Display Technology Overview

The following whitepaper provides an overview of current and emerging display technologies and is intended to familiarize the reader with them. The paper begins with an introduction to the important role display technology plays and the different display technologies covered. Technologies included are Liquid Crystal Displays, Organic Light Emitting Diodes, Digital Light Processing Technology, Plasma Displays, Field Emission Displays, and Electronic Paper. For each topic the theory of operation, the structure, the advantages, and disadvantages are discussed. A table is included in order to compare the characteristics of the different display technologies. The paper ends with a summary of the display technologies discussed, a glossary of technical terms, and a list of references.

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1.0 Introduction

Display technology plays a critical role in how information is conveyed. As a picture is worth a thousand words, display technology simplifies information sharing. Since its commercialization in 1922 up until the late 20th century, Cathode Ray Tube technology (CRT) has dominated the display industry. However, new trends such as the desire for mobile electronics have increased demand for displays that rival and surpass CRTs in areas such as picture quality, size, and power consumption. One of the latest devices likely to replace CRTs is Liquid Crystal Displays (LCD) due to their lightweight, low operating power, and compact design. LCDs allowed devices such as digital watches, cell phones, laptops, and any small screened electronics to be possible. Although LCDs were initially created for handheld and portable devices, they have expanded into areas previously monopolized by CRTs such as computer monitors and televisions. Other contenders for leadership in display technology are Organic LEDs, DLP technology, Plasma Displays, Field Emission Displays, and Electronic Paper. Organic LEDs, being composed of light emitting polymers, can emit their own light to offer thin and power-saving displays. Using many microscopic mirrors, DLP technology can generate large bright projections on screens with up to 35 trillion colours. Plasma Displays generate excellent quality images on very large screens. Field Emission Displays can produce high resolution images like CRTs without the bulky appearance. The makers of Electronic Paper are trying to replace print by developing displays with many paper-like properties. Demand for higher quality displays will drive technology evolution; this evolution will require new approaches and innovative ideas in information presentation.

2.0 Liquid Crystal Displays

Liquid crystals were discovered in 1888, but their potential application in display technology was not realized until 1968 when researchers from the RCA's David Sarnoff Research Center developed the first liquid crystal display. Since then, LCDs have revolutionized the small screen and portable electronic market offering an alternative to CRTs and making devices like calculators, cell phones, PDAs, and laptops possible. As LCD designs advance, they will remain a popular part of home entertainment systems and continue to dominate handheld electronics.

2.1 Liquid Crystals

An Austrian botanist by the name of Friedrich Reinitzer was the first person to perform research on liquid crystals. In 1888 he conducted an experiment involving a material known as cholesterly benzoate. In his experiment Reinitzer observed changes in a solid sample of cholesterly benzoate as he increased the applied temperature. He noticed that as the temperature increased the solid sample became a hazy liquid and then changed into a transparent liquid. A physics professor named Otto Lehmann having learned of Reinitzer's discovery conducted his own research confirming that the substance seem to have two distinct melting points; his research led him in 1889 to coin the term 'liquid crystal' (1).

Liquid crystals are substances that exhibit properties of both solids and liquids; they are an intermediate phase of matter. Liquid crystals can be classified into three different groups, **nematic**, **smectic**, and **cholestric** depending on the level of order in their molecular structure. Liquid crystals in the nematic group are most commonly used in LCD production because of their physical properties and wide temperature range. In the nematic phase, liquid crystal molecules are oriented on average along a particular direction. By applying an electric or magnetic field, the orientation of the molecules can be manipulated in a predictable manner; this mechanism provides the basis for LCDs.

Figure 1: Close up of nematic phase liquid. Image courtesy of Oleg D. Lavrentovich, Liquid Crystal Institute, Kent State University. (2)

There are a variety of different liquid crystal compounds, which exhibit nematic phases but not all are suitable for use in displays. The phase of matter a substance exhibits is greatly dependant on its temperature. Although many different liquid crystals exhibit nematic phases, they do not do so at room temperature. The first room temperature nematic liquid crystal was observed in 1969 in the compound 4-methoxybenzyliden-4'-butylanilin (MBBA for short). MBBA had major drawbacks including a short stable temperature range that was greatly affected by impurities; these drawbacks prevented MBBA from being used in commercial LCDs and prompted further research to be conducted to find a more stable liquid crystal.

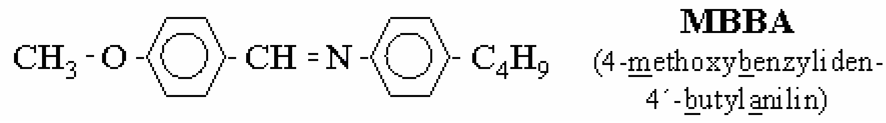


Figure 2: Structure of a MBBA molecule (3)

In 1973 Professor George W. Gray of Hull University in England discovered that cyanobiphenyl materials exhibited room temperature nematic phases. This discovery led to the compound 4-pentyl-4'-cyanobiphenyl or 5CB for short. 5CB proved to be more stable than MBBA and over a greater temperature range; 5CBs properties allowed for the first commercial LCDs to be created.

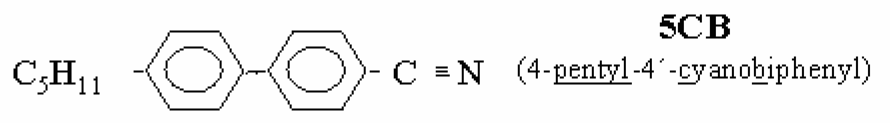


Figure 3: Structure of a 5CB molecule (3)

2.2 Liquid Crystal Display Basics

Simple LCDs consist of a liquid crystal cell, conductive electrodes and a set of polarizing lenses. The structure for a simple LCD is shown in the diagram below.

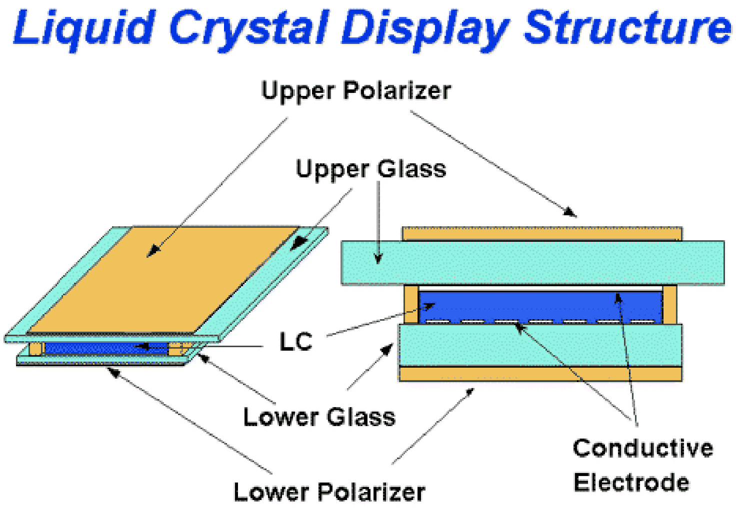


Figure 4: Basic diagram of an LCD. Image courtesy of Emerging Display Technologies. (4)

2.2.1 The Liquid Crystal Cell

To use liquid crystals in display technology, the ability to control how their molecules are naturally arranged is needed. In their natural state, liquid crystal molecules in the nematic phase are loosely ordered with their long axes parallel; to change this arrangement they are placed onto a finely grooved surface. When they come into contact with a finely grooved surface also called the alignment layer, the molecules line up parallel along the grooves.

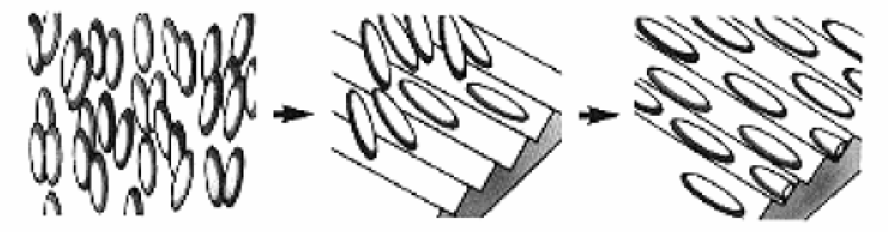


Figure 5: Liquid crystal molecules lining up parallel to the alignment layer. Image courtesy of Emerging Display Technologies. (4)

If contained between two alignment layers molecules closer to the top plate orient themselves in direction 'a' while molecules near the bottom plate orient themselves to the bottom plate in direction 'b' as indicated in Figure 6. If the alignment plates are not parallel, this forces the liquid crystal molecules into a twisted structural arrangement. (4)

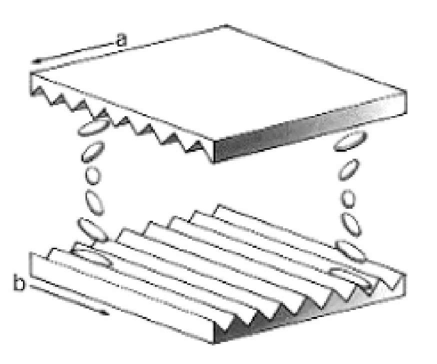


Figure 6: Molecules near each plate line up in respected directions. Image courtesy of Emerging Display Technologies. (4)

Light sent through the twisted liquid crystal structure curls following the molecular arrangement. By changing the orientation of the liquid crystals, light propagating through is also changes to follow. (4)

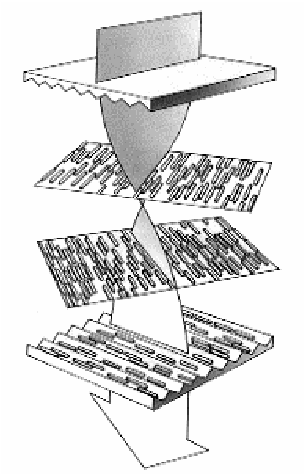


Figure 7: Light rotates following the molecular arrangement. Image courtesy of Emerging Display Technologies (4)

Conductive electrodes are used to apply voltage to the liquid crystal cell. When a voltage is applied the molecules straighten out aligning parallel to the applied electric field; this also allows propagating light to pass directly through. (4)

