

Flat Panel Displays for Portable Systems

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Received ; Revised

Abstract. Flat panel display technologies for portable and personal information systems are reviewed. The display sub-system performance requirements, and the metrics for evaluating display technologies for portable systems are discussed. The current display technology choices for high performance portable systems are active matrix liquid crystal display (AMLCD) and field emitter display (FED). AMLCD is at the forefront at an advanced state of development, and it is already in mass production for notebook computer applications. Because of the huge market size, AMLCD technology continues to be developed at an aggressive pace to address the needs of the future portable systems. On the other hand, FED technology is not currently in mass production, but it is being developed at rapid pace; Impressive technology capabilities and demonstration displays have already been shown. This review focuses on the current status and future development trends in both the these display technologies for application to portable systems. The current status of the reflective LCDs and their future development trends are also reviewed.

1. Introduction

The pervasive nature of computing and communication is bringing about a paradigm shift in the direction of merging these to provide mobile or nomadic information systems. The vision of mobile computing systems is to provide anytime, anywhere access to information [1]. The ultimate goal is to provide a system capable of moving information to and from people at all locations through an advanced computer/communication network including high-speed wireless links between sources of information and users of information [2]. A consequence of the mobile computing paradigm is the increased importance of information systems with reduced power consumption. Central to the success of any portable system is battery lifetime or time between charges. This new paradigm is manifesting itself as users travel to different locations with laptops, personal digital assistants (PDAs), cellular telephones, pagers, cordless telephones, etc. [3]. The advent of battery-powered portable information systems with

significant computational and communication capability is driving the development of low-power technologies. The growth of the market for battery-powered portables is the current dominant trend in information technology. This in turn has led to increased effort to develop portable systems that are lighter and smaller, have enhanced performance, increased functionality and longer battery life [1–3].

The term portable information system covers a broad range of computer/communication systems. It includes palm-top, notepad, notebok, laptop and sub-notebook computers and personal digital assistants (PDAs) that utilize direct view displays. Some portable systems may utilize head mounted displays (HMD) and body mounted displays, using small very high resolution image sources (displays). In this review, the main focus is on larger area, direct view displays. The most common of the portable computer systems is the letter size, A4 format notebok computer. Today's typical notebok computer includes a microprocessor, a hard drive or PCMCIA, a floppy disk drive, memory, power supply,

graphics controller, and a display. Essentially all of the current notebook computer displays are based on passive-matrix or active-matrix liquid crystal display (LCD) technologies. The typical display is 10.4" dia. in size, with a VGA (640×480) resolution, and operates in a monochrome or full color mode with a brightness of 20 fL. Because the display is the most important human-machine interface, it is a critical sub-system of the portable system. It is the primary visual source for transmitting text, graphics, images and video data to humans. Commensurate to its importance, it presently represents about 30% of the cost of most portable systems and about 50% of the power dissipation. The availability of affordable flat panel displays stimulated the development of portable computer and communication systems.

One of the anticipated devices or appliances is the wireless multi-media terminal. The proliferation of applications such as the World Wide Web (WWW) and the Internet Multi-media Backbone (the MBone) has resulted in vast amounts of image and video data on the Internet. This is because of the recent advances in several technological areas that are leading to large scale databases of visual and multi-media information. Such databases are finding ready application in a wide range of fields such as advertising and marketing, education and training, entertainment, medicine and remote sensing. All these require increasingly sophisticated viewing and authoring tools that are mobile.

The InfoPad developed at the University of California by Chandrakasan et al., [2] is an example of the future multi-media terminal that will be required for the mobile or nomadic information systems described above. The InfoPad is a portable multi-media terminal that is intended for untethered access to fixed multi-media information servers on the Web. It is designed to transmit audio and pen input data from user to the network which contains the database and the necessary computation power through a wireless uplink. The InfoPad also receives audio, graphics and compressed video from the network on a downlink. The rich data type and the requirement for full motion color video will increase the performance requirements of the displays. It is expected that SXGA (1280×1024) resolution will be required for future multi-media terminals. Furthermore, the brightness requirement is expected to increase in order to accommodate a variety of ambient lighting conditions.

The key consideration for future information systems remains the battery life, portability and the display

technology. The display is particularly important because it is the most important human/machine interface, and it continues to be a major power consumer in the portable system.

2. Display Requirements for Portable Systems

The display sub-system requirements of portable information systems are largely driven by (i) application, (ii) the data types and (iii) the environment. This is illustrated using the following examples:

A personal digital assistant (PDA) does not necessarily require a high information content, high brightness or a full motion video color display. However, such a portable system requires a low power display. Depending on the intended use of the PDA, it may require only a 1/2 VGA display that relies on ambient light that a reflective monochrome display can provide. If the PDA on the other hand is intended for accessing still photo images or full motion video sporting action clips (such as a football game), a higher performance display sub-system will be required. Another example is the use of body-worn personal electronic systems for aircraft or tank maintenance. Such a system will require a full color display with high information content and dimmable brightness that adjusts to the background illuminance of the environment. For this application, full motion video capabilities will not be necessary; however, high resolution and high pixel matrix are essential. These requirements should be contrasted to those of personal information systems that are designed to view battle field situations at a remote location either sent by a laser range finder or an unmanned aerial vehicle (UAV). This system should be capable of showing live video of battle scenes to a soldier, remote intelligence officer or a battle field commander. Such a portable system for battlefield use will require high information content, full color displays capable of showing images and full motion video and operating in almost all ambient lighting conditions. Another example is the display for distance learning information systems in which remote students can participate in classroom discussions. In such a system, high information content and full color are essential, and the display system should be bright, consume very low power and be capable of full motion video.

Central to all the examples given above is the issue of battery life. Power consumption is a major consideration for all portable system displays. It is expected that the multi-media terminal will have the most demanding

display requirements because of the rich data sets that includes, text, graphics and full motion color video. The generic requirements of a display-subsystem for future portable information systems include:

- Full Color (8 bits/color)
- High Resolution (e.g., 160 dots/inch)
- High Pixel Matrix (1280 × 1024)
- Adequate Brightness (15–100 fL)
- Full Motion Video (80 fps)
- Wide Viewing Angle ($>\pm 45^\circ$ in horizontal and vertical directions)
- High Contrast Ratio ($>100:1$)
- Light Weight
- Small Volume (small depth)
- Low power consumption/high luminous efficiency
- Low cost

There is no electronic display that meets the above requirements at the present time. Most portable notebook computers currently use the LCD because it is the closest to meeting the requirements listed above. However, much work needs to be done in order to bridge the gap between the requirements for today's notebook computers and tomorrow's multi-media terminals. A major consideration in the design of the display subsystem of today's notebook computer is the power consumed by the display subsystem. Table 1 compares the power requirements of today's (1995) notebook computer using a 10.4" dia. VGA display, with those of tomorrow's (1999) multi-media terminal, using a 13.3" dia. SXGA display. From the table we observe that the display sub-system consumes about 50% of the total energy today. Hence it is very important to develop technologies that reduce the power consumed by the display sub-system as means for reducing the power consumed by the multi-media terminal to extend its

Table 1. Power budget for a 1995 notebook computer and 1999 multi-media terminal.

Sub-system	Note book computers 1995	Multi-media terminal 1999
Display	4 W (10.4" dia. VGA)	2.5 W (13.3" dia. SXGA)
Logic/memory	2 W	1.0 W
Communications	0.5 W	0.25 W
Storage	1 W	0.5 W
DC Power Supply	0.5 W	0.25 W
Total	8 W	4.5 W

battery lifetime. As the table shows the current development efforts are targeted at reducing the display system power consumption substantially, while at the same time improving its size, resolution, brightness and image quality.

3. Review of Flat Panel Display Technologies

While the dominant display technology continues to be the CRT, its many deficiencies make it unsuitable for portable applications. To overcome the limitations of the CRT, various flat panel display technologies have been developed over the years for application to portable systems, as well as other systems where the deficiencies of the CRT are an issue. These technologies include:

- Liquid Crystal Display (LCD)
- Electroluminescent Display (ELD)
- Vacuum Fluorescent Display (VFD)
- Plasma Display Panels (PDP)

Development of these technologies spans over many years. They are relatively mature and currently in production for specific applications. Further, these technologies continue to be improved due to continuing development efforts. The LCD has been the most successful display technology for portable systems because it met the critical requirement for portability, low power, and ability to generate full color. Currently, LCD represents over 90% of the flat panel display market. Furthermore, it has also been able to give the highest luminous efficiency of all the display technologies that meet the portability requirements, leading to the longest battery lifetime for the portable system.

