5. Computer Displays

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

Electronic Paper Displays

- Electronic Paper Displays
  - Principle of Operation
  - Electrophoretic Technology
  - Color Electrophoretic Technologies
  - Interferometric Modulator Technology
  - Advantages and Disadvantages
  - Applications

Principle of Operation

- Also called electronic ink (e-ink) displays
- Reflective displays
- May use one of several technologies
  - Electrophoretic
    - Electrophoresis: motion of particles in a fluid under the influence of an electric field
  - Electro-fluidic: uses a pigment dispersion placed inside a small reservoir
  - Interferometric modulation: colors created through interference of reflected light

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Electrophoretic Technology (1)

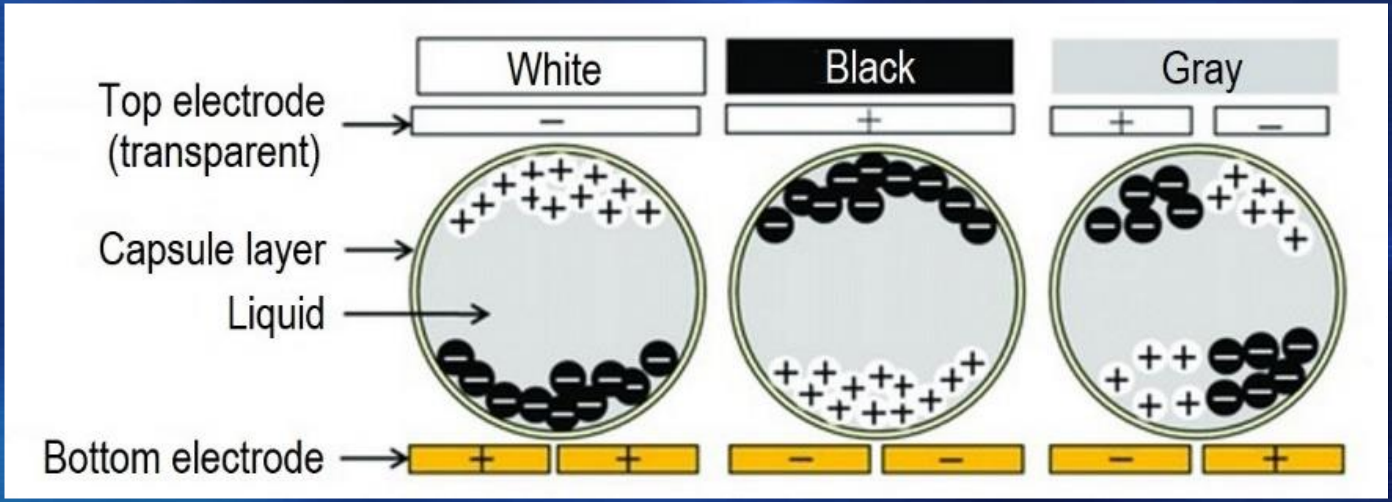
- First electrophoretic displays
  - Suspension of charged particles with pigments in a dyed insulating fluid
  - Two conducting electrode plates
  - Applying a voltage across the plates: the particles migrate towards the plate with opposite charge
    - Either the color of the pigment or of the fluid becomes visible
  - Limitations: particle migration to the electrode edges; particle settling / floating; particle sticking

Electrophoretic Technology (2)

- Electrophoretic displays with microcapsules
  - Initially developed at E Ink Corp.
  - Top electrode: continuous and transparent
  - Bottom electrode layer: divided into pixels
  - Electrophoretic ink: transparent liquid + charged microscopic pigment particles
    - Black particles → negatively charged
    - White particles (titanium dioxide – TiO_2) → positively charged
  - The ink is enclosed within microcapsules

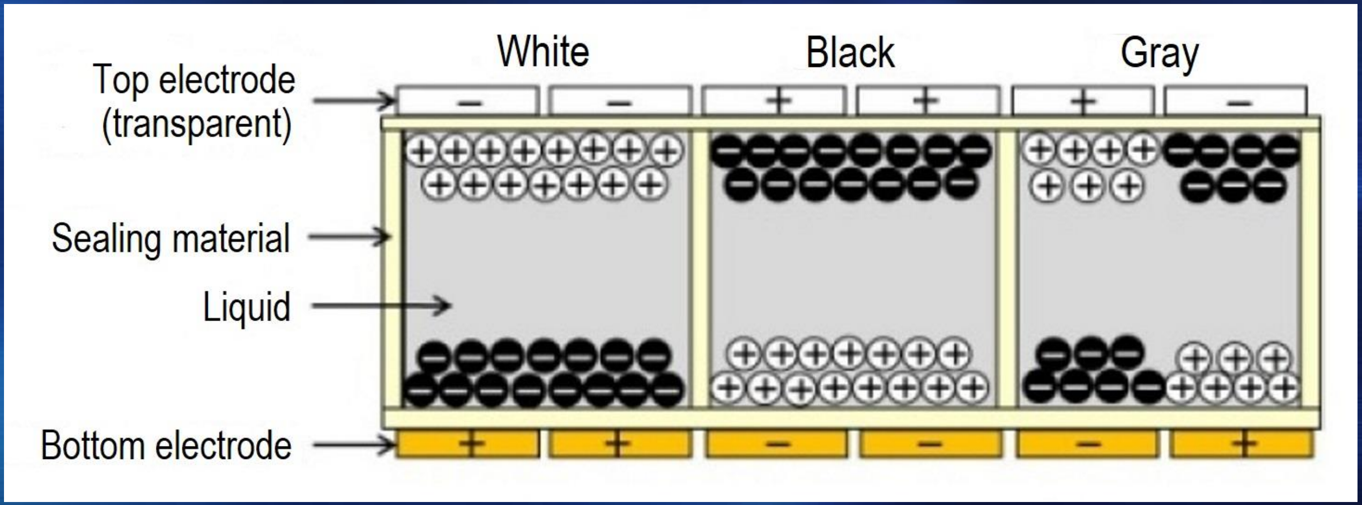
Electrophoretic Technology (3)

- The ink is laminated to a plastic film
- Applying a voltage to the bottom electrode: the particles move to the top or bottom



Electrophoretic Technology (4)

- Electrophoretic displays with micro-cups
  - The electrophoretic ink is enclosed within a micro-cup structure
  - Advantage: simple manufacturing technology