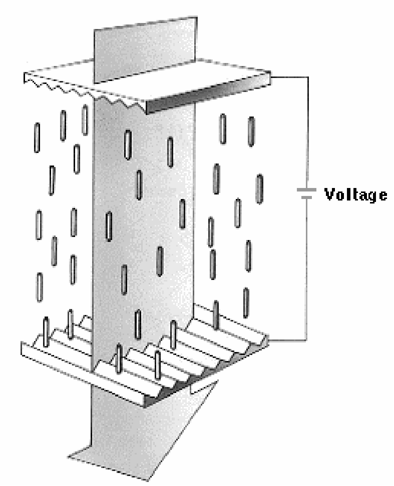


Figure 8: Liquid crystal molecules follow an applied electric field. Image courtesy of Emerging Display Technologies (4)

2.2.2 Polarizing Lenses

Polarizers are materials that contain the electric and magnetic fields of a light wave to one plane; all components not within the plane are filtered out (absorbed). Set parallel to one another polarizing filters will allow light to pass in only one plane (direction 'a' as indicated in Figure 9). When the filters are set in opposite directions or perpendicular to one another, light passes through the first filter but is blocked by the second one. (4)

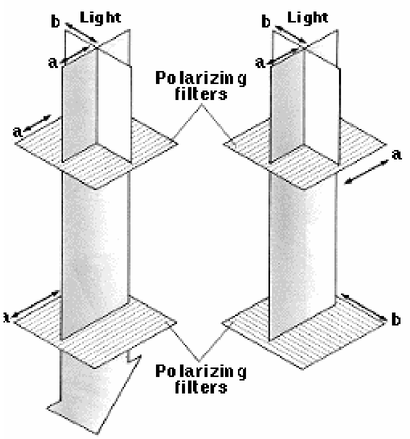


Figure 9: Polarizing filters oriented parallel and perpendicular to each other. Image courtesy of Emerging Display Technologies. (4)

2.2.3 Operation of a Simple Liquid Crystal Display

To form a working LCD the individual components (glass casing, liquid crystal cell, alignment layer, conductive electrodes, and polarizers) are combined. Light entering the display is guided by the orientation of the liquid crystal molecules that are twisted by ninety degrees from the top plate to the bottom. This twist allows incoming light to pass through the second polarizer. When voltage is applied, the liquid crystal molecules straighten out and stop redirecting light. As a result light travels straight through and is filtered out by the second polarizer. Consequently, no light can pass through, making this region darker compared to the rest of the screen. This configuration is an example of a twisted nematic LCD; other configurations will be discussed in a later section. To display characters or graphics, voltage is applied to the desired regions making them dark and visible to the eye. High-end displays today allow for 256 different levels of light or shades. This allows for a grey scale in which graphics and characters can be displayed in many varying intensities.

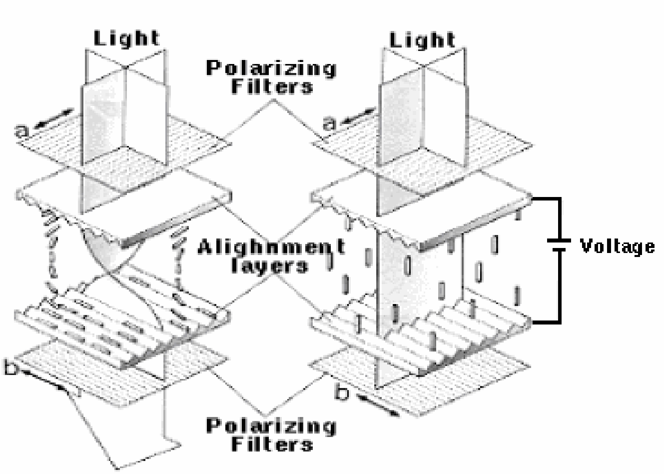


Figure 10: Example of a twisted nematic LCD. Image courtesy of Emerging Display Technologies. (4)

2.3 Display Features

LCD designs can vary depending on the desired application. Display format, resolution, response time, and contrast are all features that can vary depending on the desired use. On an LCD information is general displayed in segments or pixels. Segments are long static regions that can be arranged into different shapes. The most common segment configuration is the seven-segment display shown below. This format is commonly used in calculators, watches and other simple numerical displays.

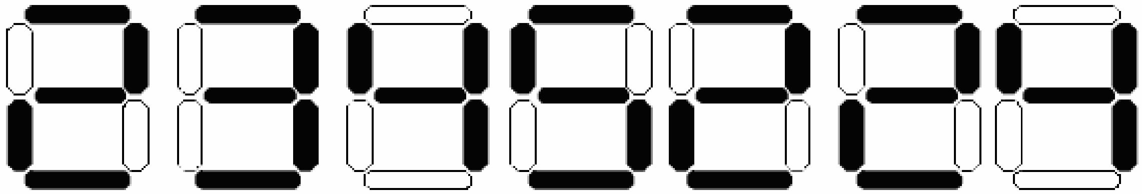


Figure 11: An example of a seven digit seven segment display

Pixels or picture elements are the smallest controllable element on a screen. A grid of pixels is used to generate various characters; these characters are formed into an array in order to create words and/or sentences.

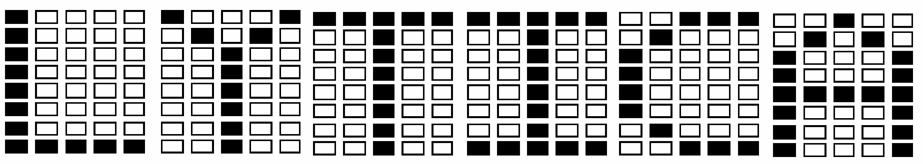


Figure 12: Example of a six by one character display

Images or graphics can also be displayed by turning on or off certain pixels.

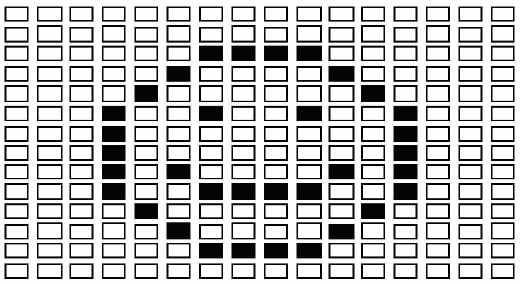


Figure 13: Example of a graphic produced on a 16x16 pixel grid. Image courtesy of Emerging Display Technologies. (4)

The greater the number of pixels on a screen, the better the quality of the image produced.

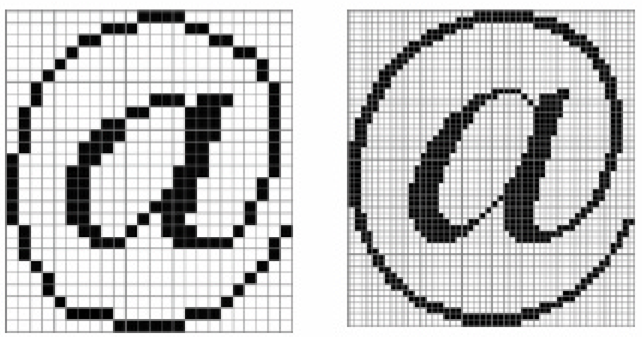


Figure 14: Effect of number of pixels: Image on left was created with 648 pixels (24x27) while the sharper image on the right uses 2592 (48x54) pixels. NCTU Display Institute. (5)

Response time is a measure of how long it takes a pixel to turn from white to black (rise time), and then back again (fall time). Rise and fall times are controlled by the viscosity of the liquid crystal, the amplitude of the driving voltage, and the thickness of the liquid crystal cell. For a given liquid crystal compound the cell thickness is usually set, to increase the response time the driving voltage can be increased or the viscosity lowered. Typical response times for today's LCD monitors and televisions range from 4ms to 30ms.

Contrast ratio is another important factor to be considered. Contrast ratio is the difference in brightness between an 'on' pixel divided by an 'off' pixel. For example a contrast ratio of 40:1 means the brightness of an activated pixel is forty times greater than an 'off' pixel.

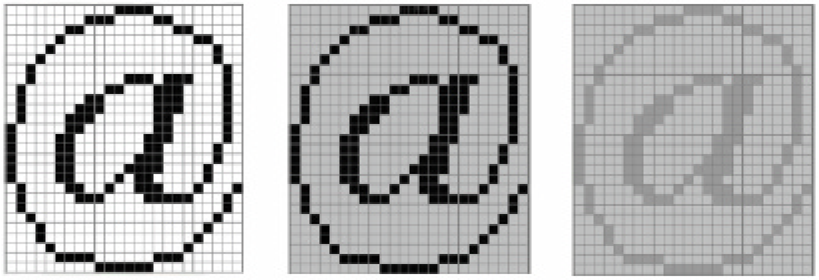


Figure 15: Image on the left has high contrast and is the easiest to see while the image on the right has the lowest contrast and looks less clear. NCTU Display Institute. (5)

2.4 Light Transmission Modes

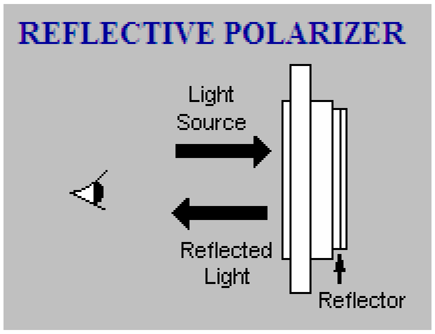


Figure 16: Reflective technology setup (6)

All LCDs are non-emissive devices, meaning they do not generate their own light. In order for information to be displayed there are three common illumination techniques; reflective, transmissive, and transflective. Reflective technology includes a diffuser attached to the lower polarizer; this layer reflects incoming light evenly back through the display. This type of display relies on ambient light to operate; they will not work in dim lit areas. Reflective technology is commonly found in calculators and digital wristwatches.

