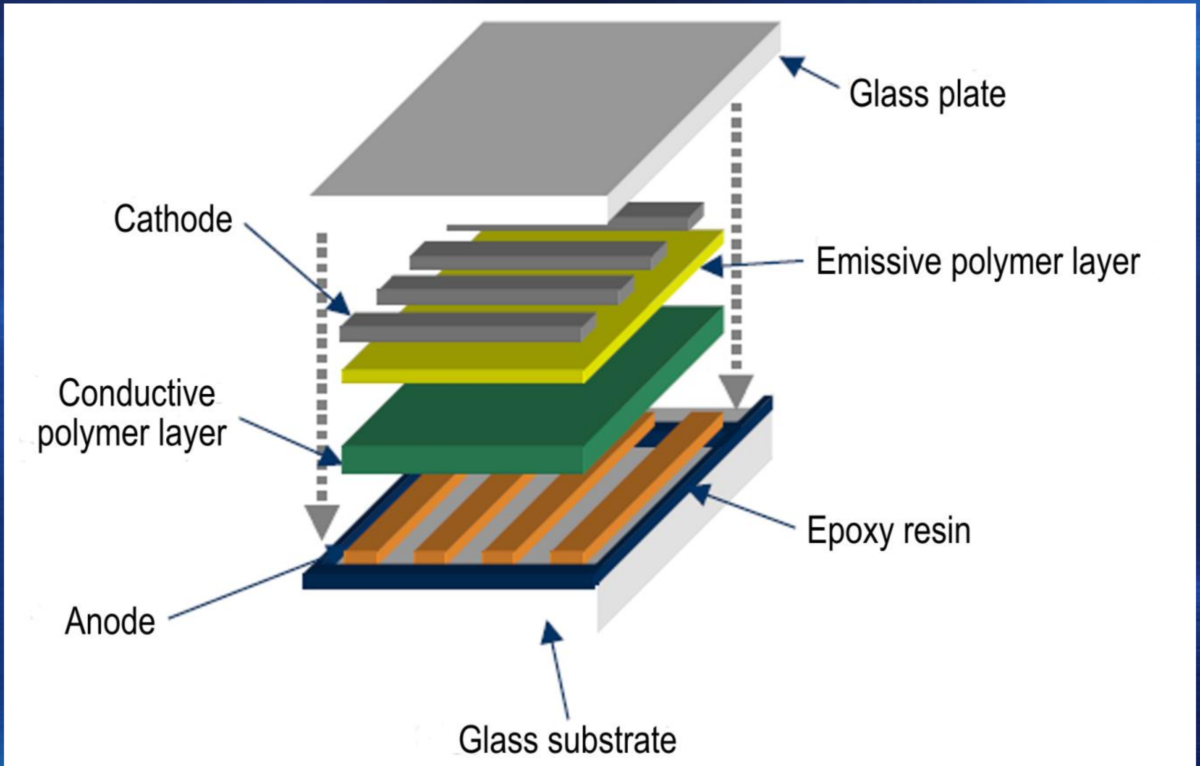
Structure and Operation (3)

- If a voltage is applied between electrodes:
  - A current of electrons flows through the organic layers (cathode → anode)
  - Electrons and holes are attracted towards each other by electrostatic forces
  - An electron and a hole may recombine → exciton in a singlet state or triplet state
  - Depending on the type of emissive material, decay of the singlet state or triplet state releases the extra energy as a photon

Structure and Operation (4)

- Top-emitting OLED displays
  - Transparent non-metallic cathode (top)
  - Reflective anode (bottom)
  - Advantage: easy integration of transistors for active-matrix displays
- Bottom-emitting OLED displays
  - Reflective metallic cathode (top)
  - Transparent anode (bottom)
  - Luminosity is limited by the transparency of the anode and driver circuitry (active-matrix)

Structure and Operation (5)