In the present notebook computers, the largest single drain on battery continues to be the flat-panel display sub-system. Most of the flat panel display systems described above are rather inefficient at converting electrical power to optical (visible) radiation. Typical conversion factors are of the order of 1 lumen/watt or less. The inefficiency is common to both emissive displays (ELD, VFD, PD) and the backlit light valve displays (transmissive LCD). The observed conversion efficiency should be contrasted with what is possible in some physical processes. For example, photoluminescence which occurs in a fluorescent lamp has a luminous efficiency (conversion efficiency) of 50 lumen/watt, while cathodoluminescence which occurs in a CRT has an intrinsic luminous efficiency of 25

lumen/watt. More striking is the fact that green light at 550 nm with a 100% electrical-to-optical conversion will have a luminous efficiency of 680 lumen/watt [4].

Below we describe the operating principles of each of the flat panel display technologies and give a short summary of their status and limitations. In the next section we propose metrics for evaluating the display technologies which explains why the LCD is the dominant display technology today.

3.1. Liquid Crystal Displays

Liquid crystals are typically organic chemicals that exhibit a meso-phase with anisotropic physical properties. These anisotropic properties include viscosity, dielectric permittivity, magnetic susceptibility and refractive index. Two important properties critical to the electro-optic effect exhibited by the liquid crystals are (i) optical anisotropy or birefringence meaning that the index of refraction is different when measured parallel and perpendicular to the optical axis, and (ii) dielectric anisotropy, which allows the LC molecule to be aligned with the electric field.

The liquid crystal display (LCD) is essentially a spatially addressable light valve that utilizes polarized light. The light valve is a “sandwich” composed of two sheets of glass with patterned transparent conductors (ITO) and a liquid crystal between them. Polarized light from an external source is sent through the light valve. The transmitted light intensity depends on the voltage applied across the liquid crystal. The LCD can be constructed to function in a transmissive mode using an external backlight, or in a reflective mode using a reflector behind the back polarizer [5]. In most instances, the reflective mode works with ambient light. Further, LCDs can be categorized in to two major types—passive matrix (PMLCD) and active matrix (AMLCD). Currently, AMLCD and super twisted nematic type passive matrix LCD (STN LCD) are most developed and widely used. We will discuss the LCD technology in greater detail in Section 5.

3.2. Electroluminescent Displays

Unlike the LCD which is a light valve, the electroluminescent display (ELD) is an emissive display. Figure 1 shows the basic structure of an ELD. It creates light by the excitation of a powder phosphor or a thin-film phosphor layer. There are four types of ELDs, based on the phosphor type and the excitation method used.

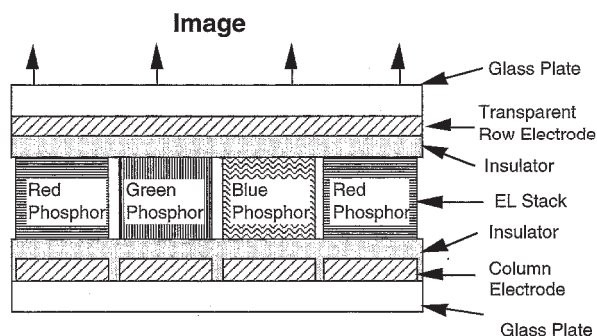


Figure 1. Device structure of the electroluminescent display (ELD).

These are: (i) dc powder ELD, (ii) ac powder ELD, (iii) dc thin-film ELD, and (iv) ac thin-film ELDs. For color displays, the red, green, and blue phosphor layers are patterned into pixel format and are encapsulated by two electrodes on either side. Parallel conductors form electrodes across the phosphor. They are fabricated in a row and column format on opposite sides of the phosphor as in the LCD [4, 6].

The ac thin-film ELD is the most viable of the four technologies. It consists of three layer sandwich structure—two insulating layers on either side of a thin-film phosphor. The row and column electrodes with the top layer being transparent are on either side of the sandwich. The basic EL device structure is purely capacitive as no current passes through the phosphor from the exciting circuit. The central thin-film phosphor layer emits light when a large enough electric field is applied across it. The required field is of the order of 1.5×10^6 V/cm. The high electric field means that the phosphor can be easily destroyed by any local imperfection in the thin film. Dielectric thin-films are thus added on either side of the phosphor to limit the current that can flow through the phosphor and prevent destructive short circuit of the phosphor. The insulating layers store charge and only allow displacement current through them to the phosphor.

When a voltage is applied across the basic EL structure, a high electric field appears across the phosphor. When the internal phosphor voltage reaches a threshold, a current flows in the phosphor layer and excites the EL center causing light emission. Typical phosphor used for ELD consist of a host material doped with an activator which is the light emission center. To be an efficient EL phosphor, the light emitting center must have a large cross-section for impact excitation mechanism but must be stable in high electric fields present in the phosphor [6].

Recently active matrix electroluminescence displays (AMELDs) for head mounted display applications have been reported [7, 8]. A 2560×2048 AMELD image source with $12 \mu\text{m}$ pixel pitch has been demonstrated. The display size is 1-inch diagonal. It uses PMOS and LDMOS transistors for local memory and driving the EL cells. Lateral DMOS transistors have the high voltage drive capabilities required for exciting the EL cells. The transistors are fabricated on single crystal silicon layers on insulators. The EL layers are deposited conformally on the transistor layers by atomic layer epitaxy.

The light production process of the ELD is rather inefficient. ELDs suffer from three major disadvantages—(i) low luminous efficiency (<1 lumen/watt), (ii) high voltage drive leading to high cost electronics, and (iii) lack of good blue phosphor making full color ELDs difficult.

3.3. Plasma Display Panels

Plasma displays operate by glow discharge of a noble gas typically Ne, mixed with a small amount of Xe or Ar. The plasma display panel consists of two glass substrates separated by dielectric spacers to form a Ne containing chamber. Figure 2 shows the typical structure of a plasma display panel. Each of the substrates has a set of transparent parallel conductors. The conductors on the two substrates are orthogonal to each other, thus forming a row and column addressing matrix. The gas is confined between the transparent row and column electrodes (on the top and bottom) and glass seal spacers on the sides. This is to isolate the plasma discharge and provide electrical isolation. When a high voltage is applied between the electrodes, the intersection produces a plasma from which light is emitted, and the

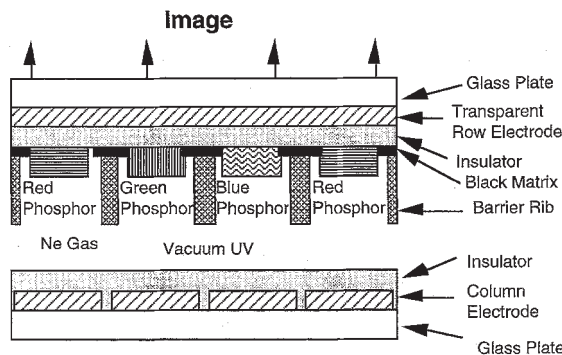


Figure 2. Device structure and operating principles of plasma display panels.

brightness of the display is related to the current of the plasma [9]. For a more detailed information on the recent developments in the plasma display technology, the reader is referred to [10–12].

In general, plasma displays are grouped according to how the current through the display is limited to prevent the destruction of the display. AC plasma displays use capacitors formed by placing a dielectric material between the plasma gas and the transparent electrode to limit the current. DC plasma displays use an external resistor to limit the current. Plasma displays have a number of desirable properties. These are (i) sharp turn-on voltages for matrix-addressing, (ii) high brightness and (iii) luminous efficiency (for monochrome displays).

The principle of operation of the full color plasma display is the same as in a fluorescent tube. A voltage applied between two electrodes creates an electric field which ionizes a gas at low pressure at a certain applied voltage. This leads to the emission of vacuum ultra violet light. The UV light is used to excite phosphors to produce visible light as in a fluorescent tube. While the plasma display has a simple basic structure and abrupt IV characteristics, it has two major disadvantages. The first disadvantage is the significant volume of gas that must be present to create sufficient brightness. This essentially places a limitation on how small the pixel can be which has implications for (i) resolution and (ii) portability—two important parameters for portable systems. The second disadvantage is the omni-directional nature of the light generated which leads to cross-talk between pixels and hence places a limitation on resolution.