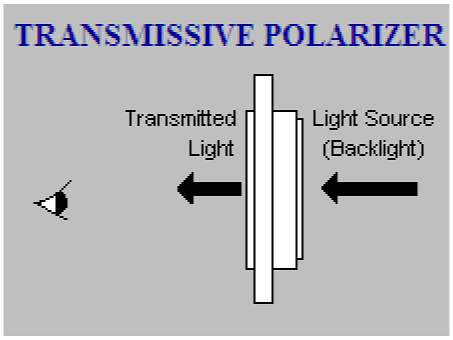


Figure 17: Transmissive technology setup (6)

Transmissive technologies have backlights attached to the lower polarizer. Instead of reflecting ambient light, the backlight supplies a light source directly to the display. Most transmissive displays operate in a negative mode, meaning that the text will be a light colour and the background a dark colour. LCDs using transmissive configurations have good picture quality indoors but are barely readable in natural sunlight. This is due to the intensity of sunlight reflecting from the surface of the LCD which is much stronger than the light coming from the backlight. Transmissive devices can be found in medical devices, electrical test and measurement instruments, and laptop computers.

Transflective devices are a hybrid of the reflective and transmissive schemes. The construction is similar to transmissive displays except a partially reflective layer is added between the backlight and the liquid crystal. Since it is a hybrid, transflective screens perform in both indoor and outdoor conditions, but are not as effective as the previous two. Transflective displays are used in devices such as cell phones, PDAs and GPS receivers.

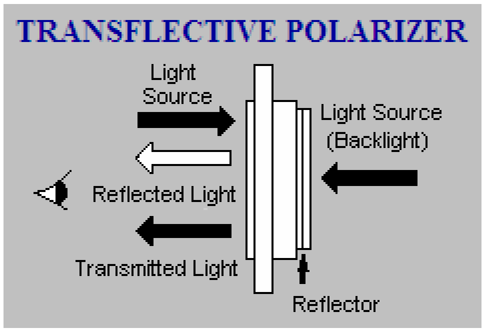
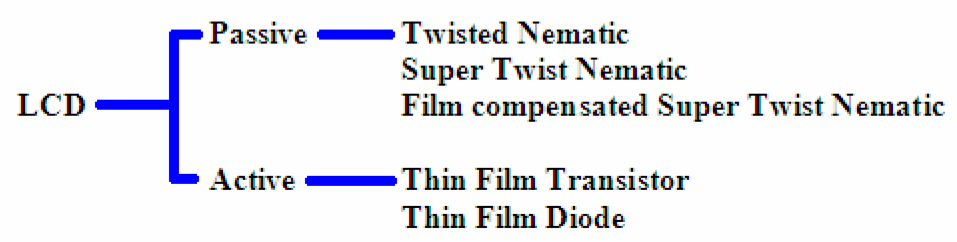


Figure 18: Transflective technology setup (6)

2.5 Liquid Crystal Display Types

LCDs are broken up into two main groups: passive displays and active displays. Passive and active refer to the circuits that are responsible for activating pixels.



2.5.1 Passive Matrix Displays

Passive LCDs use electrical components that do not supply their own energy to turn `on' or `off' desired pixels. A passive matrix LCD is made up of a set of multiplexed (a method of reducing the number of I/O lines needed) transparent electrodes. The electrodes are made of a conductive film, usually indium-tin oxide or ITO and are placed above and below the liquid crystal layer in a row/column formation (see diagram below). The rows and columns are then connected to integrated circuits, which control when and where charge is delivered. To address a pixel the column containing the pixel is sent a charge; the corresponding row is connected to ground. When sufficient voltage is placed across the pixel, the liquid crystal molecules align parallel to the electric field.

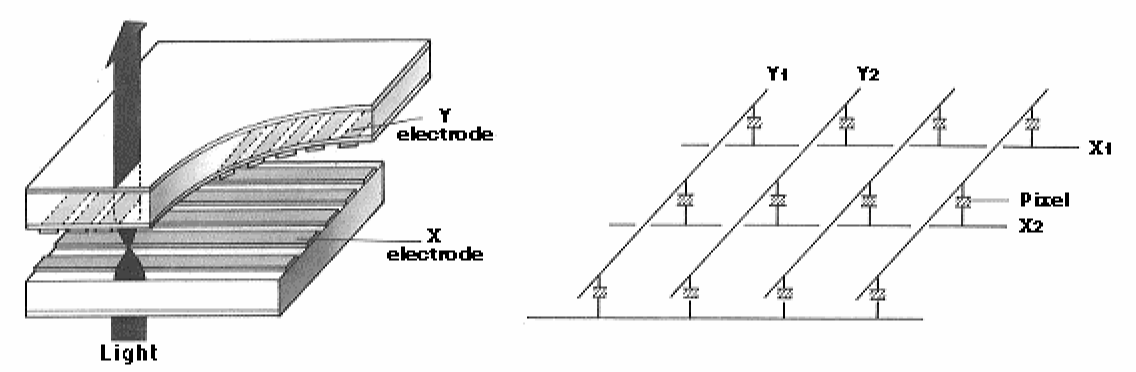


Figure 19: Structural and circuit level diagrams of a passive matrix. Above image was extracted with permission from the Sharp corporate website. (7)

Before passive matrix displays were introduced, LCDs primarily displayed information using segments. Segmented displays are driven by individual wire connections. Each segment had its own connection and can be turned on or off by applying a voltage. As screen sizes increased, so did the number of characters on them. Eventually it became no longer feasible or economical to have separate connections to each segment. It was at this time that passive matrix displays were introduced using a system of time-multiplexed lines.

Multiplexed passive screens were the solution to creating larger LCDs. In a ten by ten array of pixels one hundred separate connections would be needed to be able to address all of them. If the lines were multiplexed then only 20 connections would be needed (one for each row and column). In general the number of connections needed for non-multiplexed lines is MxN where 'M' and 'N' are the number of rows and columns in an array. When multiplexing is used, the number of connections is M+N. To activate pixels in a multiplexed array carefully timed voltage pulses are sent to corresponding rows and columns. Pulses are coordinated so that they reach the right pixel at the right time without activating unwanted pixels. Timing, duration and amplitude of pulses are controlled by driver circuitry external to the passive matrix.

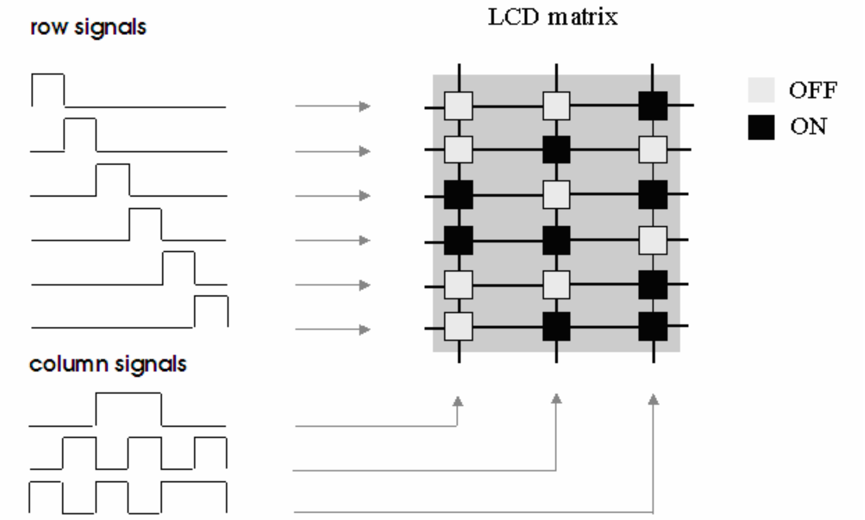


Figure 20: Example of a multiplexed array of pixels with sample voltage waveforms (8)

Passive matrix LCDs brought the advantage of simplistic low cost manufacturing and their improved design opened the way to creating larger screens; but there were some inherent problems that needed to be solved. In early development of multiplexed arrays it was discovered that as the number of multiplexed lines increased the contrast ratio decreased. This problem was investigated and later explained in a paper written by Alt and Pleshko in 1974. Alt and Pleshko found that the ratio of voltage at a selected point (for example a pixel) and an unselected point is a decreasing function of the number of rows being multiplexed. The relation is shown below:

$$\frac{V_S}{V_{NS}} = \left[\frac{\sqrt{N}+1}{\sqrt{N}-1}\right]^{\frac{1}{2}}$$

Where V_S is the voltage at a selected point, V_{NS} is the voltage at a non-selected point and N is the number of multiplexed lines (9). The phenomenon that causes this is called crosstalk. Crosstalk occurs when voltage applied to a desired pixel causes liquid crystal molecules in the adjacent pixels to partially untwist. Since the adjacent pixels are partially activated the amount of light passing through is reduced thus reducing the contrast between the desired pixel and the surrounding ones. The effect of crosstalk on a LCD depends upon the configuration of the liquid crystal cell used in its construction.

Passive matrix LCDs can be implemented using liquid crystal cells with different molecular structures. The most common cell types are twisted nematic, super twisted nematic, and film compensated super twisted nematic. Twisted Nematic (TN) was the first liquid crystal structure to be used in commercial products. TN displays are constructed with a ninety-degree twist from the molecules near the top plate to the molecules near the bottom plate. When no voltage is applied the liquid crystal molecules stay in a twisted structure and redirect light through the lower polarizer producing a bright dot on the screen; this is the 'off' state. When an electric field is applied the liquid crystal molecules untwist allowing light to be absorbed producing a black dot on the screen; this is the 'on' state. TN LCDs produce black characters on a grey background and were primarily used in segmented displays such as calculators, digital watches and clocks. TN displays were primarily limited to segmented setups since they were greatly affected by crosstalk. As mentioned before, crosstalk causes a reduction in contrast by allowing undesired pixels to receive voltage. The reason TN displays are vulnerable to cross talk can be seen by looking at the voltage/transmission curve below.

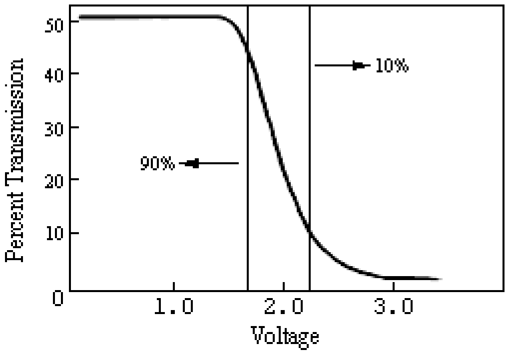


Figure 21: Voltage versus light transmission curve for TN liquid crystal cell. Above image was extracted with permission from the Sharp corporate website. (10)

Since the slope of the curve is gradual, voltage applied to undesirable pixels will cause the liquid crystal molecules to partially untwist, reducing the light transmission and be visible as a dark region.