Structure of a bottom-emitting OLED display

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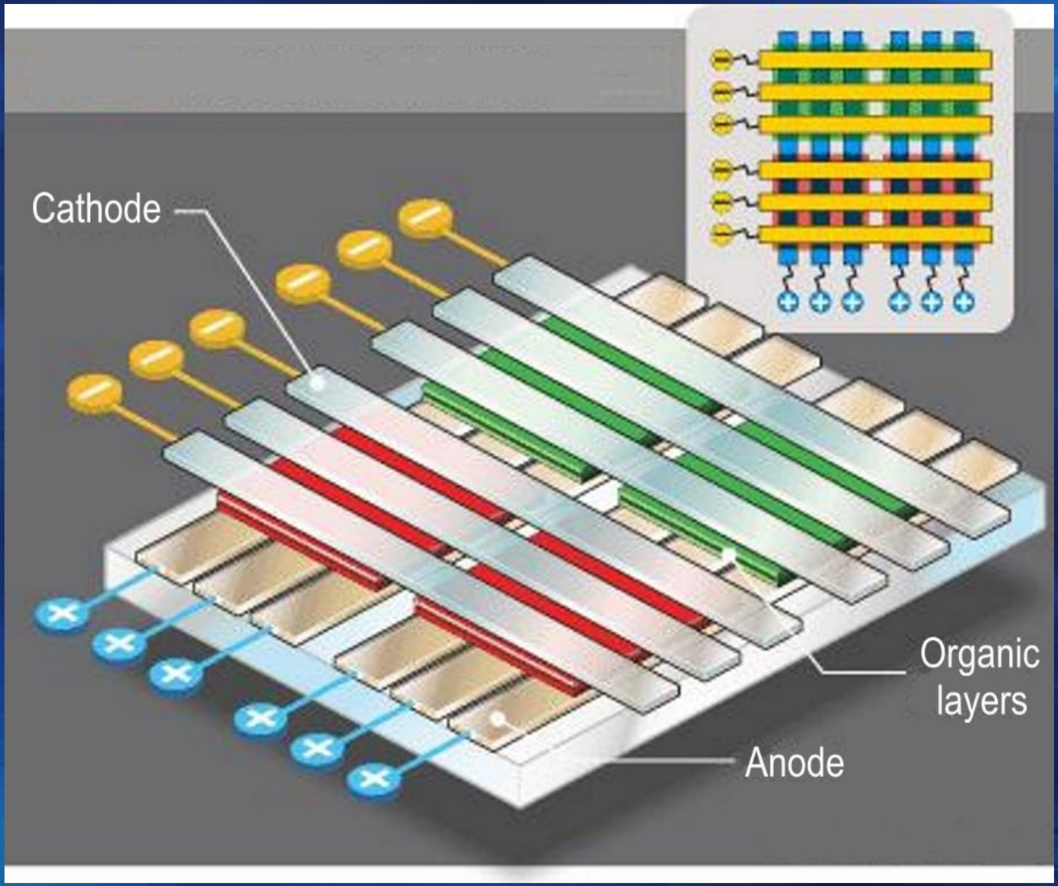
Passive-Matrix Displays (1)

- PMOLED (*Passive-Matrix OLED*)
- Drivers attached to each electrode
  - The pixel rows are selected successively
  - A certain voltage is applied to the columns of selected row → an electric current
- Advantage: manufacturing costs are low
- Disadvantages: relatively intensive currents are required → high power consumption; only suitable for small screens

Passive-Matrix Displays (2)