3.4. Vacuum Fluorescent Displays (VFD)

The green emitting VFD is the most commonly used display device in cash registers, entertainment devices and automobile dashboards [13]. The VFD uses the same light production principle as the CRT, namely, Cathodoluminescence. Figure 3 shows a typical structure of a VFD. It uses a broad-area thermionic source of electrons typically made out of heated wires to create a virtual large area cathode. Electrons from the large area cathode are then density modulated by a group of x - y addressable grids. The electrons are accelerated towards a phosphor screen where light is produced by cathodoluminescence. Typically they operate at an anode voltage of less than 50 V. There are three basic problems with the VFD. The first problem is that there

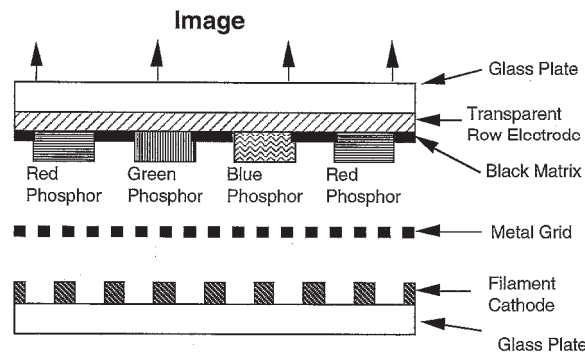


Figure 3. Device structure and operating principles of the vacuum fluorescent display (VFD).

are few known acceptable low-voltage phosphors with very high luminous efficiency to generate full color displays. The second problem is that electrons are emitted all the time from the broad area cathode which results in unnecessary power dissipation. The third issue is that matrix addressing of VFDs often result in reduced brightness due to a decrease in the duty cycle. To overcome the third problem, recently efforts have been directed towards increasing the brightness by using active matrix addressing techniques [14–16]. Troxell et al., recently reported an active matrix vacuum fluorescent display (AMVFD) technology. Thin film transistors were used to drive vacuum fluorescent displays. In this approach, a local memory is used at each pixel to achieve a 100% duty cycle, similar to an AMLCD [14, 15]. A 64×40 pixel, $450 \mu\text{m}$ pitch AMVFD was demonstrated with a spot luminance of 2500 fL at an anode voltage of 40 V.

4. Performance Metrics for Flat Panel Displays

Pankove [4] defined the ideal display many years ago thus: “the ideal device would modulate ambient light when it is abundant, but would emit bright light in the dark; it would be capable of producing saturated colors at will, be visible from all angles, have high resolution, respond in microseconds but retain image indefinitely if so desired, have a contrast ratio of over 50:1, 64 levels of gray, and consume negligible power at a low voltage”. However as he noted, there are many display devices that have subsets of these qualities, but there is none that has all these virtues. We shall go about defining the display performance metrics with Pankove’s vision in mind. To characterize and compare different display technologies, relevant performance measures and their metrics need to be defined. The relevant per-

formance measures include: luminance, contrast ratio, grayscale, color, viewing angle, power, luminous efficiency, frame rate, resolution, screen size, depth, pixel matrix, lifetime and temperature, humidity and vibration/shock resistance. In the following we will define these performance measures, discuss their significance, and describe their metrics for evaluating the available display technologies for portable system applications.

Luminance is a measure of the brightness of the display or the luminous energy emanating from the display surface. It is the luminous flux emitted per solid angle per unit area from the surface of the display. Its units are nit ($\text{candela}/\text{m}^2$) or foot-Lamberts ($1 \text{ fL} = 3.426 \text{ nit}$).

Contrast Ratio characterizes the dynamic range of the display luminance. It is defined as the ratio between the maximum brightness to the minimum brightness of the display. High contrast ratio is essential for high quality video images.

Gray Scale is defined as the number of distinguishable steps in the display luminance. For adequate number of distinguishable graylevels, a luminance dynamic range covering at least ten $\sqrt{2}$ changes in brightness is believed to be necessary. The grayscale is measured in number of bits per primary color. Present AMLCDs typically employ 6 bit column drivers (i.e., 6 bits per color). However, future developments are aimed at 8 bit grayscale (per color), to achieve true color rendition.

Color quality is characterized by the color gamut achieved. For best color rendition, the color gamut should be as broad as possible. Color performance is characterized by the CIE chromaticity coordinates of the white, black, and primary and secondary colors of the display, and their stability as a function of graylevel and viewing angle.

Viewing Angle is the ability to view the display from a direction that is at angle to the display normal without degrading the image contrast and quality. The metric for viewing angle is the size of the viewing cone in angles in the horizontal and vertical directions.

Power is the electrical power in Watts consumed by the image source and the driver circuitry needed to drive the image source.

Luminous Efficiency is the optical power or luminous flux generated per unit electrical power required to generate it. It measures the efficiency of the display in converting electrical power to luminous flux. It is measured in lumens/watt. As a benchmark, 1 W of

radiant power at 550 nm is equivalent to 680 lumens of luminous flux.

Frame Rate measures how often an image is refreshed. Typically, it is anywhere between 30 Hz and 80 Hz. In some displays, flicker or smearing of fast action images may be observed if the frame rate is not high enough.

Resolution of packing density of information depends on how small each picture element (pixel) can be made. It is a measure of fineness and visibility of detail. The metric for resolution is lines per inch (lpi) or dots per inch (dpi).

Screen Size is a measure of the display size, and is usually given as the size of the screen diagonal. For example, most notebook computers have 25 cm to 30 cm diagonal displays.

Display Depth is the physical depth of the display in the direction orthogonal to the screen. It is a measure of display bulkiness or portability.

Pixel Matrix is the number and format of pixels in the display. The standard VGA display has 640×480 pixel array, while the SVGA has 800×600 pixel array, XGA has 1024×768 pixel array and the SXGA has 1280×1024 pixel array. We expect that future multi-media applications will use the SXGA resolution displays.

Lifetime is an important parameter and depends on the physics of the operative display device processes. Typically, an operational life of over 2×10^4 hours is usually targeted in the display design.

Temperature, Humidity, Vibration/Shock Resistance are measures of the stability or ruggedness of the display to environmental and operational conditions.

Table 2, adapted from reference [17], shows a comparison of the performance attributes of various flat panel display technologies in relation to a CRT. The

Table 2. Comparison of flat panel display technologies (Table adapted from reference [17]).

Performance parameters	CRT	Plasma DC/AC	Electro-luminescent DC/AC	VFD	STN/LCD	AM/LCD
<i>Display visual parameters</i>						
Pixel density	High	High	High	Medium	Medium	High
Screen resolution	High	Med/High	Medium	Medium	Medium	High
Raster distortion	Yes	No	No	No	No	No
Flicker propensity	Yes	Yes/No	Yes	Yes	Yes	Yes
Luminance	High	Medium	Medium	Medium	Medium	High
Dimming range	High	Medium	Medium	Medium	Medium	High
Contrast	Medium	Low/Med	Med/High	Medium	Medium	High
Gray shades						
(Intrinsic)	High	Medium	Medium	Medium	Low	High
Viewing angle	High	High	High	High	Low	Medium
Ambient contrast	Low	Medium	Low/High	Low	Medium	High
Color capability	High	Med/High	Med/High	Medium	Medium	High
Screen update time	Fast	Fast	Fast	Fast	Slow	Fast
<i>Display system parameters</i>						
Power	High	Medium	Medium	High	Low	Low
Luminous efficiency (Lum/Watt)	0.5	1	1	0.5	2	2
Temperature range	Wide	Med/Wide	Wide	Wide	Narrow	Narrow
MTBF	Medium	High	High	High	High	High
RFI emanations	High	Medium	Medium	Medium	Low	Low
Vibration endurance	Low	Medium	Medium	Medium	High	High
Volume	High	Low	Low	Low	Low	Low
Weight	High	Medium	Low	Medium	Low	Low

attributes are categorized into visual and system performance parameters. From the visual performance perspective, AMLCD can be seen to have essentially all the best possible attributes, with the exception of unlimited viewing angle. More importantly, from a system performance perspective, again AMLCD can be seen to have essentially all the best attributes, with the exception of narrow temperature range. It should be noted that the narrow temperature range of the current AMLCD is not a major limitation for its use in portable systems, which in general are not expected to require a broad temperature operation such as automotive and avionic displays. Similarly, the viewing angle limitation of the current AMLCD is out weighed by its superior overall system performance attributes for portable applications. With an adequate display visual performance, the figure of merit (FOM) of a display for portable applications is essentially based on power (luminous efficiency, LE), and size characterized by weight, W , and volume (depth, D). We can define the FOM as:

$$\text{FOM} = \text{LE} / W * D$$

Higher luminous efficiency, and smaller display weight and display depth, will result in a higher figure of merit. Based on this metric, currently AMLCD can be seen to have the highest FOM of all the flat panel technologies in Table 2, and thus the best choice for portable applications requiring high performance displays.