Since crosstalk could not be removed in passive multiplexed arrays the only solution to the contrast problem was to increase the steepness of the voltage/transmission curve. By reducing the difference in voltage between the 'on' and 'off' states voltage induced from crosstalk would not be sufficient enough to activate pixels.

Research into this problem led scientist to a new type of liquid crystal structure super twisted nematic or STN. In 1983 with the help of computer modeling it was found that the steepness of the transmission curve could be greatly increased by increasing the twist angle of the liquid crystal structure greater than ninety degrees. To maintain the higher twist angle cholesteric liquid crystal molecules were added to the nematic structure. The cholesteric molecules imparted an intrinsic helical structure to the liquid crystal cell. With a steeper voltage/transmission curve much higher multiplexing and contrast ratios could be achieved than was possible with a TN structure. LCDs now had the capability to multiplex a large number of lines and still maintain reasonable contrast ratios. Although the problem of reduced contrast had been fixed, STN LCDs introduced a new problem not present in TN displays.

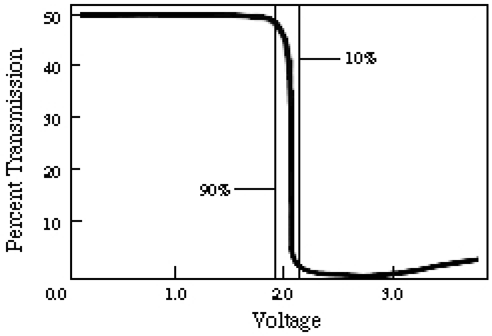


Figure 22: Voltage versus light transmission curve for STN liquid crystal cell. Above image was extracted with permission from the Sharp corporate website. (10)

As light passes through the super twisted structure it was noticed that a colour shift took place. This caused the characters to appear yellow on a blue background instead of black on a grey background. This presented a problem for producing black and white screens since black and white displays are not possible unless all wavelengths can pass through.

A proposed solution was to attach another STN cell on top of the first one. The second cell would effectively cancel the colour distortion produced by the first one by shifting the wavelength of the light back to its original state. This solution was however not efficient since the second cell reduced the brightness of the display and the added stn cell increased the unit size. A better solution to the problem was to add a polymer film retardation layer. The polymer layer would mimic the job of the second STN cell by correcting the wavelength-shifting problem, adding very little weight or material to the display unit, and caused next to zero additional losses in light. This new structure was named film compensated STN or FSTN. Improvements continued on passive LCDs, manufacturers always pushing for larger arrays, higher multiplex ratios and better contrast. Colour was added by the addition of colour filters to the pixels thus creating colour STN or CSTN displays.

To produce a colour display each pixel is subdivided into three pixels each containing a primary colour filter. Each sub pixel can be addressed allowing for any combination of colours to be made. Since each pixel has 256 different possible shades, a colour display can produce approximately 16.8 million colours (256 blue * 256 red * 256 green). Figure 23 below is an example of an LCD with colour filters added.

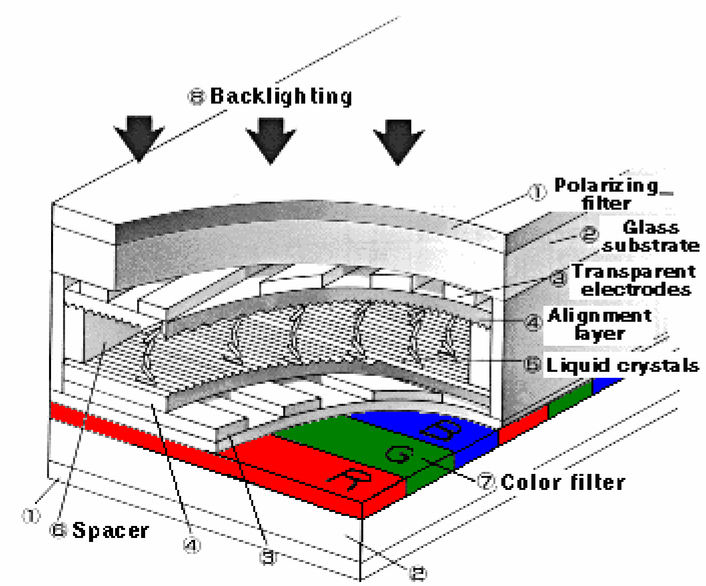
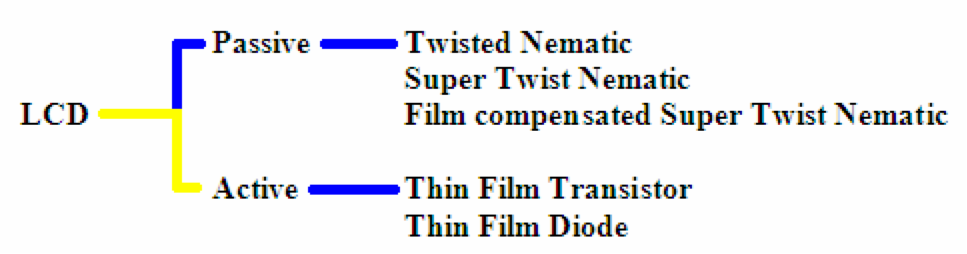


Figure 23: Diagram of LCD with colour filters added. Above image was extracted with permission from the Sharp corporate website. (7)

Overall comparing the different passives displays TN screens produce black on white characters, are low cost, consume little power are lightweight but are limited to small screen sizes. TN displays are suitable for calculators, simple electronic organizers, and any other numerical displays. STN display types produce yellow or green character on a blue screen, are thin, light weight, can handle a large capacity, consume little power, have a high contrast but colour displays are not possible. STN displays are suitable for mono colour word processors. Lastly, FSTN displays can produce black/white or full colour, are thin, light weight, can handle large capacity, have high contrast and can respond fast to changes. FSTN displays are suitable for word processors and low-end colour displays.

The inherent problems of passive implementations (crosstalk) prompted companies to move away from this technology in the search for technology suitable for high-end displays. Passive displays are still used in low power mobile devices but a new LCD technology emerged to capture the high-end market with the creation of the first active display.



2.5.2 Active Matrix Displays

Active liquid crystal displays have a similar construction to the passive implementation. Just like a passive display, active LCDs use a semi transparent conductive grid to supply charge to the liquid crystal layer. The important difference is that the active displays have a transistor built into each pixel. This thin film transistor (TFT) acts like a switch precisely controlling the voltage each pixel receives. As shown in the diagram below the basic structure of an active matrix LCD or a TFT display is a common electrode placed above the liquid crystal matrix. Below the liquid crystal is a conductive grid connected to each pixel through a TFT. Inside each pixel the structure is as follows, the gate of each TFT is connected to the row electrode, the drain to the column electrode, and the source to the liquid crystal. To activate the display voltage is applied to each row electrode line by line. To turn on a pixel the gate lines have to be activated; this closes the switch and allows charge from the drain to flow to the source setting up an electric field between the source and the common electrode above. The column electrodes connected to the drain carry the data voltages (which pixels to activate and to what shade) and are synchronized to the gate pulses. Connected to the source of each TFT in parallel with the liquid crystal is a small capacitor. When a pulse is sent to the gate, charge flows from the drain to the source where the capacitor charges to the desired level. The purpose of the capacitor is to keep voltage applied to the liquid crystal molecules until the next refresh cycle. Capacitors are sized large enough to keep a constant voltage on activate pixels, over the entire refresh cycle.

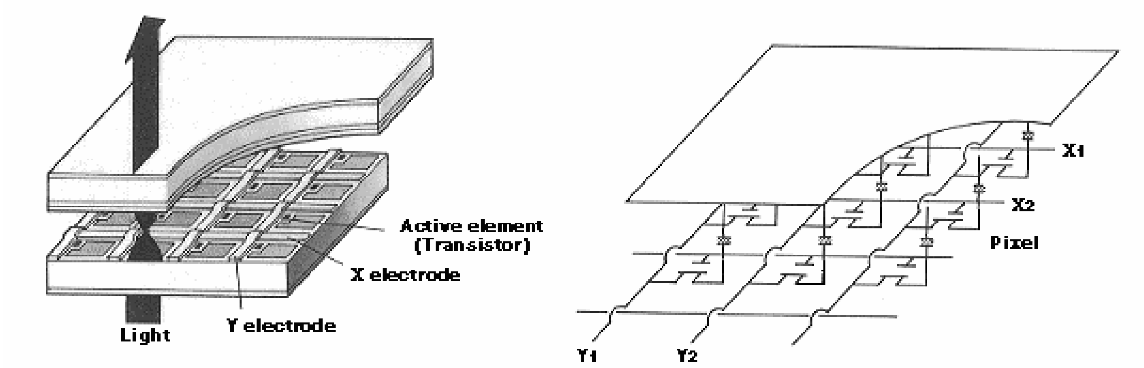


Figure 24: Structural and circuit level diagrams of an active matrix. Above image was extracted with permission from the Sharp corporate website. (7)

One of the major problems with the passive implementation was loss of contrast in bigger array sizes resulting from crosstalk. In the active matrix configuration nearly all effects of crosstalk are eliminated. When an image is to be drawn on the display, each row of pixels are activated one at a time, all other rows are turned off. Crosstalk is greatly reduced since the driving voltage is isolated from other rows in the display by the TFTs, which are turned off. The potential of this setup is almost equivalent to having individual and independent control of each liquid crystal element leading to good on/off contrast and good grey scale control. These features make TFT LCDs far superior to passive matrix designs and also make them ideal for larger screen applications such as laptop screens, computer monitors and TV's.

Since the reasons for developing STN and later technologies stemmed from problems associated with passive matrices when active displays were invented it was only natural to go back to TN implementations. Active displays have little to no crosstalk; therefore it was unnecessary to use a liquid crystal with a steep voltage transmission curve. Due to their ease of construction TN crystals were used for all active matrix displays, and are still used today.

There are several types of active matrix LCDs (AMLCD), distinguished by the active elements used. Two popular ones are TFTs built with either amorphous silicon or poly silicon and thin film diodes (TFD). As mentioned earlier TFT AMLCDs use transistors constructed inside each pixel to control the applied voltage. When TFTs were first introduced amorphous silicon (a-Si) was the dominant technology. A-Si TFT's are produced using low temperature processes using simple manufacturing methods and modest equipment costs. An example configuration for a TFT is shown below.