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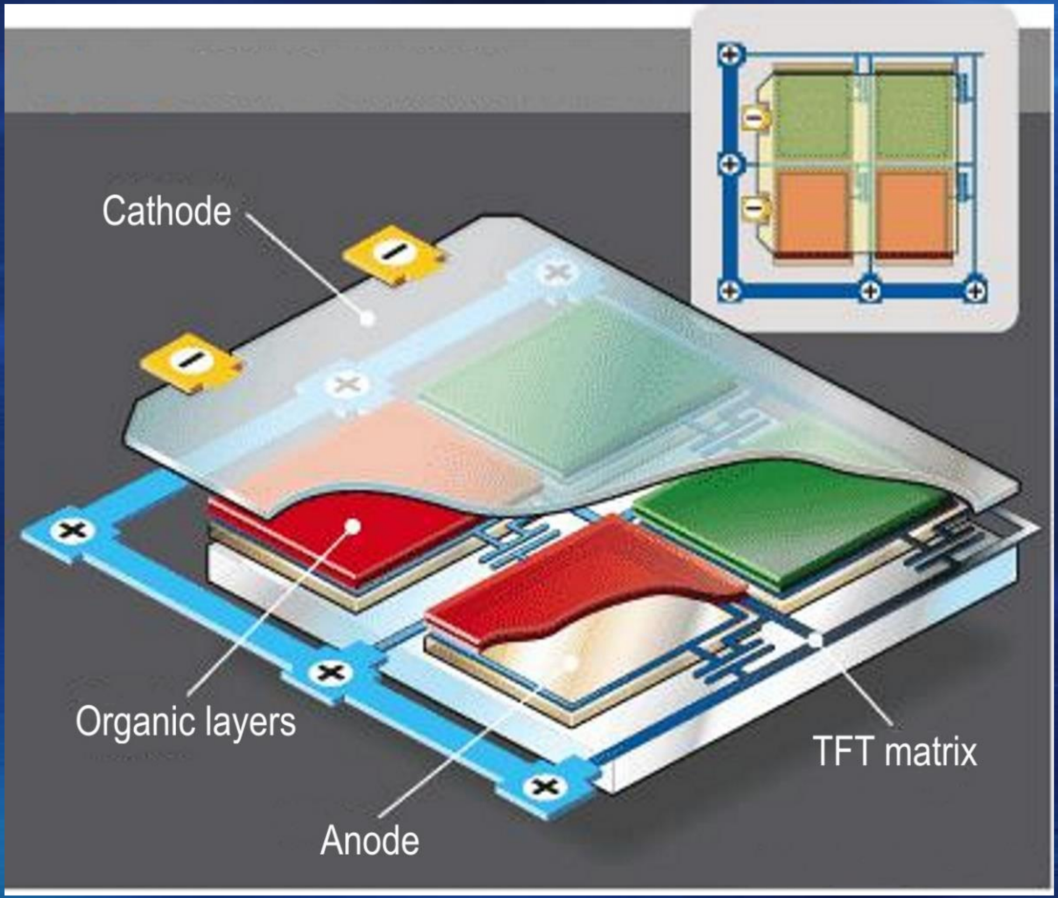
Active-Matrix Displays (1)

- AMOLED (*Active-Matrix OLED*)
- Array of thin film transistors (TFTs)
- At least two transistors and a storage capacitor are needed for each sub-pixel
  - First TFT: charges the storage capacitor
  - Second TFT: provides a correct voltage
- Advantages: higher refresh rates; higher luminosity; reduced power consumption; displays are not limited in size

Active-Matrix Displays (2)



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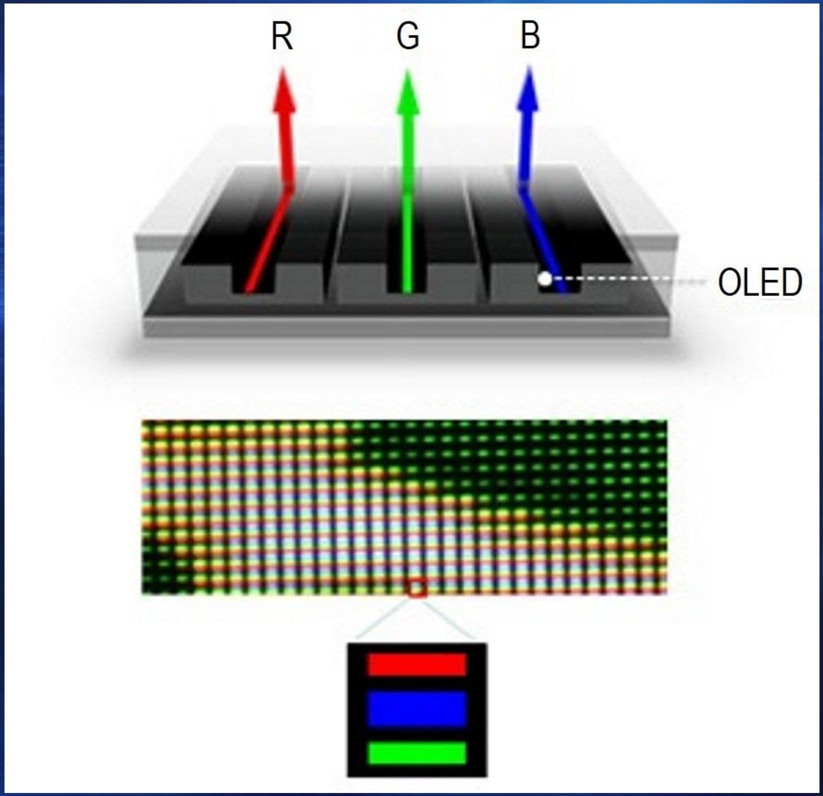
Color Generation Techniques (1)