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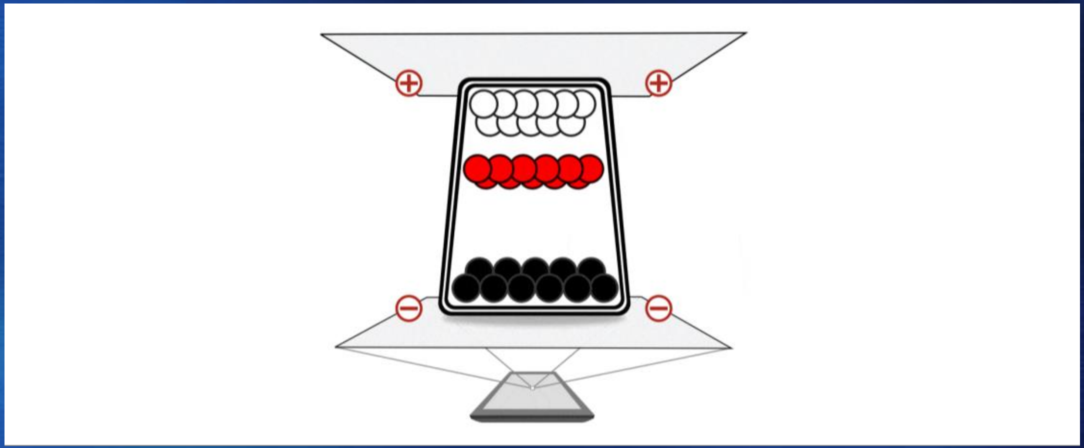
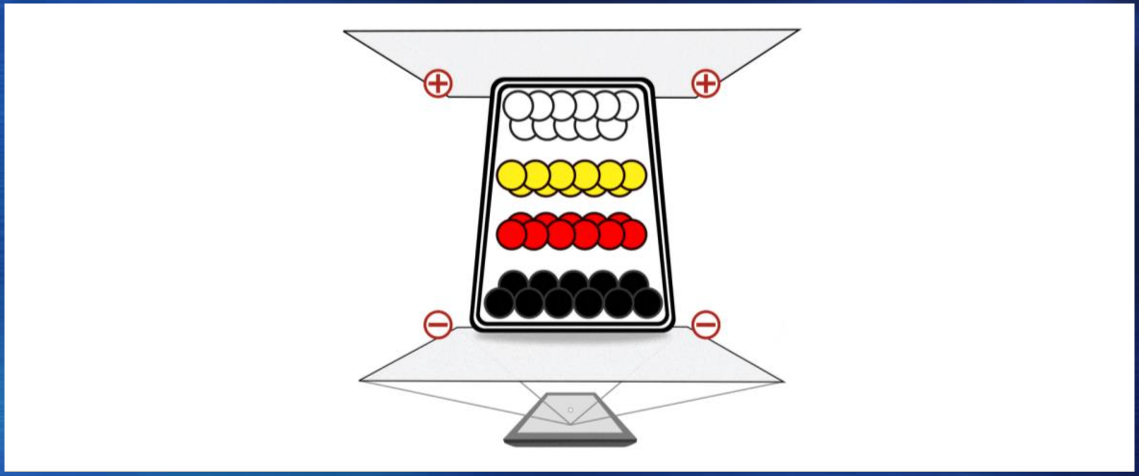
Color Electrophoretic Technologies (1)

- Three-Pigment Ink
  - Uses additional red or yellow pigment particles
  - Example: E Ink Spectra 3000 technology
    - The pigments are enclosed within micro-cups
    - Red and black pigments have different mobility



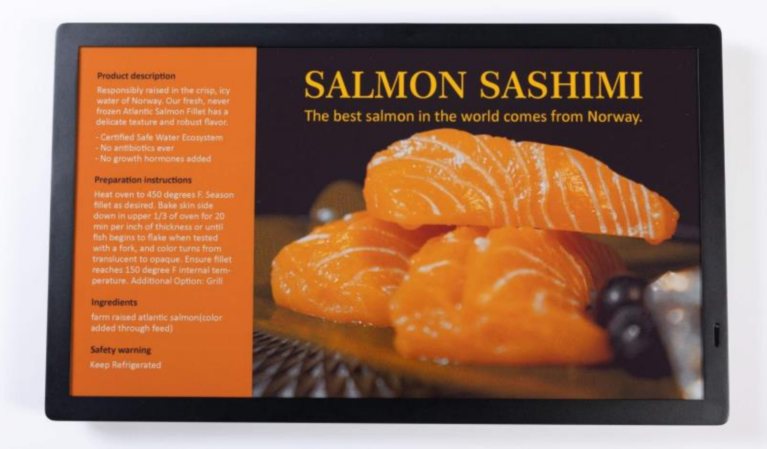
Color Electrophoretic Technologies (2)

- Four-Pigment Ink
  - Example: E Ink Spectra 3100 technology
    - Black, white, red, and yellow pigments
    - The time needed for updating is reduced



Color Electrophoretic Technologies (3)

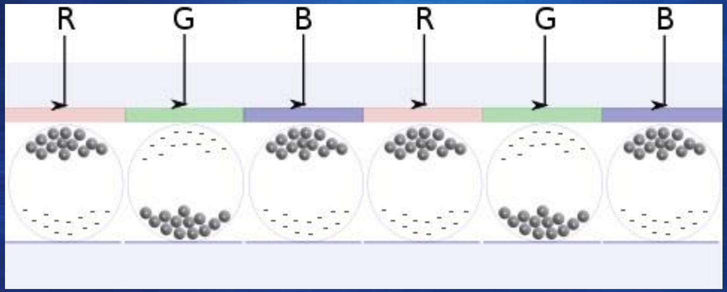
- Five-Pigment Ink
  - Example: E Ink Spectra 3100 Plus technology
    - Additional orange pigments
    - Partial image flashing effect: *E Ink Sparkle*
    - Display sizes up to 8 inch



© E Ink Holdings Inc.

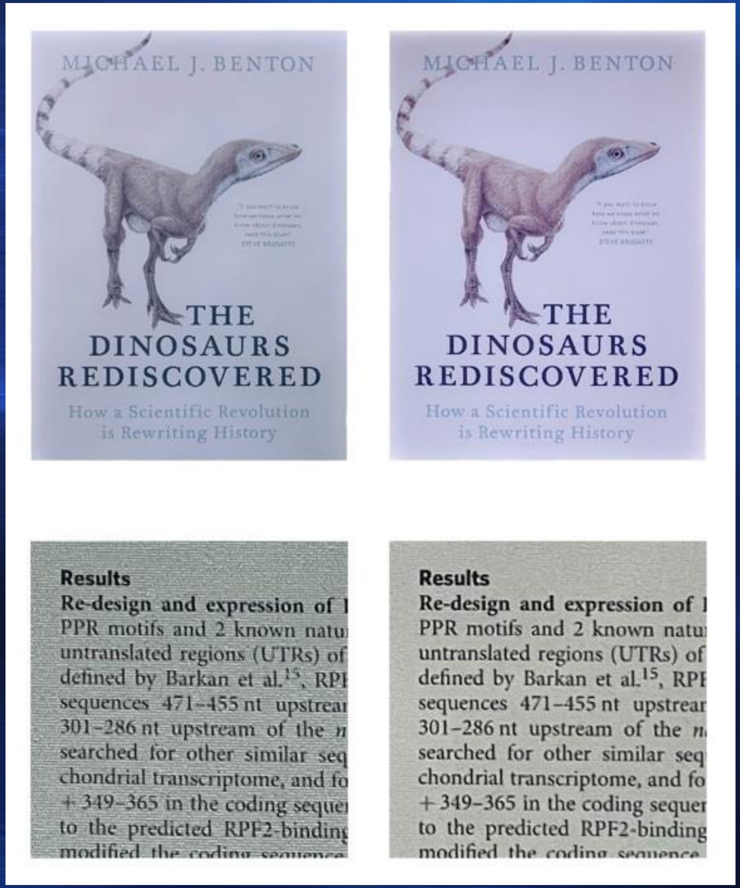
Color Electrophoretic Technologies (4)