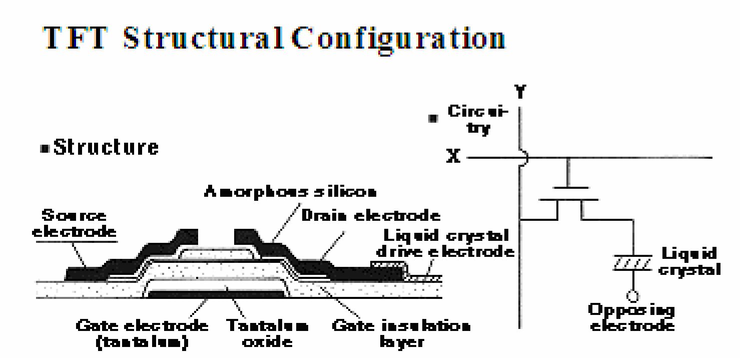


Figure 25: Example structure of an inverse staggered amorphous TFT. Above image was extracted with permission from the Sharp corporate website. (7)

The main disadvantage of a-Si TFTs is the low electron mobility. Electron mobility is a measure of how easily charge can move through a substance. Amorphous silicon has an electron mobility of 0.5cm^2/Vs meaning that it is difficult for charge to pass through at a high rate. This is a disadvantage because with a low electron mobility a-Si TFTs are unsuitable for high-speed processes. This prevents much of the display driver circuitry from being integrated into the displays glass substrate Less integration means more hardware and more external connections.

TFTs can also be produced using low temperature polycrystalline (LTPS) TFTs. LTPS has a much higher electron mobility then a-Si measured around 200 cm^2/Vs. With higher electron mobility it is possibly for the driver circuitry to be placed right onto the substrate itself leading to less connection, less components, higher integration and greater system durability.

Another type of active matrix LCD was conceived to retain fast refresh rates but address the issue of production cost. Thin film diodes (TFDs) work much like TFTs except a diode is placed at each pixel instead of a transistor. This design allowed for the quick and accurate response similar to TFTs, but is much easier and cheaper to fabricate then TFT screens. These traits make TFDs ideal for electronics that require small high quality screens but are not overly expensive. TFDs represent a compromise in performance and cost between passive and active designs; an example of a TFD structure is shown below.

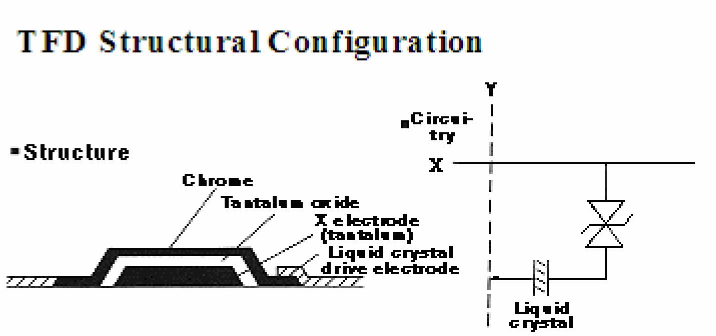


Figure 26: Example structure of a metal insulated metal TFD. Above image was extracted with permission from the Sharp corporate website. (7)

Overall TFTs have the highest performance; they are best suited for computer monitors, television screens and other high-end displays. TFTs also have the highest production cost and power requirements when compared to TFDs and passive screens. The best choice for a display type greatly depends on the application. For small screens where power consumption is an issue, FSTN or TFD screens might be the better choice. But when performance is more important than power a-Si or LTPS screens are better choices.

LCD technology had been in development for almost forty years, and will continue into the near future. Each day new ways are devised to improve the brightness, contrast, and overall picture quality of LCDs. New materials are under research in order to give TFT screens faster refresh times, and to lower power usage. LCDs are making progress, but must continue to improve if they are to remain competitive against other emerging display technology.

3.0 Alternative Displays

Display technology must evolve to keep pace with advances in other areas of technology. This evolution in display technology will produce displays that are faster, brighter, lighter, and more power-efficient. Technologies that have emerged to meet this challenge are OLEDs, DLP technology, Plasma, FEDs, and Electronic Paper.

3.1 Organic Light Emitting Diodes (OLEDs)

One of the next trends in display technology is Organic Light Emitting Diodes (OLEDs). Polymer Light Emitting Diodes (PLEDs), Small Molecule Light Emitting Diodes (SMOLEDS) and dendrimer technology are all variations of OLEDs. With all variations being made by electroluminescent substances (substances that emit light when excited by an electric current), OLED displays are brighter, offer more contrast, consume less power, and offer large viewing angles – all areas where LCDs fall short.

3.1.1 Fundamentals of OLEDs

OLEDs are composed of light-emitting organic material sandwiched between two conducting plates, one of n-type material and one of p-type material. The molecular structure in n-type material, although electrically neutral, has an extra electron that is relatively free to move around the material. In p-type material the opposite is true. The lack of an electron creates a hole that is free to move about. The creation of the extra electron or the hole comes about because of the mismatch of valence electrons in the molecular structure of the p or n-type material.

Applying a voltage between the two plates causes holes to be injected from the p-type substrate and electrons to be injected from the n-type substrate. When an electron fills in a hole, it drops from a higher energy level to a lower one; consequently, this difference in energy is released as a photon of light (light particle). The wavelength of the light generated is dependant on the energy gaps of the emitting material. In order to produce visible light, these energy gaps have to be within 1.5 to 3.5 **electron volts** (eV). For example, a photon of 3.1 eV has a wavelength of 400 nm which is visible as a violet light. Therefore, the colours emitted are dependant on the molecular composition of the organic emissive material chosen for the OLED. (12)

3.1.2 Structure and Types of OLEDs

OLEDs were first developed by Eastman Kodak in 1987. Their method of producing OLEDs was known as the Small Molecular method (explained below). Based on the Small Molecular method, PLEDs and dendrimers were later developed. While their structures remained approximately the same, the organic material was different.

3.1.2.1 Small Molecule OLEDs (SMOLEDs)

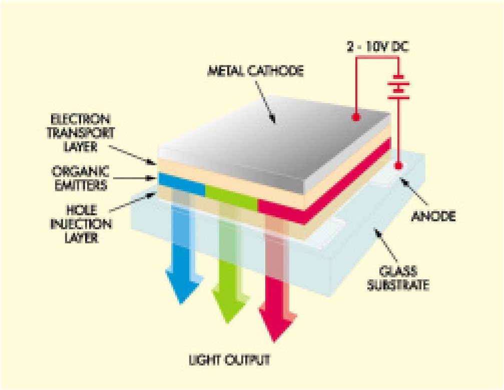


Figure 27: OLED structure (15)

The structure of a basic SMOLED contains multiple layers of organic material. Depending on the organic chemicals that are used to generate the display, different manufacturing techniques can be used. The p-type layer, known as the anode, is made from a high **work function** material such as indium tin oxide (ITO) – known for its conductive and transparent properties. The next layer is an organic material which aids in the transportation of holes known as normal-propyl bromide (NPB). Following this layer is one which aids in the transport of electrons; tris-8-hydroxyquinoline aluminium (alq$_3$) is generally used to form it. Lastly, the n-type layer, known as the cathode, is made from a low work-function material such as MgAg (magnesium silver) to produce the electrons. In order to improve efficiency, a luminescent layer is normally added in between the two layers of organic material, and is generally composed of a mixture of alq$_3$ and C540 (a carbon derivative). C540 is responsible for the added fluorescence. SMOLEDs require a complicated process of vacuum vapour deposition, where the deposition method involves sublimating the material in a vacuum. This process allows for a more accurate and better controlled application of these layers onto the display substrate; however, vapour vacuum deposition is also very complex, and as a result, this renders to higher manufacturing costs. Therefore, SMOLEDs are more suited for smaller displays such as cell phones, camera displays, etc. where they can produce excellent colour displays with a long lifetime. (13), (14)

3.1.2.2 Polymer LEDs (PLEDs)

PLEDs were developed approximately two years after SMOLEDs. It utilizes polymers made from chains of smaller organic molecules, an example being polyphenylene vinylene (PPV). PLEDs differ from SMOLEDs because the organic material is water soluble and consequently can be applied onto a substrate by common industrial processes such as spin-coating or ink-jet printing. In spin-coating, liquefied organic material is applied to a substrate which is then spun, at rates of 1200-1500 revolutions per minute, to uniformly spread the organic material and it may then be patterned as required. With ink-jet printing techniques, the substrates can be made more flexible while keeping the production costs low. This means that PLEDs can be used for larger displays such as monitors or television sets. However, the lifetimes of PLEDs are still not comparable to those of SMOLEDs as of this time. (14)

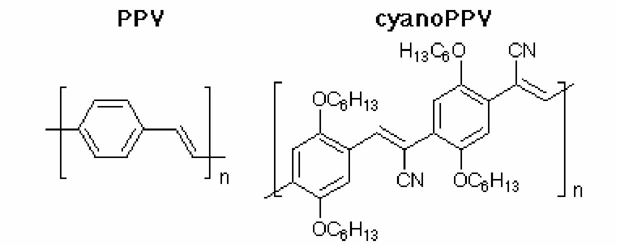


Figure 29: Structure of PLED polymers. Image courtesy of Cambridge Display Technology. (16)

3.1.2.3 Dendrimer OLEDs

Dendrimer technology is one that fuses the intense colour spectrum and lifetime of SMOLEDs with the easy production techniques of PLEDs. A dendrimer is a hyper-branched polymer. The structure of a dendrimer is comprised of a central core, and from this core are many branching polymers called dendrons. What allows dendrimers the ability to combine the benefits of both SMOLEDs and PLEDs is the fact that the central core can be tailored to determine the amounts of light emission, while surface groups located at the end of the dendrons can be modified so that the molecule can be soluble for ink-jet printing techniques. Therefore, dendrimer technology retains the control of Small Molecular technology, yet also maintains the required solubility of PLEDs. (17)

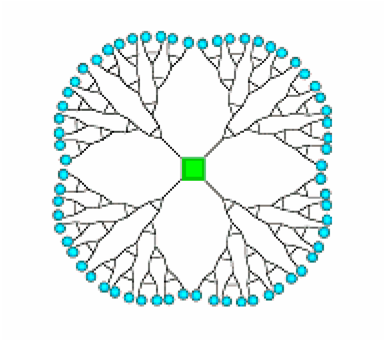


Figure 28: Structure of a dendrimer. Image courtesy of Cambridge Display Technology. (17)

3.1.3 OLED Display Methods

Aside from the different types of OLEDs, OLEDs can also be grouped into different display methods such as passive matrix and active matrix displays.