- Direct-emission OLED (RGB OLED)
  - Uses R, G, and B sub-pixels → patterning of organic materials
  - High luminous efficiency
  - More complex manufacturing process
  - Color balance may change in time



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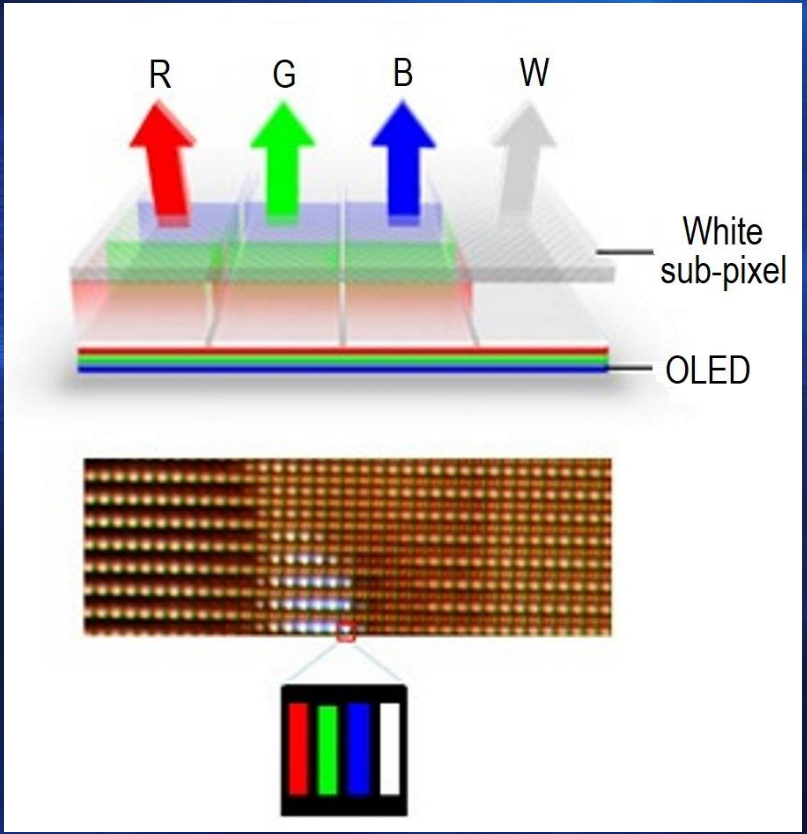
Color Generation Techniques (2)

- White-emitting OLED (WOLED)
  - The emitter layers are deposited uniformly → white light
    - Two layers: blue and yellow
  - Color filters patterned into sub-pixels (R, G, B) are applied
  - A fourth white sub-pixel (W) is added → increases the efficiency



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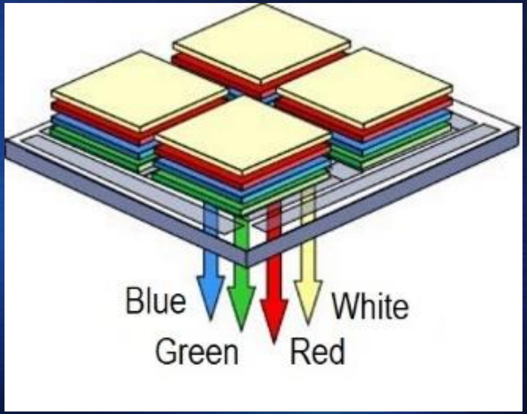
Color Generation Techniques (3)