- Using Color Filters
  - R, G, B color filter array
  - Disadvantage: reflected light is reduced
  - Example: E Ink Kaleido
    - Active-matrix backplane
    - Electronic ink: E Ink Carta
    - Color filter array (CFA)
    - Touch panel, front light
    - 4,096 colors



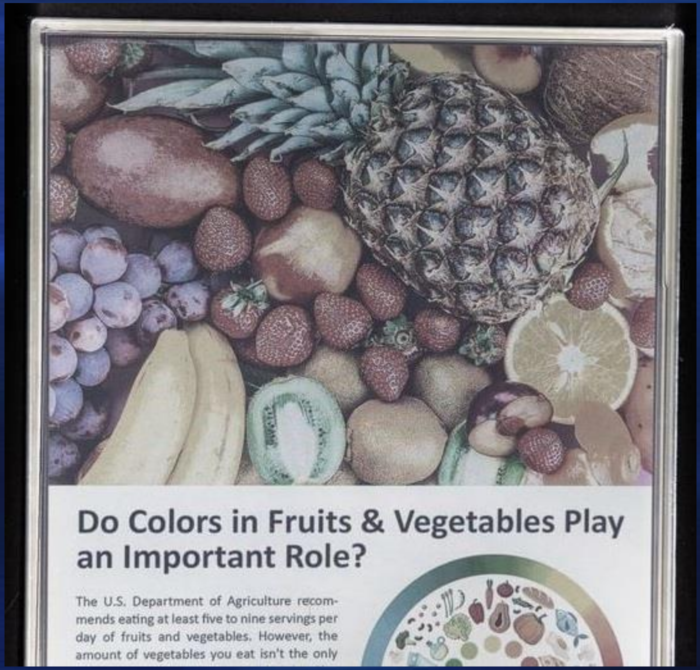
Color Electrophoretic Technologies (5)

- E Ink Kaleido Plus
  - Improvements to the printing pattern of the CFA
  - The CFA layer is placed closer to the e-ink layer
  - Improved text rendering algorithms
  - Improved front lights, light guides: better color gamut
  - Pixel density: 300 PPI (greyscale); 100 PPI (color)



Color Electrophoretic Technologies (6)

- E Ink Kaleido 3
  - Color saturation has been increased by 30%
  - Pixel density: 300 PPI (greyscale); 150 PPI (color)
  - Improved front light system: *E Ink ComfortGaze*
  - Improved response time → higher refresh rate
  - Display panel sizes: 7.8; 10.3; 13.3 (inch)



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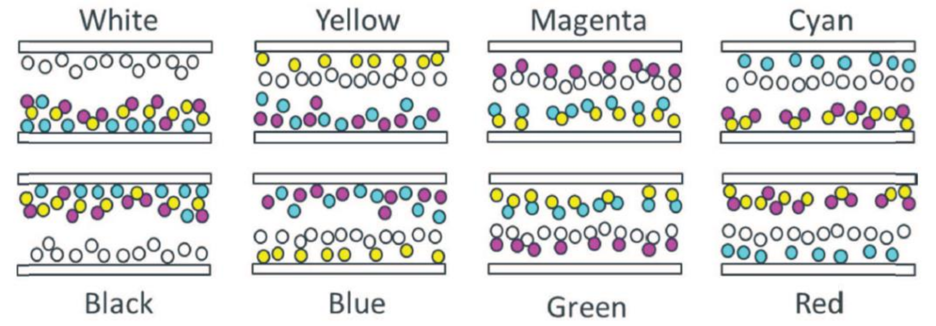
Color Electrophoretic Technologies (7)

- Advanced Color ePaper (ACeP)
  - Technology developed by E Ink Corp.
  - Does not use a color filter array
  - It eliminates the disadvantages of filters
    - Filters absorb light → limit reflectivity
    - Side-by-side combinations of the primary colors reduces resolution and color saturation
  - Three transparent, colored pigments (C, M, Y) and an opaque white pigment
  - Two pigments: positively charged; two pigments: negatively charged

Color Electrophoretic Technologies (8)

- Operation is based on selective electrophoretic motion of pigments
  - Pigments have different electrophoretic mobility
- Another phenomenon: pigment aggregation
  - Two oppositely charged pigments group together
  - May be controlled by the electric fields
  - There are four possible groupings of the C, M, Y pigments (C + M + Y → Black)



Color Electrophoretic Technologies (9)

- E Ink Gallery, E Ink Gallery Plus, E Ink Gallery 3
  - ACeP technology
  - For digital signage applications
  - Panel sizes up to 28 inch
  - E Ink Gallery Plus: improved color gamut; increased contrast ratio
  - E Ink Gallery 3: improved update time; higher pixel density (300 PPI)

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Interferometric Modulator Technology (1)

- IMOD Technology
- Based on the principles of structural color
  - Color is formed from the diffraction of light waves and not from absorption or reflection
  - Component colors are reflected away from a surface at different angles
  - Some wavelengths are cancelled out through interference, while others remain
- Technology inspired by the Blue Morpho butterfly species

Interferometric Modulator Technology (2)

- *Morpho rhetenor rhetenor*
  - The wings contain tiny scales covered with 10-12 layers of lamellae
  - Gaps in the lamellae: ~nm
  - The light is reflected by the lamellae from different depths
    - Constructive interference: the waves are in phase
    - Destructive interference: the waves cancel each other out

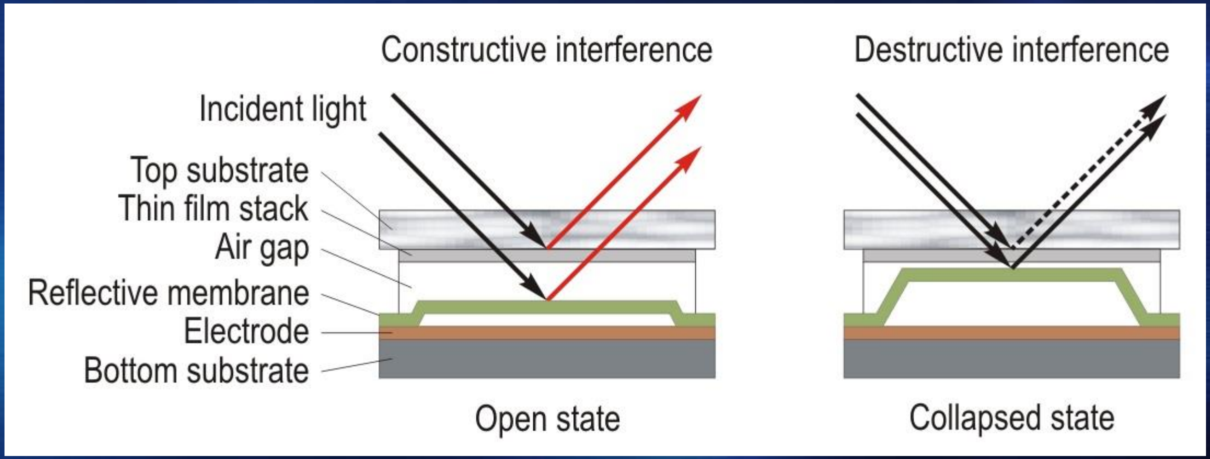
Image credit Muséum de Toulouse

Interferometric Modulator Technology (3)