3.1.3.1 Passive Matrix Displays

In passive matrix displays, a pattern of p-type lines are etched on the glass substrate of the display forming the anode. A very thin layer of organic material is then applied on top of the anode. Cathode lines are created by the same method; however, they are made in a direction perpendicular to the anode lines. In order to function, external circuitry applies an appropriate voltage across one anode line, and all the cathode lines are activated in sequence. Then voltage is applied across the next anode line, and again, all the cathode lines are activated sequentially until all anode lines have been

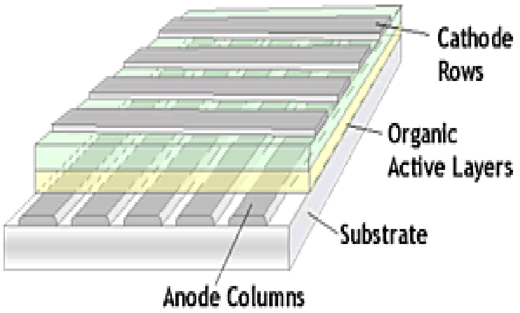


Figure 29: Passive matrix structure. Image courtesy of Cambridge Display Technology. (18)

addressed. Consequently, each row of pixels is only activated for a short time as the appropriate voltages, determined by the external circuitry, are applied and turned off when other areas of the display are being scanned. (21)

Though easy to design and manufacture, PMOLEDs require expensive current sources to operate and maintain brightness. When they are pulsed with high drive currents over a short period of time, PMOLEDs can not operate at peak efficiency due to resistive power losses in the diode structure of the p and n-type material and due to the charging effects of the address lines. Consequently, PMOLEDs are best utilized for smaller display structures such as cell phones, MP3 players, and portable games. (18), (20), (21)

3.1.3.2 Active Matrix Displays

Active matrix displays, instead of having current distributed row by row, use thin film transistors (TFTs) that act like switches to control the amount of current, hence brightness, of each pixel. Typically, two TFTs control the current flow to each pixel. One transistor is switched to charge a storage capacitor for each pixel and the other creates a constant current source from the capacitor to illuminate the pixel. Consequently, AMOLEDs operate for the entire frame scan and its operating current is only 1/nth of the PMOLED current for an n-row device which reduces the resistive losses in the structure. Therefore, AMOLEDs are suitable for larger displays such as monitors and television sets. (19), (20), (22)

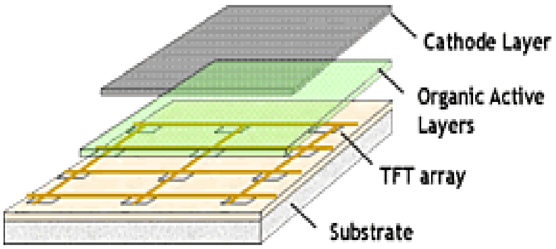


Figure 30: Active matrix structure . Image courtesy of Cambridge Display Technology. (19)

3.1.4 OLED Benefits

Because of the OLEDs' thin structure and excellent display qualities, it is ideal for use in flat-panel displays. OLEDs have many advantages compared to LCD technology – today's leader in this area. OLEDs are emissive displays (meaning they generate their own light), and as a result require no backlighting. Another significant advantage is OLED displays have extremely high switching speeds and as a result can handle high refresh rates required for full-motion video. OLEDs also have a large viewing angle as a result of its self-luminous effect. (23), (24)

Research in OLED technology is being conducted in over 80 companies and universities. Supporters of OLED development include Kodak-Sanyo, Pioneer, Sharp, Samsung, eMagin, CDT, Dow Chemical, Dupont, Three-Five Systems, Osram, Universal Display, and Phillips to name a few. OLED displays have already entered the market in the forms of digital cameras, cell phone screens, radio displays, and handheld games. Research is being done to develop highly flexible display panels on plastic substrates. This new line of displays can be "rolled up" much like real paper or form televisions that can be literally stuck to walls through the use of adhesives. In terms of disadvantages, degradation of the organic material will affect the lifespan of OLED displays. These materials can degrade through chemical processes such as oxidation and lose their light-emitting properties. As progress is made with OLED displays, this technology will undoubtedly match or surpass the current popularity of LCD displays due to its emissive direct view imaging, high switching speeds, low operating voltage, high quality imaging, and size. (23), (24)

3.2 Digital Light Processing (DLP)

DLP technology is a system that uses an optical semiconductor developed by Dr. Larry Hornbeck of Texas Instruments in 1987. This device, known as a Digital Micromirror Device (DMD chip), is essentially a very precise light switch that can digitally modulate light through the use of 2 million hinge-mounted microscopic mirrors arranged in a rectangular array; each of these micromirrors are less than 10 microns (approximately one-fifth the width of a human hair). Combined with a digital video or graphic signal, a light source, and a projection lens, the mirrors of the DMD chip can reflect an all-digital image onto any surface. (25), (26)

Figure 31: DMD chip. Image courtesy of Texas Instruments Inc. (25)

3.2.1 DLP Structure

By mounting these micromirrors on tiny hinges, they are able to tilt either toward the light source where they are noted as being "on" or away from the light source where they are noted as being "off". Consequently, depending on the state of these mirrors, a light or a dark pixel is projected onto the screen. The mirrors are instructed to switch on or off several thousand times per second by a digital signal entering the semiconductor. A lighter shade of grey is produced when a mirror is switched on more frequently than off; whereby a darker shade of grey is produced when a mirror is switched off more frequently than on. Using this method, DMD chips can generate up to 1024 shades of grey and consequently produce a highly detailed greyscale image. (26)

3.2.2 DLP in Colour

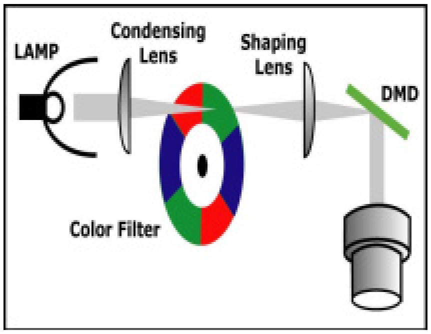


Figure 32: DLP colour display process. Image courtesy of Texas Instruments Inc. (26)

In most DLP systems, a colour wheel is placed between the light source and the mirrored panel. As the colour wheel spins, it causes the white light generated by the light source to filter into red, green, and blue light to fall on the DMD mirrors. When the on/off states of each mirror are coordinated with the flashes of coloured light, the DLP system can generate approximately 16 million colours. For example, a purple pixel is created by switching on the mirror only when red or blue light is falling on it. Our eyes then combine these primary colours to see the intended purple. (26)

3.2.3 DLP Uses

Projectors, TVs, and home theatre systems are currently based on DLP systems that use a single DMD chip. Larger venues like cinemas tend to use DLP systems that use three DMD chips. The difference being the white light generated by the light source is passed first through a prism and is then filtered into red, green, and blue. Each DMD chip is then dedicated to each primary colour and the reflected light is then combined and passed through the projector lens to a screen. The result is a system that can produce up to 35 trillion colours for the ultimate movie experience. (26)

As mentioned previously, DLPs are currently limited to projection technology and have not been developed for smaller screen displays such as monitors and cell phones.

3.3 Plasma Display Panels (PDPs)

Plasma displays are noted for their flat screen presentation and large screen sizes. They are able to generate excellent image quality in large scales, and consequently are the leading display technology when it comes to HDTV (high definition television).

3.3.1 PDP Structure

Plasma screens are composed of millions of cells sandwiched between two panels of glass. Placed between the glass plates extending across the entire screen, are long electrodes known as address electrodes and display electrodes which form a grid. The address electrodes are printed onto the rear glass plate. The transparent display electrodes, insulated by a dielectric material and covered by a protective magnesium oxide layer, are located above the cells along the front glass plate. The electrodes intersecting a specific cell are charged in order to excite a xenon and neon gas mixture contained within each cell. When the gas mixture is excited creating a plasma, it releases ultraviolet light which then excites the **phosphor** electrons located on the sides of the cells. When those electrons revert back to their original lower energy state, visible light is emitted. Each PDP pixel is

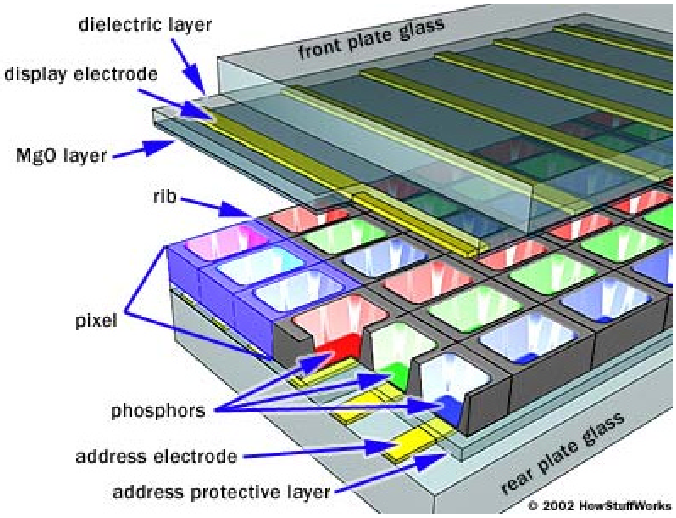


Figure 33: Plasma display structure (27)

composed of three cells containing red, green, and blue phosphors respectively. The phosphors are separated by ribs which prevent the phosphors from chemically contaminating each other (crosstalk). Activating these colour combinations at varying intensities, by the amount of current generated, results in the colour generation as seen on the display. (27),(28),(29)