- Color filter deposition: photolithographic methods, also used for LCDs
- Advantages:
  - Simpler and scalable manufacturing process
  - Lower production costs
  - No color balance problems occur
- Disadvantages:
  - Lower efficiency due to the color filters
  - Additional cost of the color filters and the more complex addressing (four sub-pixels)

Color Generation Techniques (4)

- Stacked OLEDs (SOLED - *Stacked OLED*)
  - Each pixel contains R, G, and B emitters
  - The emitters are stacked vertically, separated by transparent intermediate electrodes
  - Advantage: potential increase of resolution
  - A white-emitting OLED can be added



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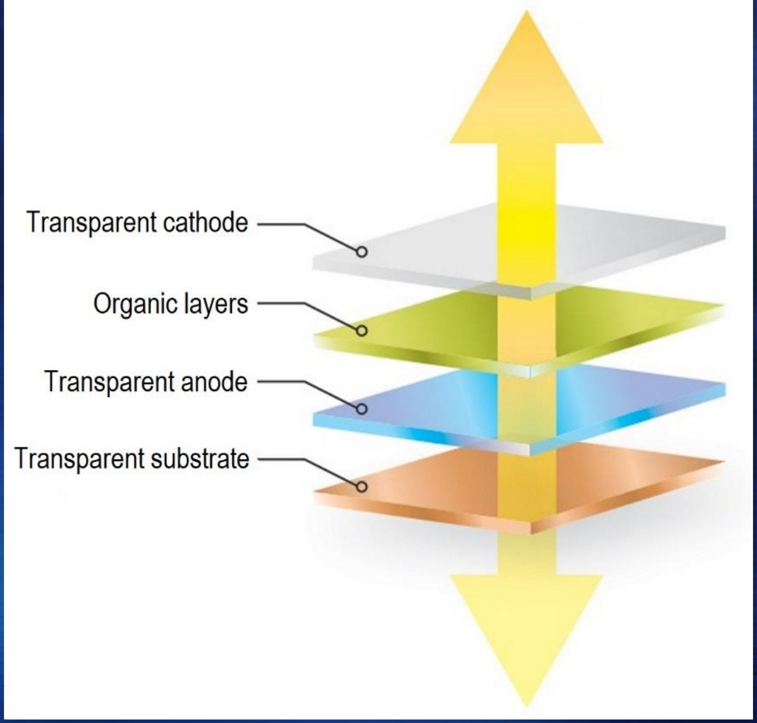
Transparent and Flexible Displays (1)

- TOLED (*Transparent OLED*)
  - Both the anode and cathode are transparent



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Transparent and Flexible Displays (2)

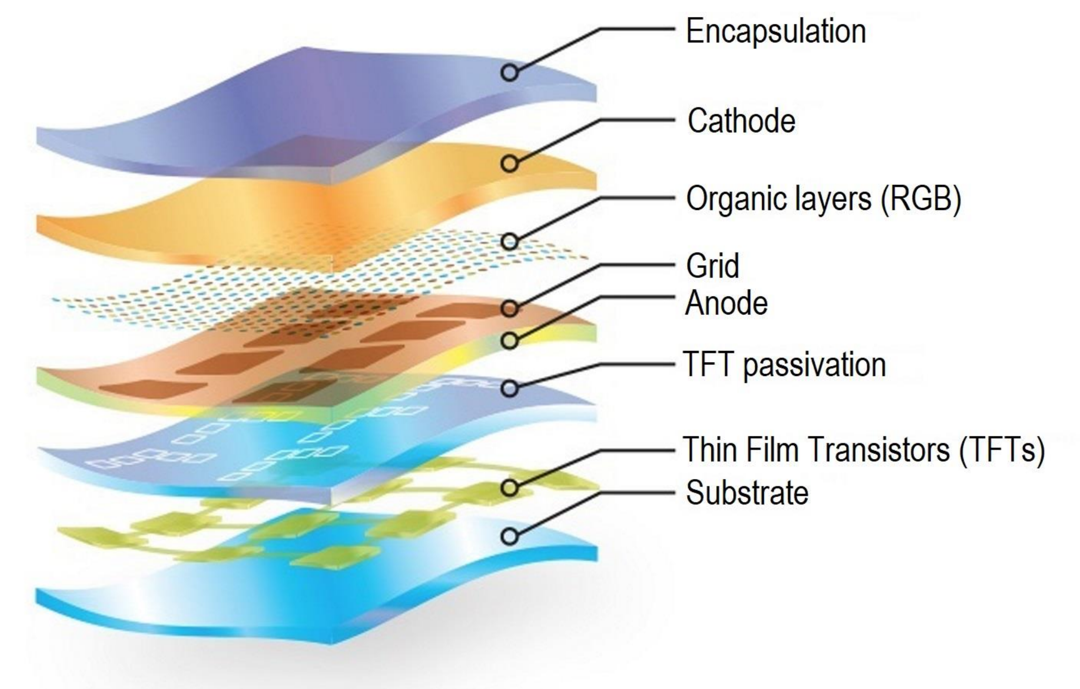
- OFF pixels: transparency may reach 85%
- Active-matrix addressing: transparency is slightly reduced
- Example of material: PEDOT:PSS
  - Polymer based on polythiophene and sulfonated polystyrene
  - Conductive material with high efficiency
  - Transparent and easy to process
  - Can be used as hole transport layer and replacement for ITO electrodes