- Idea of the IMOD technology: the color effect can be achieved at the nanoscale
  - The interference of light waves is controlled via microelectromechanical systems (MEMS)
  - Light modulator: optical cavity
  - Can be switched on/off using driver circuits similar to those used for addressing individual pixels of other types of displays
  - IMOD display: contains individually addressable optical cavities

Interferometric Modulator Technology (4)

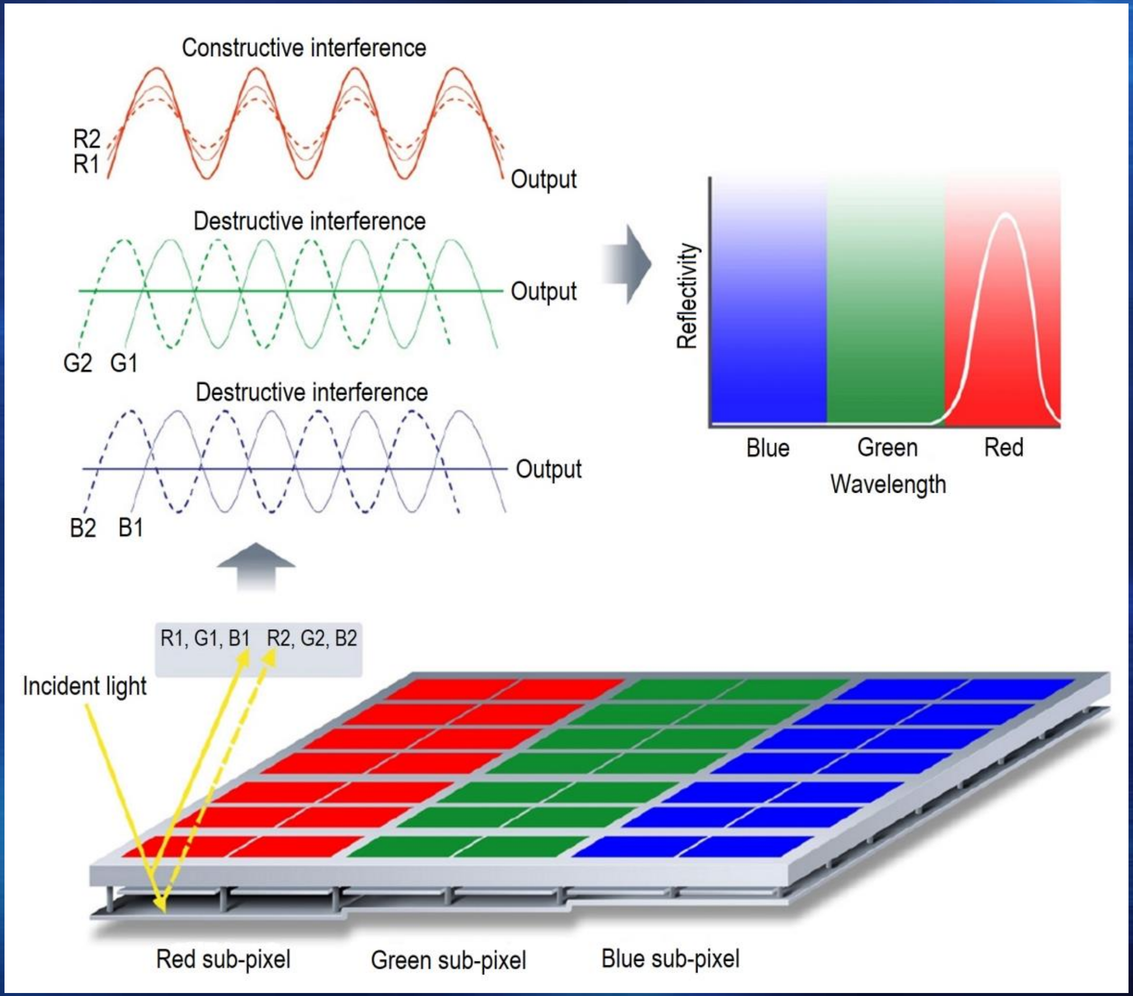
- Principle of an optical cavity
  - The reflected light can be of a certain color, or it can be blocked
    - Open state → light of a certain color
    - Voltage applied between the thin film stack and the electrode: collapsed state → light blocked



Interferometric Modulator Technology (5)

- Color generation
  - Adjusting the height of the optical cavities
  - For each height, a certain color is generated in the open state of the cavity
  - A color display contains spatially ordered optical cavities for the R, G, and B sub-pixels
  - To create different color shades, some type of dithering is used
  - Spatial dithering: each sub-pixel is divided into individually addressable elements

Interferometric Modulator Technology (6)



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Advantages and Disadvantages (1)

- Advantages
  - Extremely low power consumption
    - Bi-stable technology: a static image is retained even when the power source is removed
    - No need for constantly refreshing the screen
    - No need for backlight
  - High contrast
    - Reflective displays
    - Same pigments are used as in the printing industry → same readability as printed paper

Advantages and Disadvantages (2)

- Wide viewing angles
- Very good visibility in direct sunlight or in dimmed light

Advantages and Disadvantages (3)

- High resolution
- Robustness: plastic film substrate; plastic-based TFT backplane
- Light and thin displays
  - Plastic materials can be used as conductors and semiconductors; e.g., PEDOT:PSS
  - Organic TFTs
- Flexible displays
  - Flexible and transparent substrates obtained by printing or vapor deposition processes

Advantages and Disadvantages (4)

- Disadvantages
  - Low refresh rate
    - Not suitable for interactive applications
  - Shadow images
    - Visible after refreshing the screen
    - The screen needs to be refreshed several times
  - Difficulty to build color displays
    - Color technologies that do not use filter arrays are complex
    - Color displays are considerably more expensive

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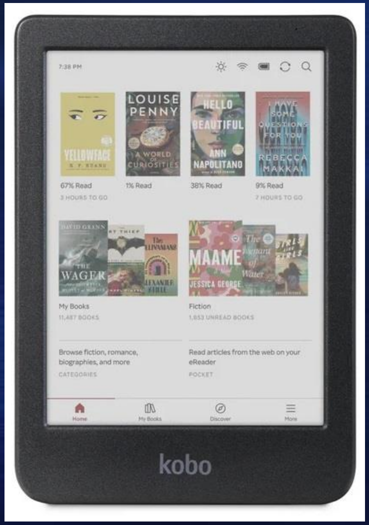
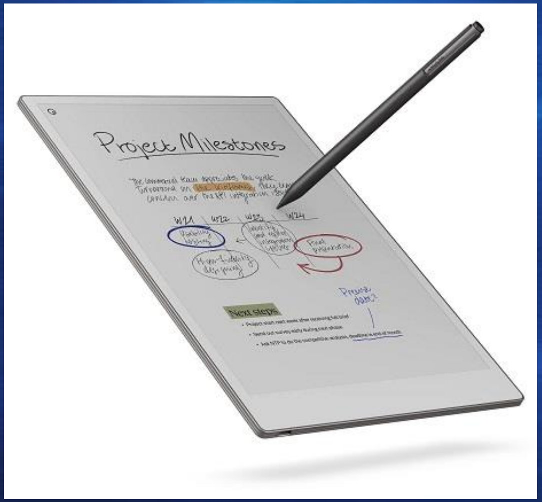
Applications (1)