3.3.2 PDP Advantages & Disadvantages

Due to phosphorescence, every single pixel generates its own light and as a result viewing angles are large, approximately 160$^{?}$, and image quality is superior. Another advantage is the image quality is not affected as the display area becomes larger; plasma displays can be built in dimensions nearing 2 m. Unlike CRTs, plasma displays are able to provide image quality and display size without the disadvantage of being bulky and blurry around the edges; PDPs can generally be built with a depth of 15-20 cm and as a result can be mounted or used in space limited areas. Due to the fragile nature of plasma screens (it utilizes glass panels as a substrate), professional installation is required. Another disadvantage is that PDPs are susceptible to burn-in from static images and as a result they are not suitable for billboard-type displays, or channels that broadcast the same image constantly, i.e. news station logos. Increased power consumption is also a problem because ionizing the plasma requires a substantial amount of power; consequently, a 38-inch colour plasma display can consume up to 700 W (power levels generally used by appliances such as vacuum cleaners) where the same sized CRT would only require 70 W. Lastly, unless the prices of these displays are reduced, many other high quality display technologies can replace plasma displays and hence render it useless in the future. (25),(30),(31),(32)

3.4 Field Emission Displays (FEDs)

Field emission displays (FEDs) function much like CRT technology. Instead of using one electron gun to emit electrons at the screen, FEDs use millions of smaller ones. The result is a display that can be as thin as an LCD, reproduce CRT-quality images, and be as large as a plasma display. Initial attempts in making emissive, flat-panel displays using metal tipped cathodes occurred nearly 20 years ago, however, with reliability, longevity, and manufacturing issues, these types of FEDs do not seem commercially viable.

3.4.1 Field Emission Fundamentals

The foundation of Field Emission technology is the extraction of electrons from a material using the "tunnelling" effect. Tunnelling describes the phenomenon of electrons being able to behave likes waves as well as like particles. Within a conductor, free electrons are generally mobile within a certain degree. What prevents these electrons from simply escaping the bounds of conductors is a potential energy barrier. In order to surpass this potential energy barrier, electrons must be provided with enough energy. However, with the tunnelling effect, if a high enough electric field is applied outside the conductor, the strength of the potential energy barrier will be reduced, and consequently it will get to the point where an electron wave can extend itself across the barrier. (32),(33)

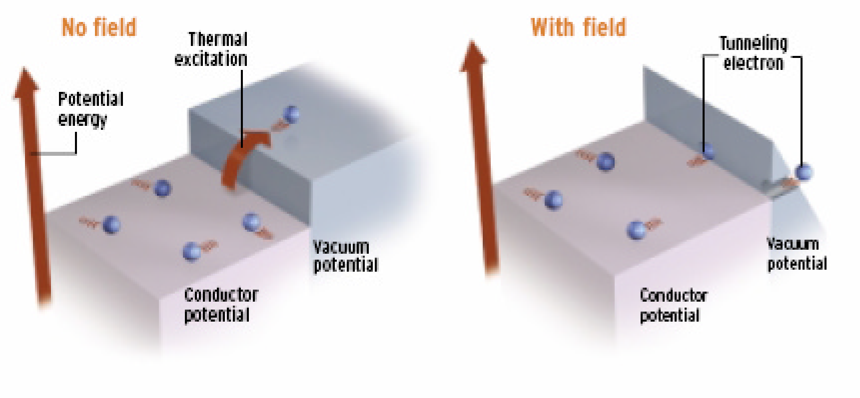


Figure 34: The tunnelling effect (32)

The emitted current, or moving electrons, depends on the electric field strength, the emitting surface, and the work function. In order for field emission to function, the electric field has to be extremely high: up to 3 x 10^7 V/cm. This value, though large, is accessible by the fact that field amplification increases with a decreasing curvature radius indicating that the pointier the object, the more charge it will have at its tip, and hence the larger the electric field. As a result, if such a material can be found, a moderate voltage will cause the tunnelling effect, and hence allow electrons to escape into free space without the heating of the cathode like the traditional Cathode Ray Tube (CRT) technology.

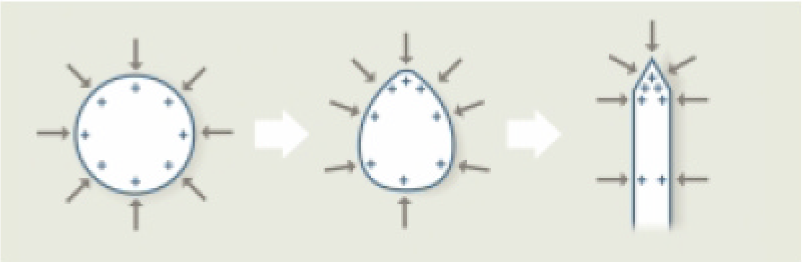


Figure 35: Demonstration of electric field concentration around a pointy object (32)

3.4.2 Traditional FED Structure

The basic structure of the first FED was comprised of millions of vacuum tubes, called microtips. Each tube was red, green, or blue and together, formed one pixel. These microtips were sharp cathode points made from molybdenum from which electrons, under a voltage difference, would be emitted towards a positively charged anode where red, blue, and green phosphors were struck, and as a result emit light through the glass display. Unlike CRTs, colour was displayed sequentially, meaning the display processed all the green information first, then refreshed the screen with red information, and finally blue. (34), (35) The advantages of the traditional FED included the fact that they only produced light when the pixels were "on", and as a result power consumption was dependent on the display content. A FED also generated light from the front of the pixel, providing an excellent viewing angle of 160 degrees both vertically and horizontally. These FEDs also had a high product yield as thousands of electron emitters were in place for each pixel; they suffered no brightness loss even if 20% of the emitters failed. Though this technology seemingly could have been a huge contender in the flat panel business, it was plagued with many problems due to the extreme electrical environment of the display. One problem being the metal molybdenum, used to make the microtips, would become so heated that local melting would result and consequently deform its sharp tips needed to form the electric field used for electron emission. Another problem caused by the electrical environment was the hot cathodes would react with the residual gases in the vacuum consequently reducing the field emission even more. (32),(34),(35)

3.4.3 Carbon Nanotubes

FEDs are making a resurgence in the flat panel industry utilizing carbon nanotubes (CNTs) which bypass all of the problems experienced by the preceding FED technology. Carbon nanotubes were first discovered in 1991 by Sumio Ijima in the NEC Research Laboratories of Japan. A carbon nanotube is a very small piece of graphite (a derivative of carbon) rolled up into a very small tube. It is not a metal but a very strong structure built entirely out of **covalent bonds** with field emitting properties. Made by reducing a sheet of graphite so that it becomes a narrow strip approaching 30 nm, the strip curls up and forms a tube with a diameter of 10 nm – this singular tube is known as a single-walled nanotube (SWNT). Multiple walled nanotubes (MWNT) are several SWNTs nested inside one another where each carbon atom is bound to three other carbon atoms. The exact arrangement of carbon atoms, and whether the tubes are open-ended or closed, can determine whether these CNTs are semiconducting or conducting. CNTs are chemically stable therefore they only react under extreme conditions such as extremely high temperatures (2500°C) with oxygen or hydrogen; consequently, the problems of reacting with resident gases, overheating, or tip deformation are solved with CNTs. (32),(37)

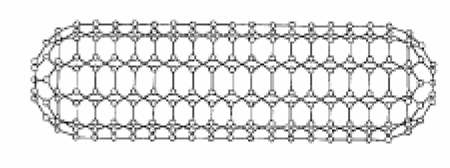


Figure 36: A carbon nanotube structure. (36)

3.4.3.1 CNT-FED TV (Carbon Nanotube Field Emission Television)

Much like its molybdenum-made FED predecessor, one pixel is composed of 3 subpixels where the combination of these subpixels allows for the intense colour manipulation found in CRTs. Each microtip is now replaced with many carbon nanotube-based emitters which act as cathodes that produce electrons via field emission. The electric field required for field emission is generated by a gate electrode contained within every subpixel. Attracted to the positively charged anode placed in between the display glass and the phosphor layer, emitted electrons are swept through a vacuum towards their respective phosphors (red, green, or blue) where light is emitted when the phosphors are struck. This technology is very similar to that of CRTs; however, with the absence of a huge electron gun, CNT-FEDs can be made to be only a fraction of the width. An image can be formed by selectively addressing different positions of the grid in which all of these pixels are built upon – much like the grid in LCD technology. Figures 37, 38 illustrate the structure of one subpixel and the location of one full pixel on the display (respectively). (32),(37)

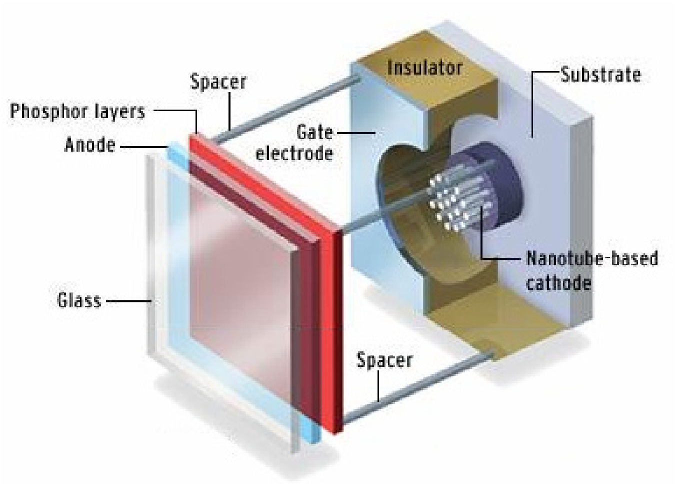


Figure 37: Structure of one subpixel containing carbon nanotubes (32)