Transparent and Flexible Displays (3)

© Samsung Display

Transparent and Flexible Displays (4)

- FOLED (*Flexible OLED*)
  - Substrate of plastic or metal foil



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Transparent and Flexible Displays (5)

- Conformable (curved) displays
  - Slightly bent by the manufacturer
- Foldable displays
  - Can be folded with a small curvature radius
  - Examples: Royole FlexPai, Samsung Galaxy Z Fold5

© Royole Corporation

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Transparent and Flexible Displays (6)

- Rollable displays
  - TV sets that roll up into a cylinder
  - Tablet-sized devices that roll up into a pen
  - Example: LG Signature OLED TV R (LG Display)

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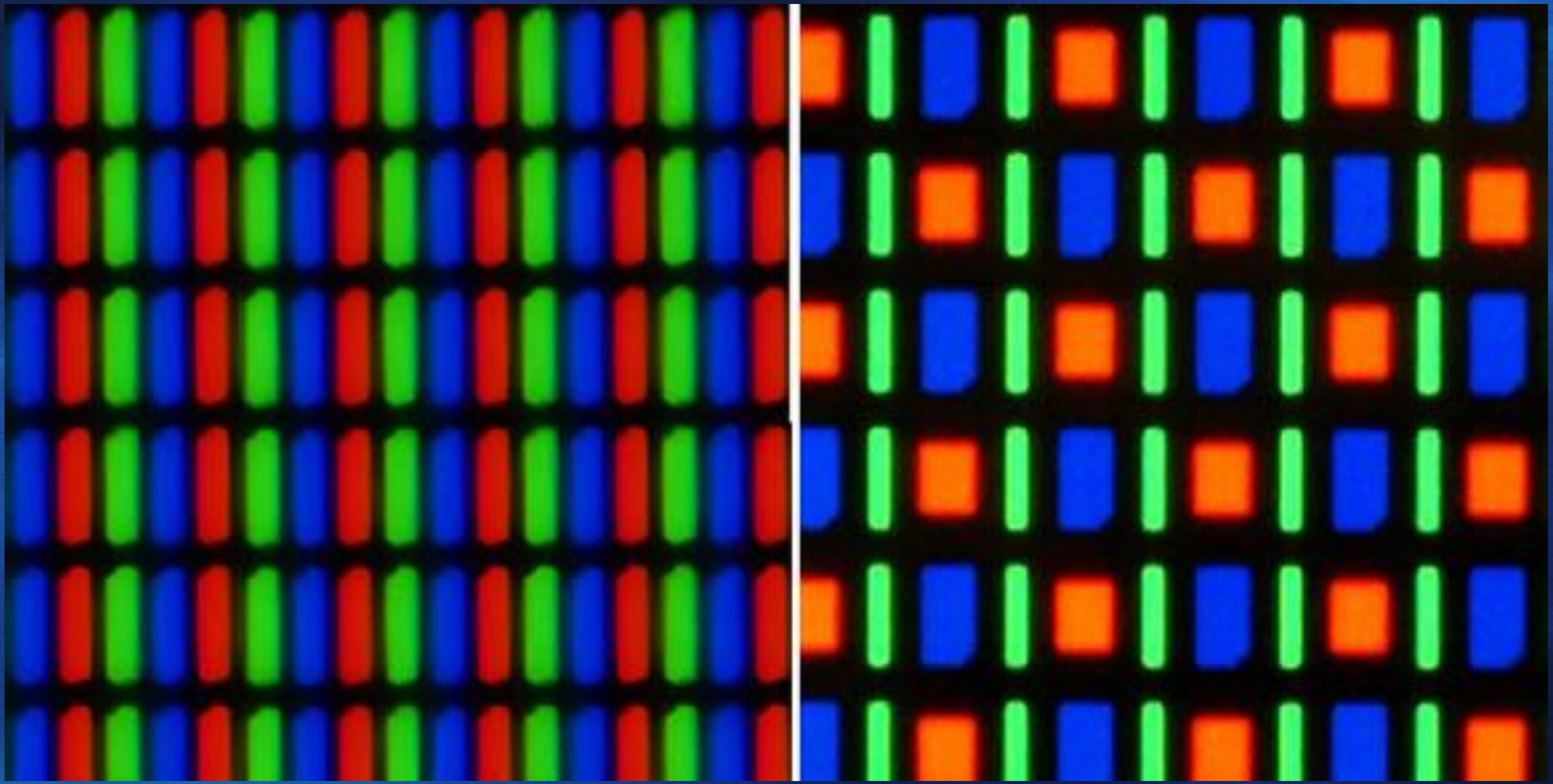
Sub-Pixel Layouts (1)