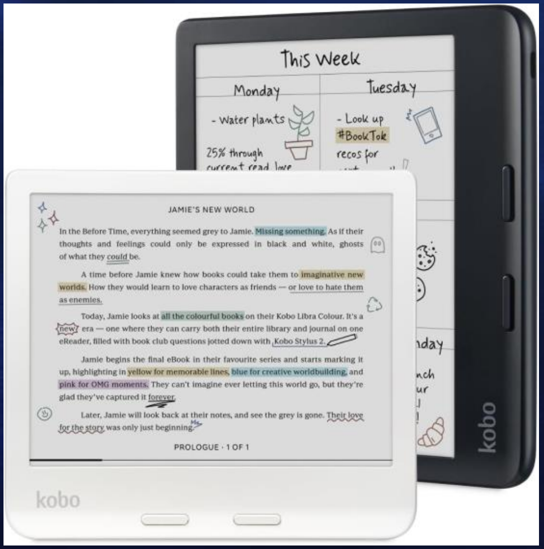
- E-Book Readers
  - Advantages over tablets:
    - Better screen readability
    - Longer battery life
    - Lower weight
  - Examples:
    - Amazon: Kindle Paperwhite; Kindle Colorsoft (top image)
    - Rakuten Kobo: Kobo Clara 2E; Kobo Clara Colour
    - PocketBook: Verse Pro Color



Applications (2)

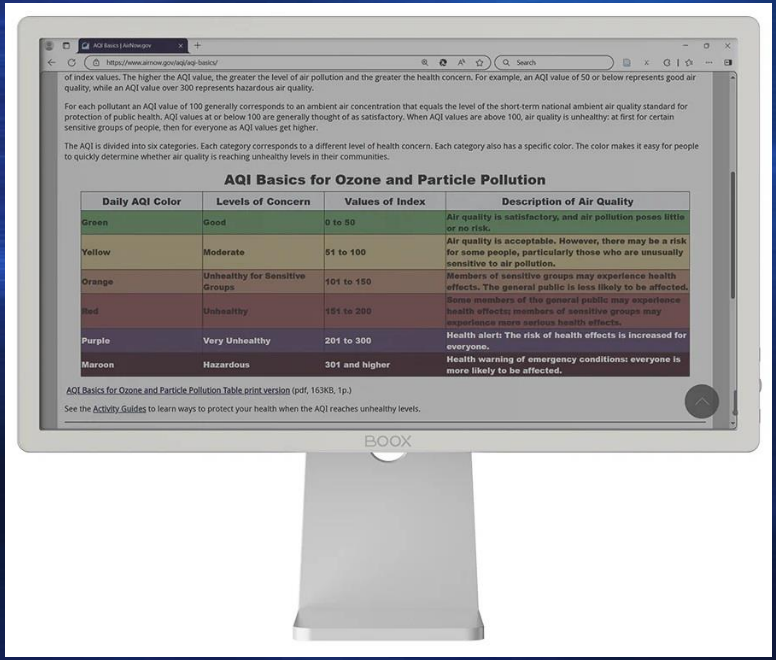
- E-Note Devices
  - Can be used for note-taking and document annotation
  - Example: reMarkable Paper Pro tablet (top image)
    - 11.8-inch display (Canvas Color), based on E Ink Gallery 3 display
    - Pen: pressure and tilt sensitivity
    - Converts handwritten notes to typed text
  - Example: Kobo Libra Colour
    - 7-inch E Ink Kaleido 3 display





Applications (3)

- Computer monitors
  - May reduce eye strain
  - Example: BOOX Mira Pro
    - B&W and color versions
    - Used as primary or secondary monitor
    - 25.3-inch display, E Ink Carta / Kaleido 3
    - Resolution: 3200 x 1800
    - Pixel density: 145 PPI
    - Four screen refresh modes



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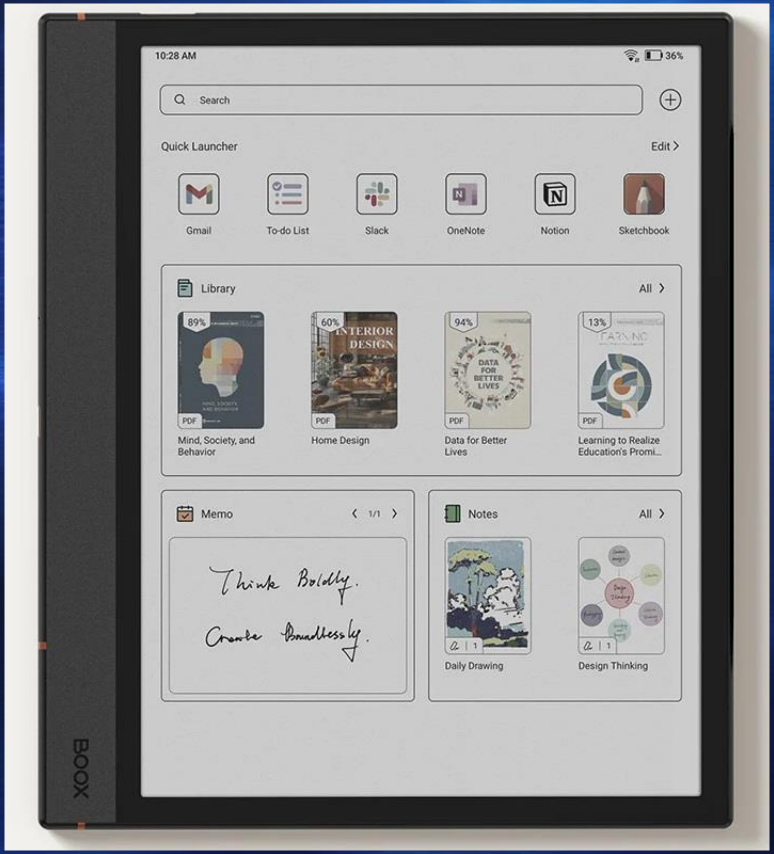
Applications (4)

- Tablets
  - Example: BOOX Note Air4 C
    - 10.3-inch display: E Ink Kaleido 3 (color), HD Carta 1200 (greyscale)
    - Resolution: 2480 x 1860 (grey), 1240 x 930 (color)
    - Pixel density: 300/150 PPI
    - Two touch-sensor layers: capacitive + inductive
    - BOOX Super Refresh (BSR)



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Applications (5)

- Digital Signage
  - Suitable for indoor and outdoor displays
  - Legible, robust, durable, weatherproof
  - Electronic shelf labels
  - Public information display: events, wayfinding signs
  - Public transportation signs: timetables, maps

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Quantum Dot Displays

- Quantum Dot Displays
  - Quantum Dots
  - Technologies for Liquid Crystal Displays
  - Quantum Dot on OLED Technology
  - Quantum Dot on MicroLED Technology
  - Quantum Dot Electro-Luminescent Technology

Quantum Dots (1)