5. Liquid Crystal Display (LCD) Technology

LCD is one of the enabling technologies for the acceptance and rapid growth of the present portable systems such as the note book computers. The acceptance of LCDs for these systems is primarily based on their low power, and full color capabilities. While LCD technology development has a long history, its rapid pace and wide market acceptance based on price and performance criteria, started happening only since the past few years. Because LCD is a nonemissive display, in contrast to the competing technologies which are emissive displays, its intrinsic power consumption can be very low. While there are many types of liquid crystal materials such as smectics, nematics, and cholesterics, and display modes using these materials, twisted nematic (TN) display mode is the most advanced and popular. For a general overview of liquid crystal technology, the reader is referred references [18, 19]. Figure 4

shows the basic principle of operation of a twisted nematic display in a normally white mode. The incoming light from a back-light source, which is typically a fluorescent lamp with a diffuser, is linearly polarized using a sheet polarizer. In the voltage-off state, the 90° twisted nematic liquid crystal pixel rotates the polarization direction of the incoming linearly polarized light by 90° , which then goes through the exit polarizer which is set in a crossed polarizer configuration, thus creating the bright (white) state of the display pixel. In the voltage-on state, the liquid crystal molecules tilt so that their director orientation is parallel to the field, due to the positive dielectric anisotropy of the LC material. This allows the incoming linearly polarized light to go through the liquid crystal with its polarization state unaltered. When this linearly polarized light encounters the crossed exit polarizer, it is blocked, thus creating a dark (black) state for the display pixel. A full color display can be created by incorporating red, green, and blue color filters at the pixels. Figure 5 shows the transmission (luminance) versus applied voltage characteristic for a typical TN LCD. Grayscale can be achieved by varying the voltage applied across the LCD using the pixel transmission versus voltage characteristic shown in Fig. 5. Note that the transmission-voltage curve shown in Fig. 5 is for a normal viewing angle. Unfortunately, the transmission-voltage curve is viewing angle dependent as shown in Fig. 6, which leads to grayscale errors and color shifts in a display when it is viewed from significant angles to the display normal. We will discuss the current solutions to this problem later in this section.

This display shown in Fig. 4 can be made to operate in a normally black mode simply by changing the polarizers to a parallel orientation. There are performance and cost trade-offs for selection between a normally black mode and normally white mode of operation. The majority of the present applications use a normally white mode; they are easier to manufacture, but provide a limited viewing angle. Normally black displays require tighter manufacturing tolerances, but provide an enhanced viewing angle particularly when used in combination with multi-gap [20] and halftone grayscale [21]. Presently only specialized applications such as avionics requiring a wide viewing angle, superior color and grayscale performance use normally black mode [22]. In the rest of the following discussion, we will focus on the normally white AMLCD that is typically employed in the present portable systems. It remains the configuration of choice for the

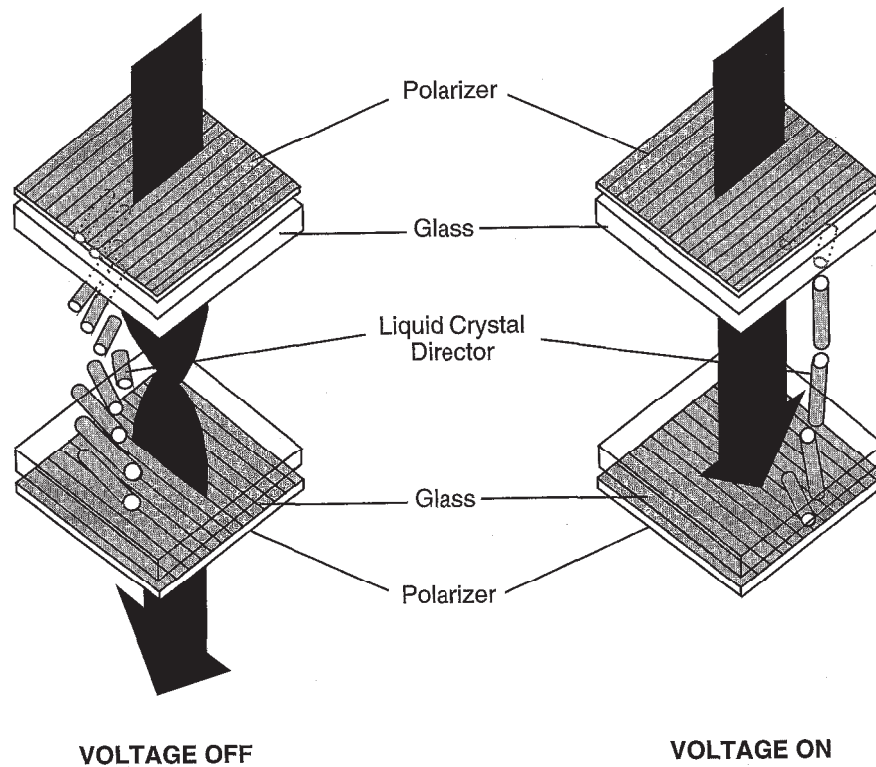


Figure 4. Principle of operation of a twisted nematic LCD in a normally white mode.

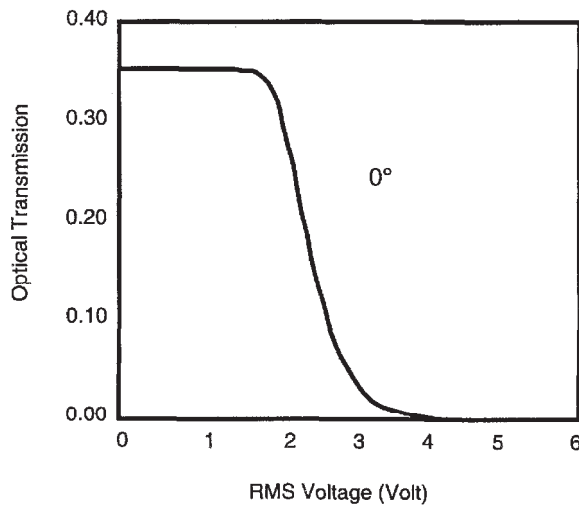


Figure 5. Transmission versus voltage for a typical TN LCD, for normal viewing angle ($0^\circ = 0^\circ$).

portable systems based on the projected cost and performance.

There are two broad categories of LCDs, namely passive matrix LCDs (PM LCD) and active matrix LCDs

(AMLCD). A passive matrix display comprising a liquid crystal between a matrix of transparent conducting row and column electrodes, is the simplest and least expensive liquid crystal display to manufacture. In a PM LCD, the row voltages are scanned in succession with a voltage, V_r , while all the columns in a given row are driven in parallel, during the row time, with a voltage of $\pm V_c$ depending on whether the pixel is selected to be ON or OFF. This approach is acceptable for low resolution displays. As the resolution increases, the difference between the select and non-select voltages (V_{on} , and V_{off}) decreases due to cross-talk between select and non-select pixels. The cross-talk is a result of the sneak paths in the row/column electrode matrix, which allows the non-select pixels to receive part of the applied voltage, thus degrading the contrast ratio of the display. Alt and Pleshko [23] analyzed this situation and derived an expression for the voltage ratio between the select and non-select pixels as a function of number of rows in the display:

$$\frac{V_{on}}{V_{off}} = \sqrt{\frac{(\sqrt{N} + 1)}{(\sqrt{N} - 1)}}$$

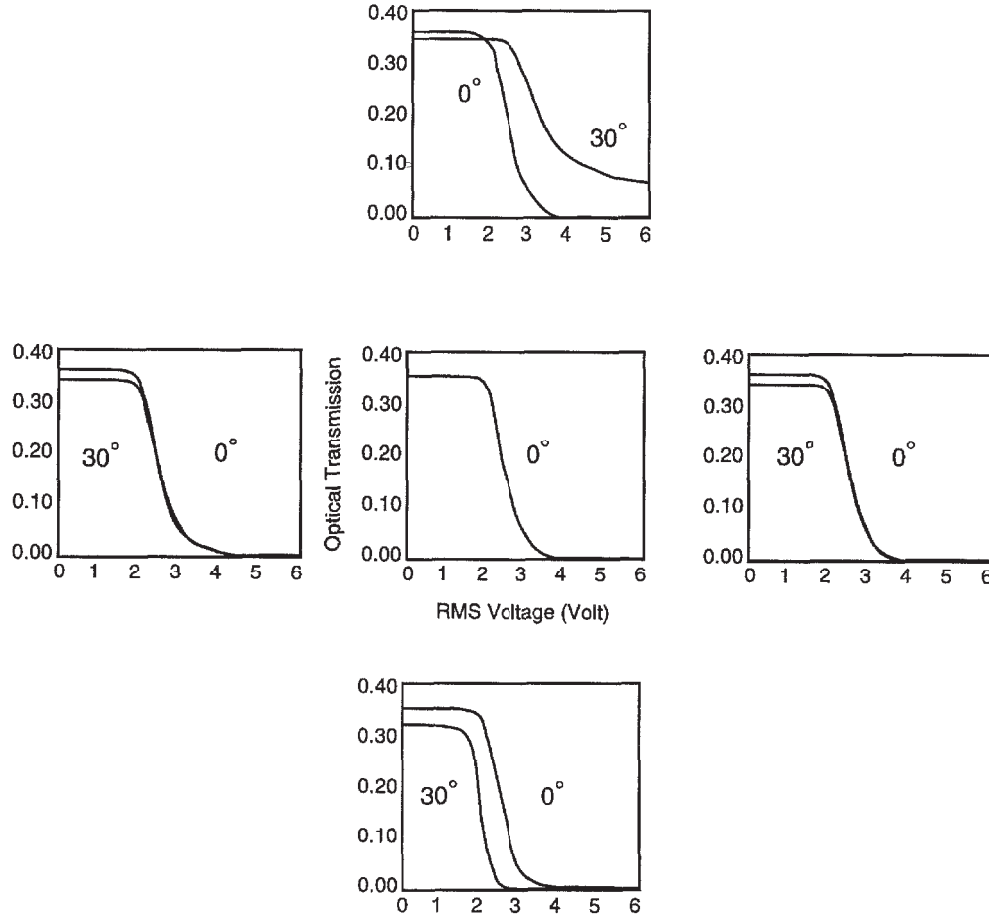


Figure 6. Viewing angle dependence of transmission versus voltage for a typical TN LCD. The figure shows the transmission for on-axis and 30° off-axis in four directions.

where N is the number of rows in the display. A transmission—voltage curve (Fig. 5) with a shallow slope requires a large voltage ratio, $V_{\text{on}}/V_{\text{off}}$, for an acceptable contrast ratio, thus limiting the display size to a small number of rows. To some extent, the steepness of the luminance-voltage curve of the TN displays can be somewhat improved by optimizing liquid crystal material parameters. However, passive matrix TN displays are still not suitable for fabrication of high information content displays requiring large number of rows and columns. The steepness of the luminance-voltage curve can be dramatically improved using the supertwisted nematic (STN) approach [24], employing a much higher twist angle such as 270°. Thus STN approach allows fabrication of LCDs with large number of rows for high information content display applications. The relative ease of the STN display manufacturing and their low cost, has created a huge

demand for these displays for note book computer applications, in spite of their marginally acceptable performance. To enhance the operating margin for improved contrast ratio, DSTN (dual scan STN) configuration is used. In a DSTN, the display is separated into two halves, and the rows in each half are scanned simultaneously and synchronously, to essentially double the duty ratio of the “on” pixels to increase the contrast ratio.

One of the major shortcoming of the STN display is the slow response time of the liquid crystal which is of the order of 150 m Sec. This low response time is not adequate for video applications and barely fast enough for a graphical interface of a computer. The response time of the STNLCDs can be improved by active addressing or multi-line addressing techniques [25, 26]. These techniques involve simultaneous addressing of several rows of a display to suppress the frame response

problems of conventional STNLCDS. The cost and performance of the active addressed PMLCDs is expected to lie in between that of a conventional STNLCD and an AMLCD. The active addressed STNLCDS are more suited to the medium information content display applications requiring video response rate. Even with active addressing the STNLCDS will still be limited by the multiplexability limit of the PMLCDs [23].

In addition to the slow response time, the performance of a STNLCD is inferior to that of an AMLCD with respect to contrast ratio, grayscale, viewing angle, and color gamut. AMLCDs offer a significantly higher potential for meeting the performance requirements for the future high information content portable systems. Further, the recent major development efforts have reduced the cost difference between a STNLCD and an AMLCD considerably, making AMLCD the most likely technology of choice for future portable systems. AMLCD is most suitable for applications requiring high image quality such as from a CRT, but having a flat profile, lower power consumption, lower weight, and viewability under a variety of ambient lighting conditions. During the past ten years AMLCD technology has progressed from being a laboratory novelty to having commercial viability for applications ranging from

hand held TVs to portable notebook computers, engineering workstations, and avionic displays. AMLCDs are in current use for large area direct view displays as well as small high resolution light valves for helmet/head mounted displays (HMD) for military and commercial applications as well as large area projection displays. AMLCD with sizes of up to 28" diagonal have been demonstrated for direct view applications [27]. Similarly AMLCDs with high resolutions such as 1440×1024 and a pixel size in the range of $25 \mu\text{m}$ [28] have been demonstrated for HDTV projector and HMD applications. In the following we will discuss the active matrix technology, AMLCD components, display module electronics, optical performance and efficiency characteristics, and future developments.

5.1. Active Matrix Technology

Active matrix addressing removes the multiplexing limitations [23] of the PMLCDs, by incorporating a nonlinear control element in series with each pixel, and provides 100% duty ratio for the pixel, using the charge stored at the pixel during the row addressing time. Figure 7 illustrates an active matrix array with

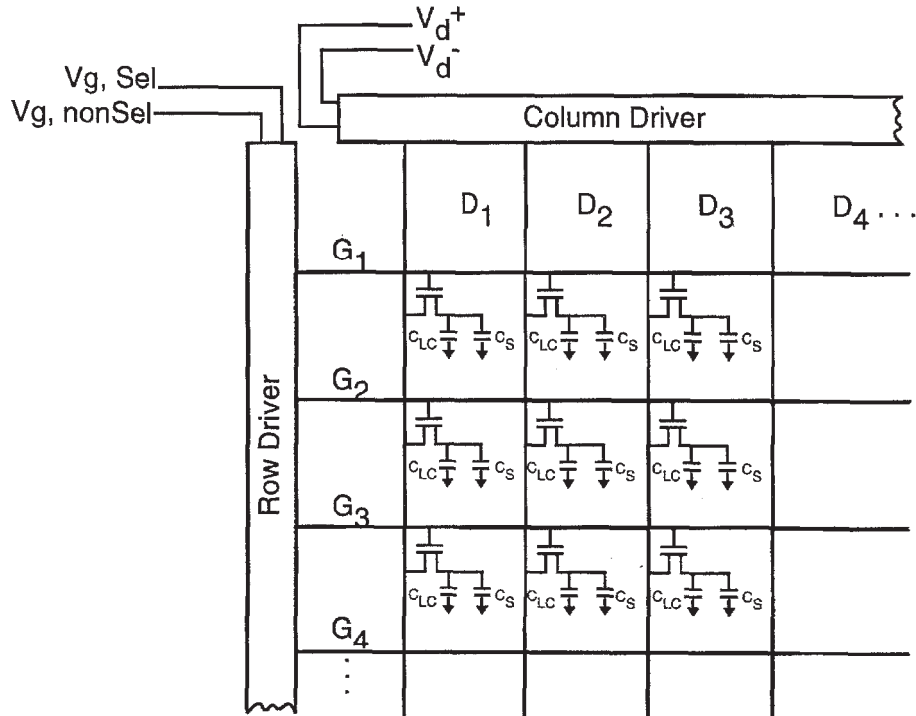


Figure 7. Schematic of a TFT active matrix array.