- Conventional layout: RGB
- RG-B-RG PenTile Layout
  - Inspired by peculiarity of the human retina → fewer sensors for perceiving blue colors
  - Uses proprietary algorithms for sub-pixel rendering
  - Any input pixel is mapped to a logical pixel → either a red-centered or a green-centered logical pixel

Sub-Pixel Layouts (2)

- RG-BG PenTile Layout
  - G sub-pixels, alternating R and B sub-pixels
  - The input image is mapped to sub-pixels → 1:1 mapping only for G sub-pixels
  - Only two sub-pixels are used for a pixel → the sub-pixel density can be reduced
  - Resolution of the luminance information is not affected significantly
  - Disadvantage: the pixel structure may be more visible

Sub-Pixel Layouts (3)



RGB layout (left) and RG-BG PenTile layout (right)
(Image credit Stuff-Review)

Sub-Pixel Layouts (4)

- Diamond Pixel Layout
  - Developed by Samsung Electronics
  - The number of G sub-pixels is double than that of R and B sub-pixels
  - Oval shape for G sub-pixels
  - Diamond shape for R and B sub-pixels

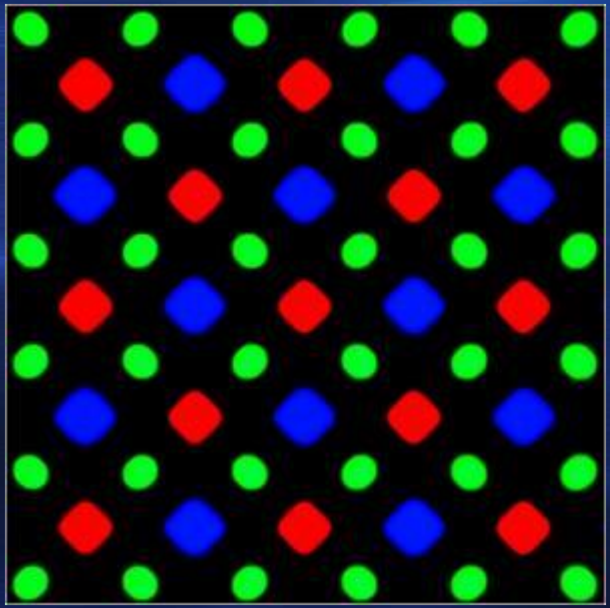
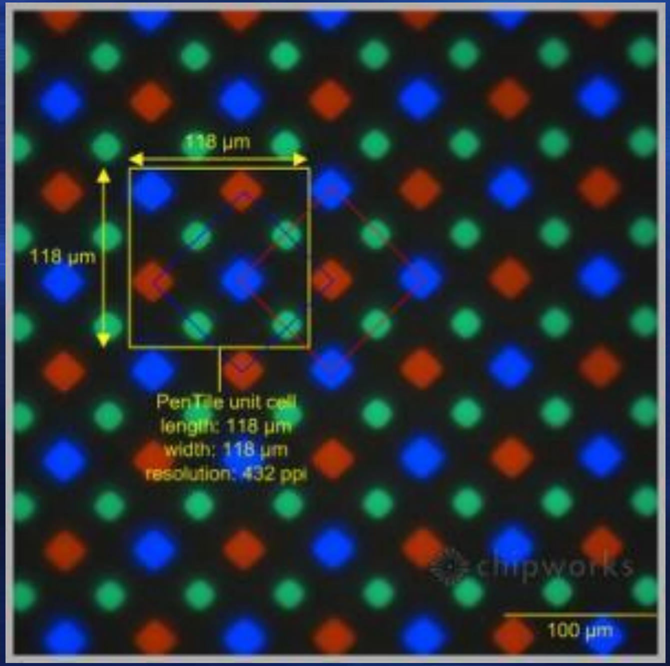