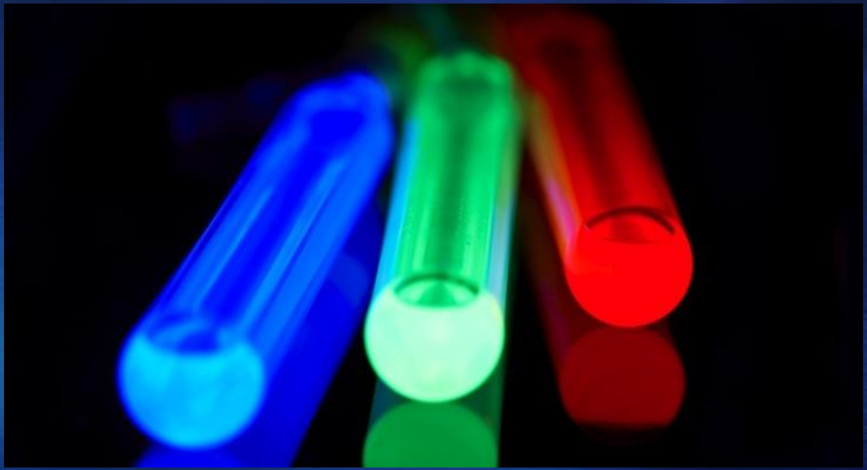
- Quantum dots (QDs)
  - Semiconductor nano-crystals
  - Diameter: 1.5 nm .. 7 nm
  - Emit monochromatic light when illuminated or subjected to an electric current
  - The color of emitted light depends on the size
    - Smaller size: higher frequency
    - Larger size: lower frequency
  - Photo-emissive: emission after absorption of photons
  - Electro-emissive: emission when an electric current passes

Quantum Dots (2)

- Synthetic quantum dots
  - Their size and shape are controlled by the parameters of chemical reactions used
  - Only emit light with a certain color
    - Diameter of 7 nm (150 atoms): red light
    - Diameter of 3 nm (30 atoms): green light
    - Diameter of 2 nm (15 atoms): blue light
  - Structure: core; shell; stabilizer
  - Materials based on cadmium: CdSe
  - Materials based on indium: InAs, InP

Quantum Dots (3)

- Advantages
  - Ability to create pure primary colors
  - High brightness
  - Wide viewing angles
  - High energy efficiency



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Quantum Dot Displays

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Technologies for Liquid Crystal Displays (1)

- Improve the color quality and extend the color gamut of liquid crystal displays
- QDEF (*Quantum Dot Enhancement Film*)
  - Backlight: blue → blue LEDs
    - Used as the blue primary color
    - Supplies the energy required for the photo-emissive quantum dots
  - Light Guide Plate (LGP): diffuses the light emitted by the LEDs
  - QDEF sheet: QDs for the R and G colors + resin + two barrier films

Technologies for Liquid Crystal Displays (2)

- A much purer white light is generated
  - Optical films for mixing the R and G primary colors with the B color of the backlight
- The white light is passed through the same layers as in a traditional panel

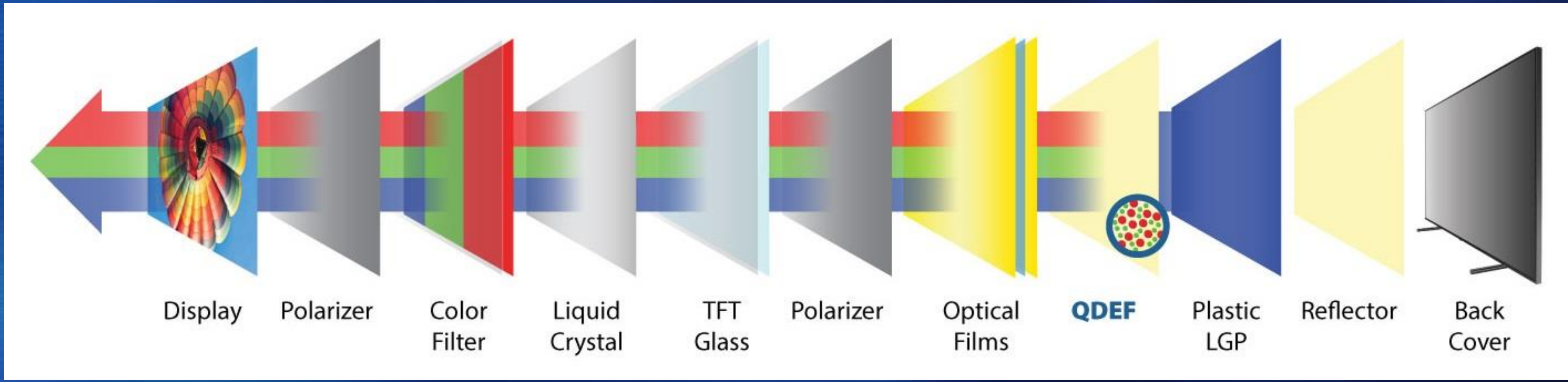


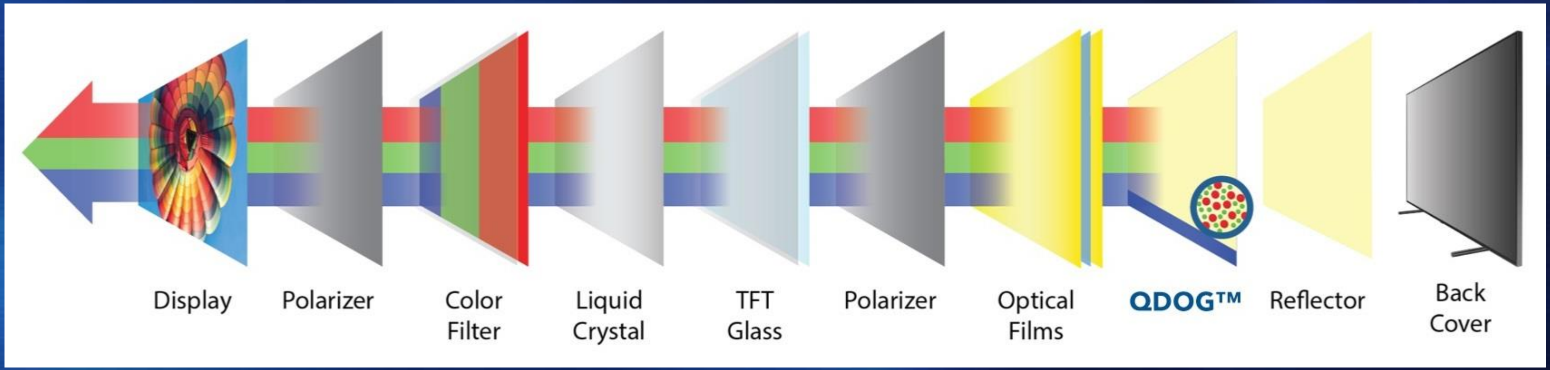
Image credit Nanosys Inc. (Shoei Chemical Inc.)