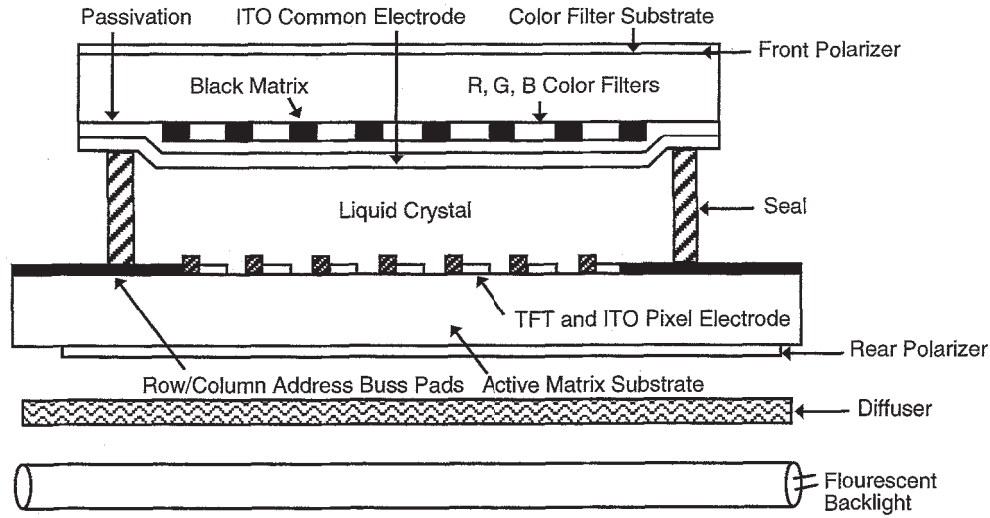


Figure 8. Schematic cross-section of an AMLCD.

row and column drivers. In the figure C_{LC} and C_s represent the pixel capacitance and the pixel storage capacitance. Figure 8 shows the cross section through an AMLCD illustrating various elements of the display. Figure 9 shows a typical AMLCD pixel, showing the gate and data busses, a thin film transistor (TFT), ITO pixel electrode, and the storage capacitor buss.

Fabrication of the active matrix substrate is one of the major aspects of the AMLCD manufacturing. Both two terminal devices such as back to back diodes [29], and metal-insulator-metal (MIM) diodes [30] as well as three terminal thin film transistors (TFTs) are developed for active matrix addressing. While 2-terminal devices are simple to fabricate, and cost less, their lim-

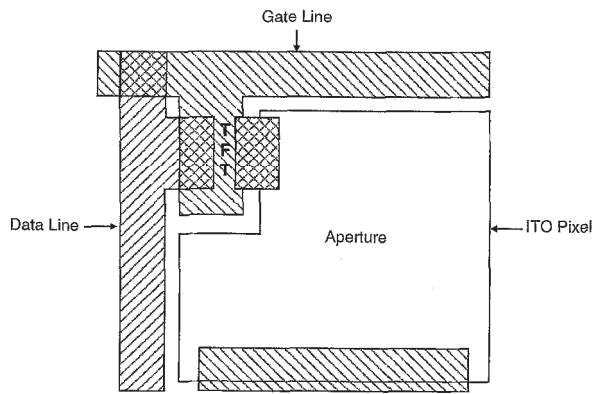


Figure 9. Typical TFT-LCD pixel layout.

itations include difficulty in achieving uniform device performance (breakdown voltage/threshold voltage) over a large display area, and lack of total isolation of the pixel when neighboring pixels are addressed. As a result, most of the current AMLCDs use TFT for the active matrix device, which provide a complete isolation of the pixel from the neighboring pixels.

Figure 10 shows the electrical equivalent of a TFT-LCD pixel, the display drive wave forms and the resulting pixel voltage. As in most matrix addressed displays with a line-at-a-time of addressing, the rows (gates) are scanned with a select gate pulse, $V_{g, sel}$, during the frame time t_f , while all the pixels in a row are addressed simultaneously with the data voltage $\pm V_d$ during the row time $t_r (= t_f/N)$. During the row time the select gate voltage, $V_{g, sel}$, "turns-on" the TFT and charges the pixel and the storage capacitor to the data voltage V_d . After the row time, the TFT is "switched-off" by application of the non-select gate voltage, $V_{g, non-sel}$; the voltage (charge) at the pixel is isolated from the rest of the matrix structure until the next frame time. Note that the LC pixel must be driven in an AC fashion with $+V_d$ and $-V_d$, during alternate frame periods, with no net DC across the pixel. A net DC voltage across the pixel results in flicker and image sticking effects [31]. Large and sustained DC voltages degrade the LC material due to electrolysis. The shift in pixel voltage, ΔV_p shown in Fig. 10, at the end of the row time is due to the parasitic gate-to-drain capacitance, C_{gd} , of the TFT. When the gate voltage is switched, the distribution of the charge from the TFT gate dielectric causes

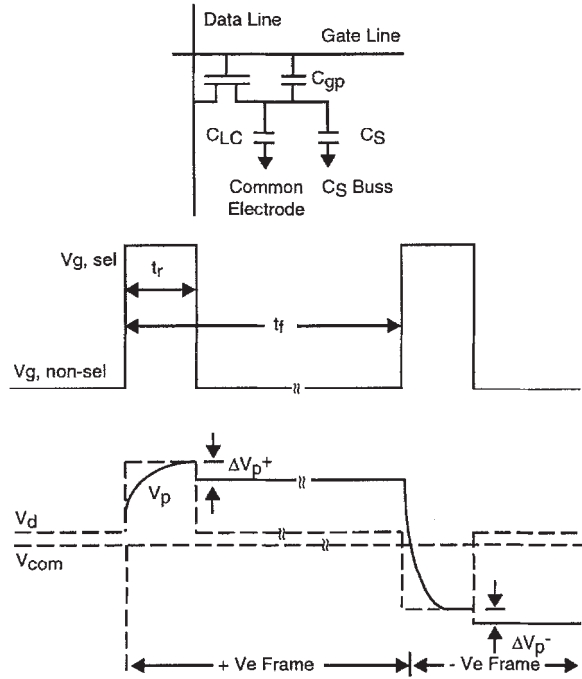


Figure 10. Electrical equivalent of a TFT-LCD pixel, and its operation.

the pixel voltage shift, ΔV_p , given by:

$$\Delta V_p = V_{g,sel} * C_{gd} / (C_{gd} + C_{lc} + C_s)$$

For the n -channel enhancement mode TFT switching device used, this voltage shift ΔV_p is negative for both the +ve and -ve frames, and thus it helps pixel charging in the negative frame and hinders it in the +ve frame. Further, due to increased gate bias during the -ve frame, the pixel attains the data voltage much more rapidly during the addressing period. Hence, the TFT is designed for the worst case +ve frame conditions. ΔV_p is reduced by minimizing C_{gd} by decreasing the source drain overlap area of the TFT, and by using a storage capacitor, to minimize DC voltage shift across the pixel. Further ΔV_p is compensated by adjusting the common electrode voltage V_{com} as shown in Fig. 10. Note that C_{lc} is a function of the V_p (V_{lc}) due to the dielectric anisotropy of the LC, and hence adjustment to V_{com} alone does not eliminate DC for all graylevels. Either special addressing techniques [31] or modification of the grayscale voltages is required to compensate for the dielectric anisotropy of the LC.

Presently, most of the AMLCDs are fabricated using amorphous silicon (a-Si) TFTs. The advantages

of the a-Si TFTs include low processing temperatures (compatible with the use of glass substrates), large area deposition capability, and compatibility with the well established silicon IC industry. a-Si TFT has a typical mobility of $0.5 \text{ Cm}^2/\text{V.Sec.}$ which is adequate for active matrix devices. However, this low mobility is not suitable for the fabrication of row and column driver circuitry for a high information content displays, which require large bandwidth drivers, which in turn requires higher mobility TFTs. In addition to lower mobility, a-Si TFTs are characterized by a higher threshold voltage (typically 3–4 Volts), threshold voltage instabilities due to gate bias stress particularly at elevated temperature operation, and difficulty in fabricating self aligned source/drain-to-gate structure. These limitations have motivated the development of polysilicon, and single crystal silicon TFT technologies. We will discuss these technologies below under future developments.

5.2. Display Components

The major display components include fluorescent backlight, diffuser, rear polarizer, liquid crystal cell assembly comprising the active matrix substrate and the color filter substrate sandwiching the liquid crystal material, and front polarizer (see Fig. 8). The row and column drivers are attached to the liquid crystal cell assembly (not shown in Fig. 8) either by a TAB or chip-on-glass assembly techniques. The front polarizer of the display may include antireflective and EMI coatings. The display may further include compensation films between the display glass and polarizers for enhanced viewing angle performance [32].