Image credit DisplayMate Technologies Corporation

Sub-Pixel Layouts (5)

- Modified Diamond Pixel layout
  - First used with the Galaxy S5 series
  - All sub-pixels are diamond-shaped
  - B sub-pixels have the same size as the R sub-pixels → improved efficiency of B emitter
  - Densities of over 400 or 500 pixels/inch (PPI)



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Advantages and Disadvantages (1)

- Advantages
  - High contrast ratio (>1,000,000:1), both static and dynamic
  - Wide viewing angles $\rightarrow$ no color shifting
  - Wide color gamut
  - Fast response time (0.01 ms .. 1 ms)
  - On average, power consumption is lower compared to LCDs (40% .. 80%)
  - The plastic substrate is lightweight
  - Flexible and transparent displays can be built

Advantages and Disadvantages (2)

- Disadvantages
  - Currently, the cost of the manufacturing process is relatively high
  - The lifetime of some organic materials (blue OLEDs) is limited (e.g., between 20,000 and 50,000 hours)
  - Color balance may change in time
    - Biasing the color balance towards blue
    - Optimizing the size of R, G, and B sub-pixels → larger blue sub-pixels

Advantages and Disadvantages (3)

- Image persistence may occur
- The display may be damaged by prolonged exposure to ultraviolet rays
- The organic materials can be damaged by water
- Readability in outdoor conditions may be limited
  - Circular polarizer; anti-reflective coating
- Power consumption is increased when displaying images on white background

Summary (1)

- Types of OLEDs based on the size of molecules: SM-OLED and P-OLED
  - SM-OLED: manufacturing process based on evaporation under vacuum
  - P-OLED: can be processed from solutions
- Based on the type of emission: fluorescent and phosphorescent OLEDs
- Their operation is based on forming electrons and holes, and then recombining them
  - Decay of the singlet and/or triplet state releases photons

Summary (2)

- Active-matrix OLED displays require two transistors and a capacitor for each pixel
  - Advantages: higher luminosity; reduced power consumption
- Color generation techniques: direct-emission (RGB OLED); white-emitting OLED (WOLED); stacked OLEDs (SOLED)
- Advantages: high contrast; wide viewing angles; fast response time
- Disadvantages: limited lifetime of blue OLED materials; color balance may change in time

Concepts, Knowledge (1)

- Small-molecule OLEDs
- Polymer OLEDs
- Fluorescent OLEDs
- Phosphorescent OLEDs
- Structure and operation of an OLED cell
- Structure of a bottom-emitting OLED display
- Passive-matrix OLED displays
- Active-matrix OLED displays

Concepts, Knowledge (2)

- Direct-emission OLEDs
- White-emitting OLEDs
- Stacked OLEDs
- Transparent OLED displays
- Flexible OLED displays
- Sub-pixel layouts
- Advantages of OLED displays
- Disadvantages of OLED displays