Technologies for Liquid Crystal Displays (3)

- Advantages
  - Compatibility with manufacturing processes used for liquid crystal display panels
  - Extended color gamut
  - High brightness: 2000 cd/m^2 (nits)
- Disadvantage
  - Requires color filters
- Example products
  - TV sets: Sony (Triluminos brand); Samsung Display (QLED brand)
  - Monitors: Philips, HP, Samsung Display, ASUS

Technologies for Liquid Crystal Displays (4)

- QDOG (*Quantum Dot on Glass*)
  - Uses a glass light guide plate
  - The QD layer is coated directly onto the glass light guide plate
    - Covered with a thin film → replaces the barrier films used with the QDEF technology



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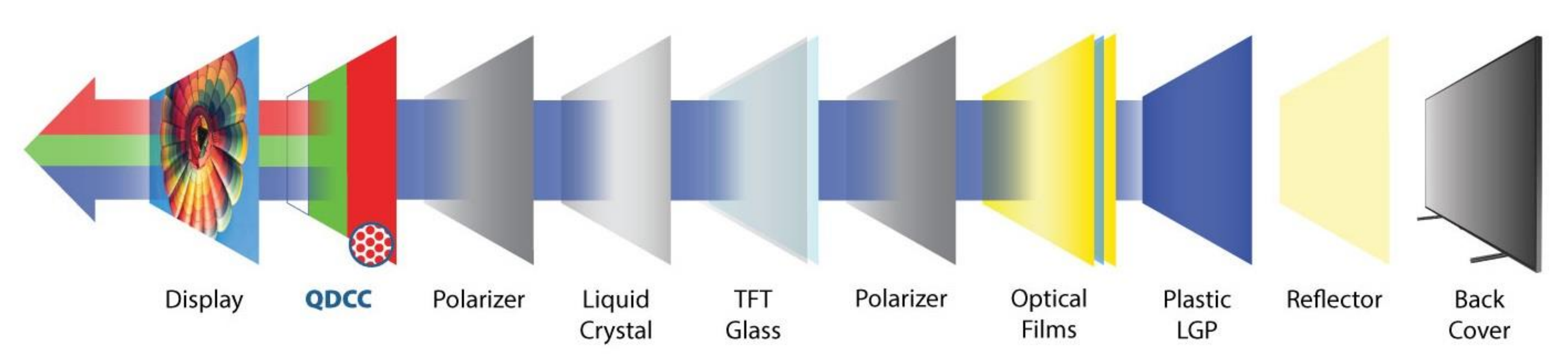
Technologies for Liquid Crystal Displays (5)

- QDCC (*Quantum Dot Color Conversion*)
  - Color filters are still needed by the previous technologies → reduce the brightness
  - QDCC: replaces the color filters with a layer of QDs patterned into sub-pixels
    - Blue sub-pixels are transparent to allow passing the blue backlight
  - Quantum dots depolarize the light
    - The QDCC layer is moved in front of the second polarizer → embedded into the glass panel

Technologies for Liquid Crystal Displays (6)

- The viewing angle is improved by moving the emissive QDCC layer to the front
- Technologies for creating the QDCC layer
  - Photolithography: high rate of QD wastage
  - Ink-jet printing: cost is reduced



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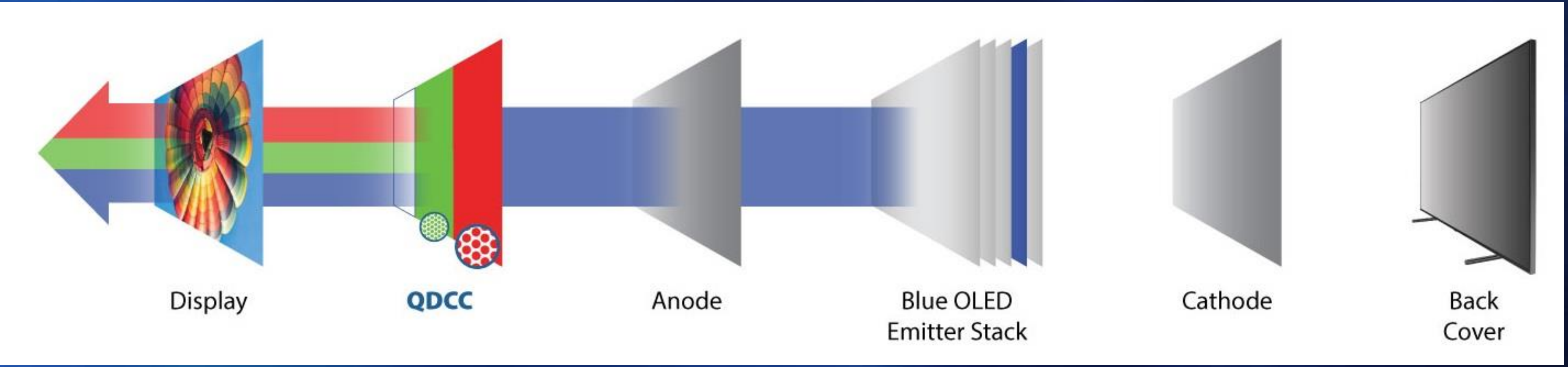
  - Quantum Dot on OLED Technology
  - Quantum Dot on MicroLED Technology
  - Quantum Dot Electro-Luminescent Technology

Quantum Dot on OLED Technology (1)

- QD-OLED (*Quantum Dot on OLED*)
  - Uses a layer of quantum dots patterned into sub-pixels for color conversion (QDCC)
  - The blue backlight is generated with a blue OLED emitter stack



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Quantum Dot on OLED Technology (2)

- The liquid crystal layer is eliminated
- The display becomes fully emissive
- Advantages
  - The color gamut is extended compared to white-emitting OLED displays (WOLED)
  - The structure of WOLED displays is simplified
  - The manufacturing costs are reduced
  - The technology provides high resolutions, especially with photolithographic processes
- Pilot production: Samsung Display, LG Display

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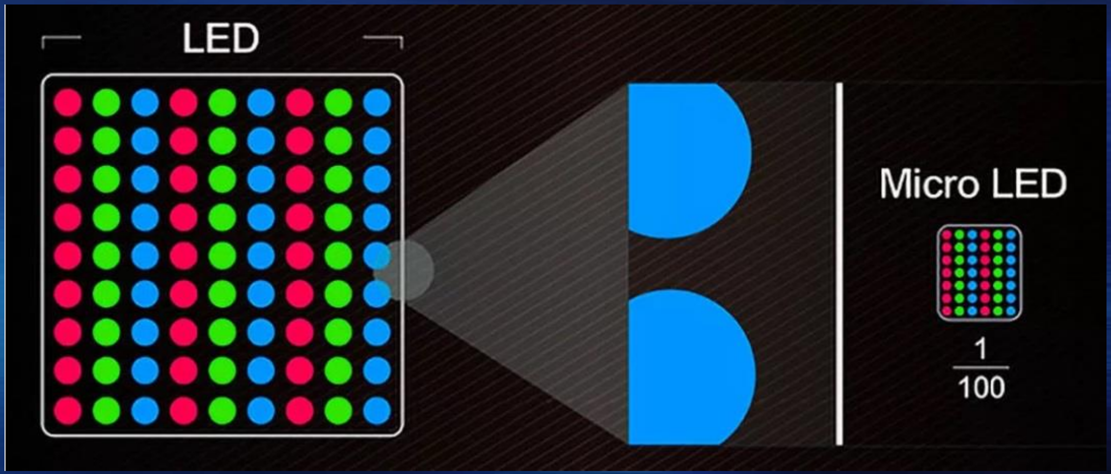
Quantum Dot on MicroLED Technology (1)

- QD-MicroLED (*Quantum Dot on MicroLED*)
  - For each sub-pixel, there is a microLED
  - The manufacturing technology is difficult
  - Advantages: image retention is eliminated; higher brightness; higher energy efficiency