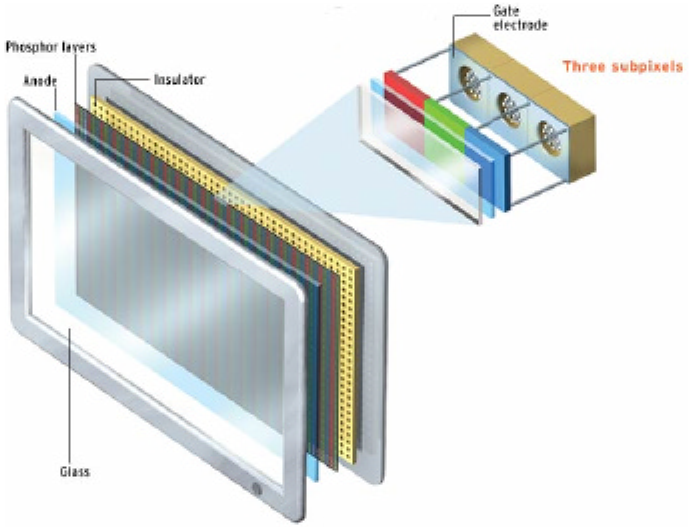


Figure 38: A pixel of a CNT-FED display (32)

3.4.3.2 Carbon Nanotube Advances

For 20 years, researchers have tried to make the traditional FED technology commercially viable, but with the difficulties of microtip deformation, overheating, and unwanted chemical reactions, this technology had too many problems to overcome. However, carbon nanotubes seem to be the key that is needed for FEDs to become successful. FEDs are able to combine the high quality images and large viewing angles of CRTs while delivering it in the flatness attributed to LCDs, and utilizing just a fraction of the power required by PDPs. As a result, companies such as Motorola, Samsung, and Sony (amongst others) are actively researching FEDs with the use of nanotubes. Samsung has already produced a full colour, 38-inch prototype capable of handling video and more advances are soon to follow. (32),(38)

3.5 Electronic Ink Displays

Electronic ink displays, or Electronic Paper, are active matrix displays utilizing "electronic ink". Rumoured to be the next technology that will replace paper, electronic ink displays use a pigment that resembles the ink used in print; consequently, contents of the display can be viewed in full daylight. Anywhere print can be viewed, electronic ink displays can also be viewed. E Ink, a maker of electronic ink displays utilizing their patented electronic ink formula, claim that their displays need only 1/1000th the power a similar LCD display would need; the reason being the display can preserve its contents even when switched off and does not need a backlight. (39),(40)

3.5.1 Electronic Ink Composition

Electronic ink is composed of millions of microcapsules, each about 10 μm. Each microcapsule contains positively charged white and negatively charged black particles suspended in a clear liquid. The black particles are similar to toner particles found in laser printers and photocopiers. The white particles are made of titanium dioxide. Together, these particles once enclosed in a clear liquid are capable of producing the resolution only found in print. A user will see a white spot on the surface when a negative electric field is applied; the white particles move to the top of the microcapsule and the black particles move to the bottom where they remain hidden. The reverse is also true – when a positive electric field is applied, the black particles appear at the top and as a result the user sees a dark spot at the surface. (39)

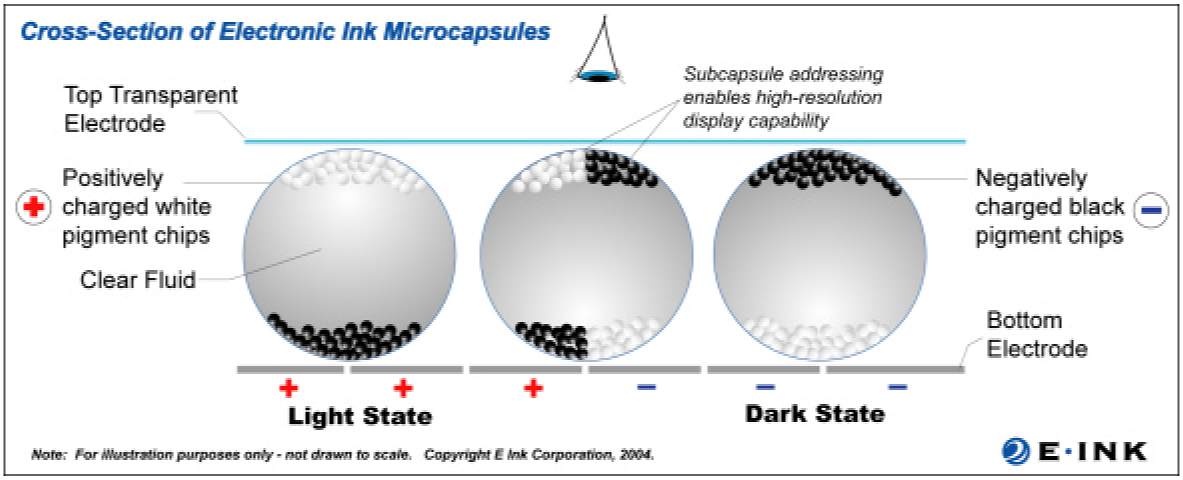


Figure 39: Structure of Electronic Ink particles. Image courtesy of E Ink Corporation. (39)

3.5.2 Electronic Ink Displays

To form an electronic ink display, or electronic paper, the ink is printed onto a sheet of plastic film which functions as the front viewing plane (FPL) of the display. These sheets are then laminated onto their active matrix backplanes forming a display. Driver integrated circuits and controllers are then added to the display module to control the pattern of the pixels. (41)

3.5.3 Electronic Ink Uses

The microcapsules forming the pixels are suspended in a fluid "carrier medium" enabling them to be printed using existing screen printing processes. These processes can be printed on any surface including plastic, fabric, glass, and paper which enables any surface capable of becoming an electronic display. Researchers plan to have electronic paper resemble newspapers or magazines that can be updated daily via wireless connections. Other applications include smart cards that can inform the user of their credit balance, computer clothing that can be worn, electronic devices such as clocks and watches, and electronic signs to list a few.

Figure 40: Citizen launches revolutionary curved clock utilizing E Ink's electronic paper display. Image courtesy of E Ink Corporation. (42)

4.0 Display Technology Comparison Chart

The table below is a snapshot of the characteristics of some display technologies. The data was derived from products readily available in the market.

Technology	LCD Monitor	LCD TV	OLED[1]	DLP	PDP	Electronic Paper[2]
Cost (USD)	200-1000	800-6000	n/a	1500-7000	2500-25000	500
Power Consumption (W)	28 - 75	60 - 300	400 mW	100–200	300-660	0 – 1.5
Resolution (pixels)	1024x768-1600x1200	640x480-1920x1080	521x218 (dots)	1280x720 – 1920x1080	852x480-1366x768	800x600, 170 pixels per inch
Colours	16.2-16.7 million	16.7million-3.2 billion	16 million	16.7 million	16.7 million – 3.62 billion	greyscale
Brightness (cd/m^2)	250-300	350-500	120	400-800	700-1000	no data
Contrast	350:1-800:1	350:1-3000:1	100:1	1000:1 - 2500:1	1000:1-4000:1	10:1
Display Area	15"-21.3"	15"-65"	2.2"	30"–70"	32"-65"	6"
Response Time	4-25ms	8-30ms	5 µs	no data	11–13 ms (75-85 Hz)	300 ms (1 sec address time)
Viewing Angle	140/120-178/178	160/140-170/170	170	160	160	>70 degrees all directions
Dot Pitch (mm)	.264-.297	.24-.75	0.172	0.4	1.02-1.55	0.164
Lifespan (hrs)	45,000-60,000	50,000-60,000	2000 (avg. for most cameras)	30,000-80,000	20,000-60,000	10000 pages for 4 AAA batteries

[1] Value based on Kodak's NUVUE display found in its EasyShare LS633 Zoom Camera – world's first camera with an active OLED display

[2] Based on the Sony Librie – world's first e-book reader using electronic paper technology

*FEDs were not included due to the lack of available information on commercial products

5.0 Conclusion

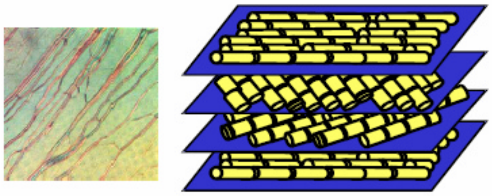
Today's display market offers an abundance of choices, each with their own advantages and disadvantages. The choice of technology greatly depends on the intended application, whether it is home entertainment, portable electronics, or industrial. Where CRTs had initially monopolized the display industry, they are now being replaced by newer technologies. Currently, LCDs using passive or active matrices have captured portable devices and are expanding into larger screen applications such as computer monitors and televisions.

Alternate displays such as OLEDs will compete with and have the potential to replace LCDs. Proposed OLEDs designs are thinner, more power efficient, and produce higher quality images. In other display applications, technology such as DLPs, PDPs, FEDs, and Electronic Paper are also competing for market share.

Display technology is the most effective way to communicate information. As researchers continuously create innovative ideas, display technologies are becoming more sophisticated. Next generation displays will be lighter, thinner, flexible, more adaptable, power efficient, and conform to the changing needs of society.

6.0 Glossary

Cholestric: (Also called chiral nematic) are liquid crystals whose structure is composed of a stack of nematic layers with each layer rotated at an angle to the previous layer (11).

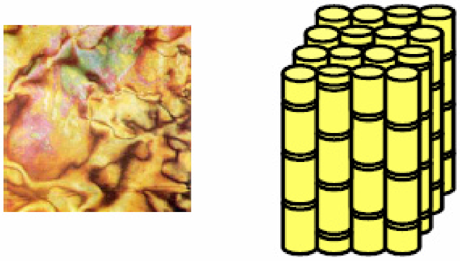


Cholesteric

Covalent Bond: A chemical bond formed when two atoms share some of their valence electrons, electrons in the outer shell of an atom.

Electron Volt: 1 eV is the kinetic energy gained by an electron when it is accelerated by a potential difference of 1 volt.

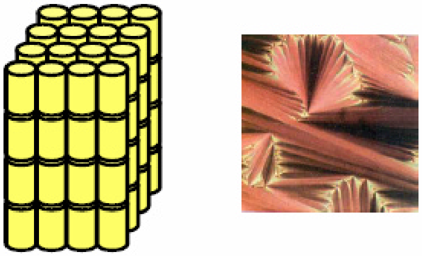
Nematic: From the Greek word 'nemato' meaning thread, nematics are thread or rod like molecules, which tend to organize themselves in a parallel fashion (11).



Nematic

Phosphor: A substance that emits light when stimulated by another substance (i.e. light photons)

Smectic: Much like the nematic phase, smectic molecules have orientational order but in addition, possess positional order leading to the formation of layers (11).



Smectic

Work function: The minimum amount of energy required to remove an electron from the surface of a metal.

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