The optical efficiency of the AMLCD may be examined by considering the optical losses at each of the components. Starting from the diffuser, the rear polarizer transmits only a maximum of 50% of the incoming light. This transmission is then reduced by the aperture ratio of the pixel, and the transmission through the color filters. Using a typical aperture ratio of 50%, and R , G , B color filter transmission of about 33%, the maximum transmission of the light from the diffuser can be calculated to be about 8%. In reality, due to absorptive losses and reflection losses the polarizer transmits only about 43%. Also, due to mismatch of the backlight spectrum and the color filter transmission spectrum, the transmission of the color filters is only about 25%, and the reflection losses at each optical interface in the display, reduce the optical transmission by another 10%. This results in a typical display transmission to about 4.5%.

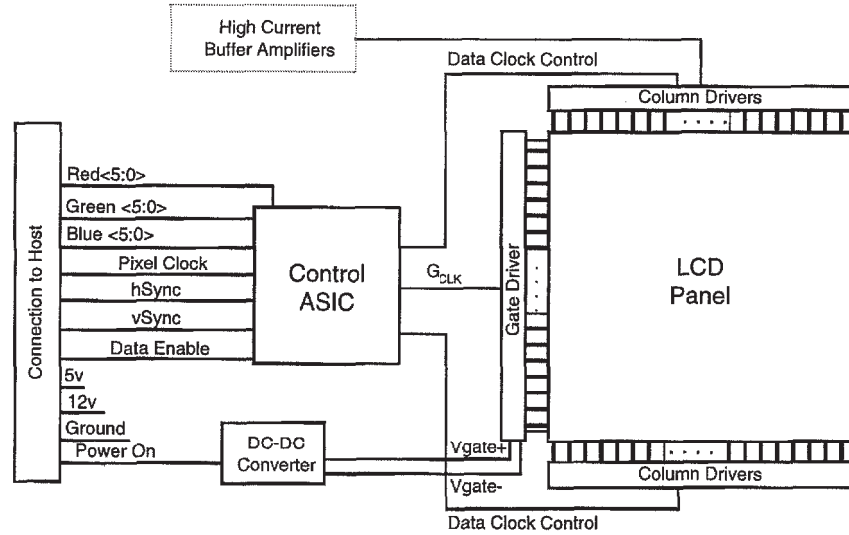


Figure 11. AMLCD module electronics block diagram.

On top of this, when we consider that the lamp to diffuser coupling is typically about 50% efficient, it can be seen that AMLCD is optically a very inefficient device. However, there are many opportunities for improving the optical efficiency of an AMLCD in the future. These will be discussed under the future developments.

5.3. Display Module Electronics

Figure 11 shows an example of a block diagram for an AMLCD module electronics [33]. The row and column drivers are typically mounted on a TAB which is interconnected to the row and column electrodes on the display glass. In some cases the row and column drivers are mounted directly on the row and column electrodes of the display glass (chip-on-glass). The control block and power supply generation means are separately mounted on a PC board and connected to the row and column drivers on one side and to the host controller on the other. The control block may include level shifters, timing generators, and analog functions in some cases. Essentially, the purpose of the control block is to take in digital data from the host system, which is typically a graphics controller chip and convert it into timing and signal levels required by the row and column drivers. The architecture and design of the module electronics encompassing row and column drivers have a significant impact on not only the display system cost and power consumption, but also the image quality.

The liquid crystal material typically requires about 5 V to achieve optical saturation (see Fig. 5). Considering the need for an AC drive (Fig. 10), the required voltage swing across the LC material is about 10 V. To achieve this 10 V swing across the LC material, the column drivers typically use 12 V power supplies. The requirement for the gate voltage driver outputs $V_{g, sel}$ and $V_{g, non-sel}$ is as follows: The $V_{g, sel}$ must be higher than the most positive column voltage by at least the TFT threshold voltage (V_t). The $V_{g, non-sel}$ must be lower than the lowest column voltage by at least the TFT threshold voltage. This ensures that TFT stays “turned-on” to charge the pixel to the desired column voltage during the addressing period, and stays “turned-off” during the non-addressing period to hold the pixel charge. Column driver voltage can be reduced by using V_{com} modulation drive method. In this method, the V_{com} node (which is connected to all pixels in the display) is driven above and below a 5 V range of the column drivers. Each and every row time, the V_{com} node is alternated between a voltage above and a voltage below the 5 V output range of the column drivers. This achieves 10 V across the LC material using 5 V column drivers. This method requires additional components and consumes additional power due to the oscillation of the V_{com} node. In addition, to avoid capacitive injection problems, the row drivers usually have their negative supply modulated with the same frequency as the V_{com} node. Note however, that compared to 10 V column drivers, 5 V column drivers

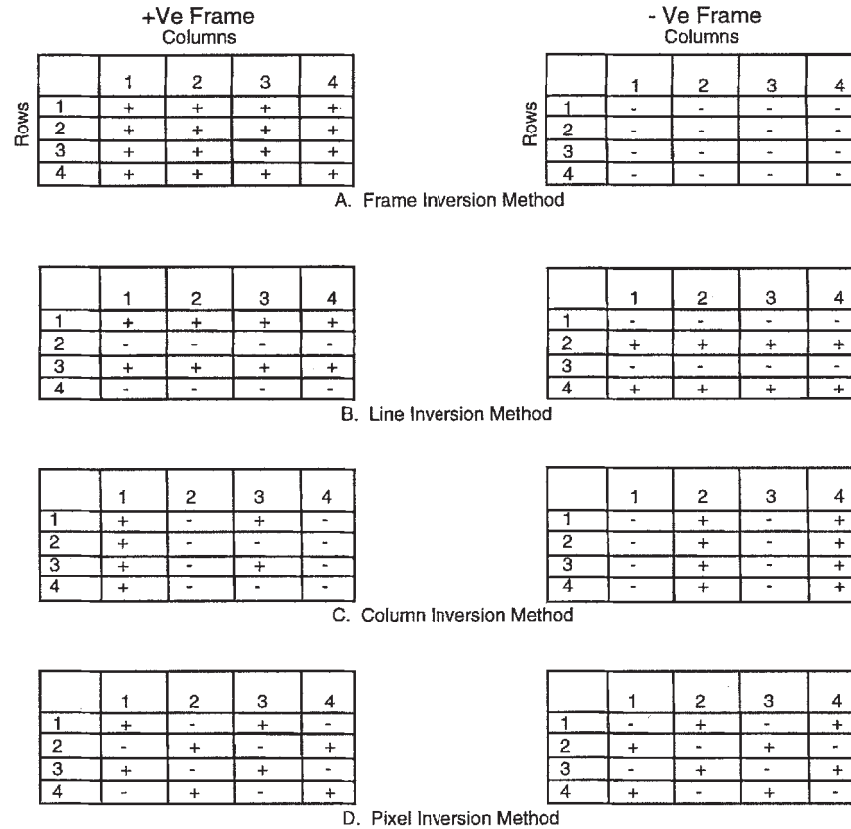


Figure 12. Typical AMLCD Polarity Inversion Methods.

consume less power, and are simpler to design and fabricate using small geometry CMOS.

Polarity inversion method is used to eliminate DC voltage across the liquid crystal, as well as to eliminate the influence of pixel flicker on the display image quality. The type of polarity inversion method used has an impact on the power consumption. Figure 12 shows the four widely used polarity inversion methods. In the frame inversion method, all pixels in one frame period are driven to +ve polarity in one frame period, and then all of them are driven to the -ve polarity during the next frame period. This method consumes the lowest driver power. However, it is sensitive to flicker due to slight transmissivity mismatch between the +ve and -ve polarities. It is also sensitive to horizontal and vertical cross-talk. As a result, this method is not generally employed when high image quality is required. In the other methods, flicker is eliminated by spatial averaging of the adjacent pixels with +ve and -ve polarities with slight transmissivity mismatches. In the line inversion method, the polarity

of pixels in the adjacent rows is alternated. This method is compatible with the V_{com} modulation drive scheme. It has much reduced sensitivity to vertical cross-talk, and more propensity for horizontal cross-talk. Also, it consumes more power than column inversion method, because the capacitance of all the row busses is charged and discharged every row time. In the column inversion method, alternate columns are driven with +ve and -ve polarities. This method is not compatible with the V_{com} modulation drive scheme and requires higher voltage column drivers. It has greatly reduced horizontal cross-talk, and low-power operation. Pixel inversion method is the ultimate scheme for spatial averaging of the +ve and -ve polarity pixels. In this scheme, the polarity of each pixel is inverted from the polarity of each of its neighboring pixels, by a combination of simultaneous row and column inversion. This produces the highest quality image, by total elimination of flicker and cross-talk. This method is incompatible with the V_{com} modulation drive scheme, and thus requires high voltage column drivers. Also, it consumes

more power due to the row inversion component. For a typical 10.4" diagonal VGA display the power dissipation for driving a global V_{com} node can be estimated to be in the range of 200 mW–350 mW [33]. This has to be balanced against the simplicity and lower cost of the low voltage column drivers.