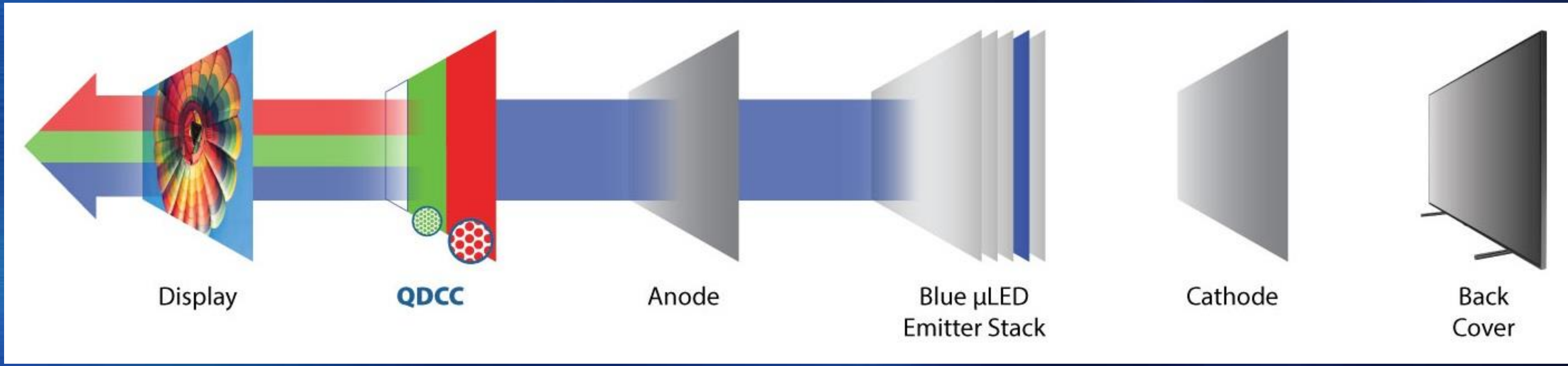


Quantum Dot on MicroLED Technology (2)

- Reducing the size of LEDs is difficult
  - Prototype of a 75-inch TV set: 0.15 mm
- When the size of LEDs is reduced, the amount of light emitted is also reduced
  - Increasing the current for driving the LEDs or increasing the efficiency of LEDs
- Possible approach to reduce the complexity of manufacturing: using only blue microLEDs
  - Color converters are used to create the red and green sub-pixels
  - A single semiconductor process is required
  - Quantum dots can be used as color converters

Quantum Dot on MicroLED Technology (3)

- Technical challenge when integrating quantum dots into microLED wafers
  - The quantum dots are exposed to high temperatures and continuous light fluxes
  - Their rapid degradation may occur
- Structure similar to that of a QD-OLED display



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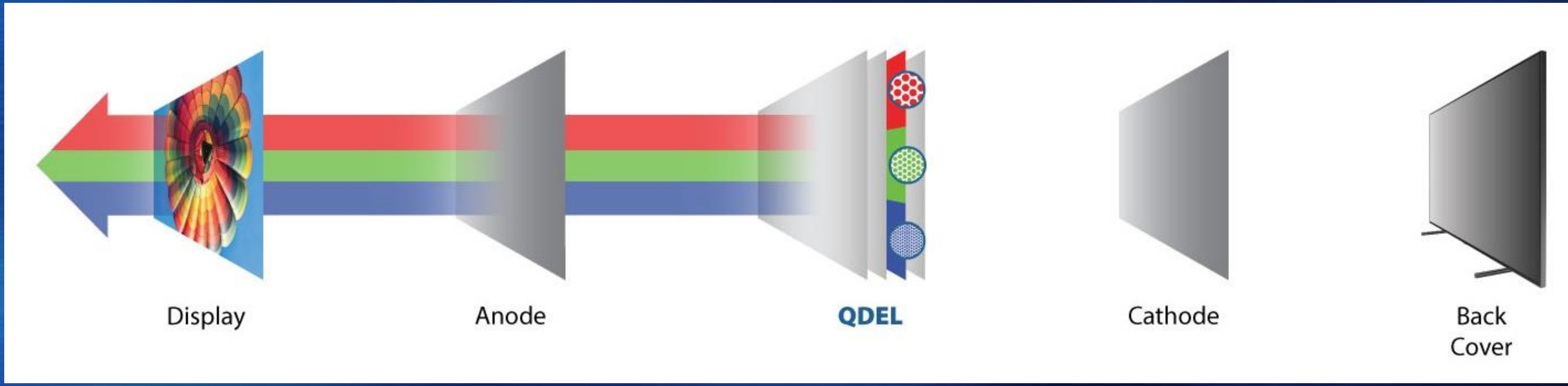
Quantum Dot Electro-Luminescent Technology (1)

- QDEL (*Quantum Dot Electro-Luminescent*)
  - Uses electro-emissive quantum dots
    - Similar to organic LEDs (OLEDs)
    - Inorganic materials placed between electron-transporting and hole-transporting layers
    - Same function as that of a conventional LED or microLED
    - More susceptible to damage than photo-emissive quantum dots used as color converters
    - Currently, their stability is poor

Quantum Dot Electro-Luminescent Technology (2)

- The QDEL technology is not available yet
- Potential advantages of QDEL displays
  - Very high efficiency
  - High brightness levels
  - Enable to use low-cost manufacturing processes



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Summary (1)

- Electronic paper (e-paper, e-ink) displays are reflective
  - The electrophoretic technology is the most widely used
  - Electrophoretic displays with microcapsules or micro-cups are used in practice
  - Color technologies developed:
    - Three-pigment ink
    - Using color filters
    - Advanced Color ePaper (ACeP)

Summary (2)

- The interferometric modulator technology is based on the principles of structural color
  - Color is formed from diffraction of light waves
  - Constructive or destructive interference occurs
  - Light modulator: optical cavity
- Advantages: good visibility even in bright lighting conditions; low power consumption; robustness
- Disadvantages: low refresh rate; shadow images; complex color technologies

Summary (3)

- Quantum dots: semiconductor crystals a few nanometers in diameter
  - Emit monochromatic light when subjected to light or electric current
  - The wavelength of emitted light depends on the diameter of the crystal
  - Photo-emissive or electro-emissive
  - Synthetic quantum dots: their size can be controlled during the production process
    - Only emit light at a certain wavelength

Summary (4)

- Quantum dot technologies for liquid crystal displays
  - QDEF: uses red and green quantum dots; the backlight is blue
  - QDOG: uses a glass light guide plate, with the quantum dots coated directly onto it
  - QDCC: replaces the color filters with R and G quantum dots, patterned into sub-pixels
- The QD-OLED technology uses blue OLEDs for generating the backlight

Summary (5)

- The QD-MicroLED technology uses one microLED for each sub-pixel
- The QDEL technology uses electro-emissive quantum dots
- Advantages of quantum dot displays
  - Extended color gamut: covering more than 90% of the BT.2020 color space; ability to build high dynamic range (HDR) displays
  - High brightness
  - Low power consumption

Concepts, Knowledge (1)

- Electrophoretic e-paper displays with microcapsules
- Electrophoretic e-paper displays with micro-cups
- Three-pigment e-ink technology
- Advanced Color ePaper (ACeP) technology
- Interferometric modulator technology
- Advantages of e-paper displays
- Disadvantages of e-paper displays

Concepts, Knowledge (2)

- Properties of quantum dots
- QDEF technology
- QDOG technology
- QDCC technology
- QD-OLED technology
- QD-MicroLED technology
- QDEL technology