The current trends in display module electronics developments are aimed at going to higher gray shades (going to 8 bit column drivers from the current 6 bit drivers) to achieve true colors, full motion video, lower power consumption (going to 0.5 W for SVGA from the current 1.5 W for driver power), higher levels of integration (higher column driver output count), and smaller bezel width for maximizing the display size for a given portable system size.

5.4. *AMLCD Optical Performance, and Efficiency Characteristics*

The relevant optical performance measures for an AMLCD include:

- Luminance range
- Luminance contrast ratio
- Color gamut
- Viewing angle
- Graylevel stability across the viewing angle
- Chromaticity stability as a function of graylevel and viewing angle
- Response time, and
- Reflectivity

For the display to be viewable comfortably under a variety of ambient lighting conditions ranging from dark to full sun light, it should have a controllable (dimable) luminance range extending up to 100 fL. This luminance range can be presently achieved with a fluorescent backlight and a diffuser with appropriate control circuitry. Note that in a transmissive LCD, the luminance can be arbitrarily increased by merely using a brighter backlight (provided thermal issues are manageable). Unfortunately, use of brighter backlights increases the power consumption, and thus is not a preferable approach for portable systems. As a trade-off between acceptable luminance and lower power consumption, the present AMLCDs for notebook computers typically use a maximum display luminance of about 25 fL. The present AMLCDs achieve an on-axis luminance contrast ratio in excess of 100:1 (in a dark ambient) which is acceptable.

Color gamut is a function of the spectral characteristics of the backlight used and the color filter transmission characteristics. By suitable choice of these parameters, AMLCD can achieve a color gamut comparable to that of a high quality CRT. However, in many of the present notebook computer displays, the color filter transmission characteristics are chosen to achieve a higher transmission and thus higher display luminance to reduce power at the expense of color gamut. This results in unsaturated display colors.

LCDs have been notorious for having a very limited viewing angle. In general, portable systems do not require a very wide viewing angle such as $\pm 60^\circ$, that avionic displays with cross-cockpit viewing, and multi-viewer television displays characteristics. However, it is desirable for portable systems to have viewing angle up to $\pm 45^\circ$, for comfortable viewing in a variety of situations. LCDs have intrinsically poor viewing angles compared to emissive displays. The asymmetry of the LC director orientation around the display normal, and the variation of retardation of the liquid crystal cell with viewing angle result in variation of the off-state luminance with viewing angle. This leads to a decreased contrast ratio, as the viewing angle is increased. Figure 13 shows the contrast ratio as a function of horizontal and vertical viewing angles in a typical notebook computer display today. A significant drop in contrast ratio at large viewing angles can be clearly seen in Fig. 13.

In addition to a high contrast ratio, grayscale displays must have stable graylevel luminances across the viewing angle. Figure 14 shows the luminance variation as a function of viewing angle for 8 graylevels in a typical AMLCD used in the present notebook computers. While the graylevel luminances are reasonably stable in the horizontal direction, they vary significantly in the vertical direction, becoming brighter in the upper direction and darker in the lower viewing direction. Notice the graylevel inversion at larger viewing angles. This instability of graylevel luminances leads to chromaticity tolerances problems and color shifts that are not acceptable in a high quality display. Thus, presently the viewing angle of an AMLCD is limited by the lower contrast ratio, graylevel inversion, and unacceptable color shifts. However, several approaches are being developed to overcome these limitations which will be discussed under the section "future developments".

Due to the advances in the liquid crystal materials and the AMLCD drive techniques, the response time

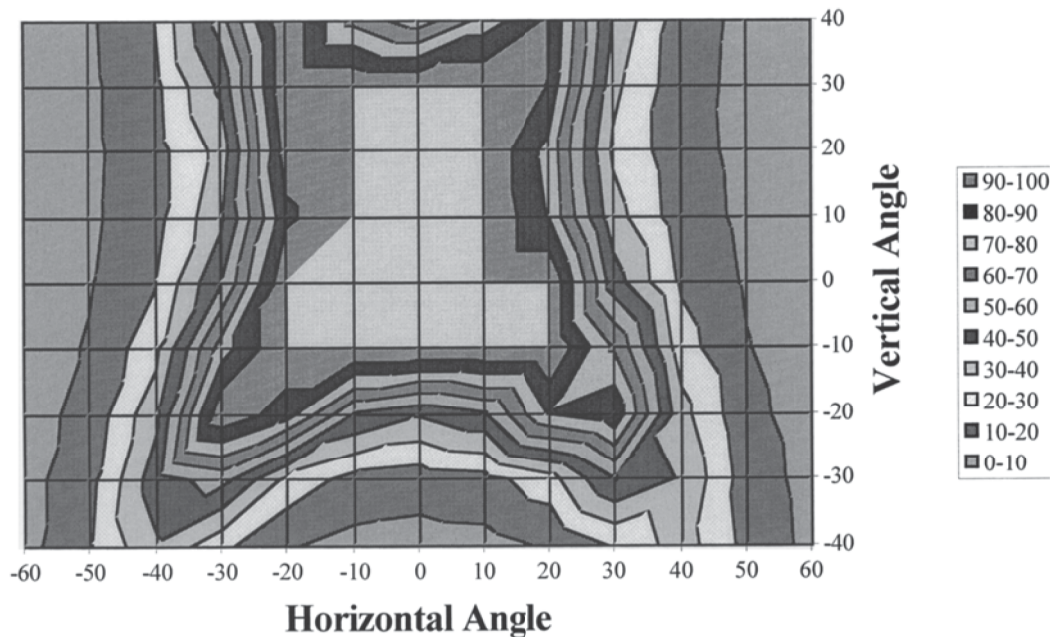


Figure 13. Contrast ratio as a function of horizontal and vertical viewing angles in a typical normally white AMLCD.

(raise time + fall time) of the AMLCDs used in the current notebook computers is less than about 40 msec which is adequate for full motion video at 72 fps.

For viewability under high ambient lighting conditions, the reflectivity of the display must be low. Reflection of the ambient light from the display panel reduces the contrast ratio. Presently, a typical AMLCD used in a notebook computer has a reflectivity of about 2%. This is only marginally acceptable now, and too high to meet the requirement of a display for the future portable multi-media systems. It must be reduced to less than 0.75% by use of improved AR films, and by reducing reflectivity of various layers in the display panel.

5.5. Future Developments

Presently, there is much development activity aimed at reducing the deficiencies of AMLCDs for high information content portable systems with low power consumption. One of the major activities is the development of a high mobility TFT (on glass). This allows fabrication of row and column driver circuitry on glass, to eliminate the cost of externally connected silicon driver chips, improve reliability, and reduce package size and weight. The ultimate vision

of this development is to fabricate other functions—logic, memory and control circuitry—also on the display glass (system-on-glass). Quartz substrates and high temperature TFT device processing can be used for fabricating single crystal silicon thin film transistors [34, 35] with a typical mobility of over 600 $\text{cm}^2/\text{V} \cdot \text{sec}$, for small high resolution displays with integrated drivers for HMD applications. However, lower temperature TFT device processes are required for large area displays. Recently, significant progress has been made on low temperature polysilicon TFTs, and mobility in excess of 100 $\text{cm}^2/\text{V} \cdot \text{sec}$ has been demonstrated. Sieko Epson has reported a 10.4" diagonal SVGA display with integrated 6 bit data drivers, using low-temperature (425°C) polysilicon TFTs [36]. Driver voltage reduction is another future development trend. Because power consumption is proportional to the square of the voltage (V^2), significant reduction of the panel power can be achieved by this approach. While 5 V drivers are more common now, the conversion to 3.3 V has already been started. This requires development of new LC materials with a low switching voltage, as well as advances in the TFT technology.

Weight is a significant parameter for portable systems. While mostly 1.1 mm thick glass has been utilized for the AMLCD fabrication now, it is being replaced with 0.7 mm thick glass. Use of 0.5 mm thick

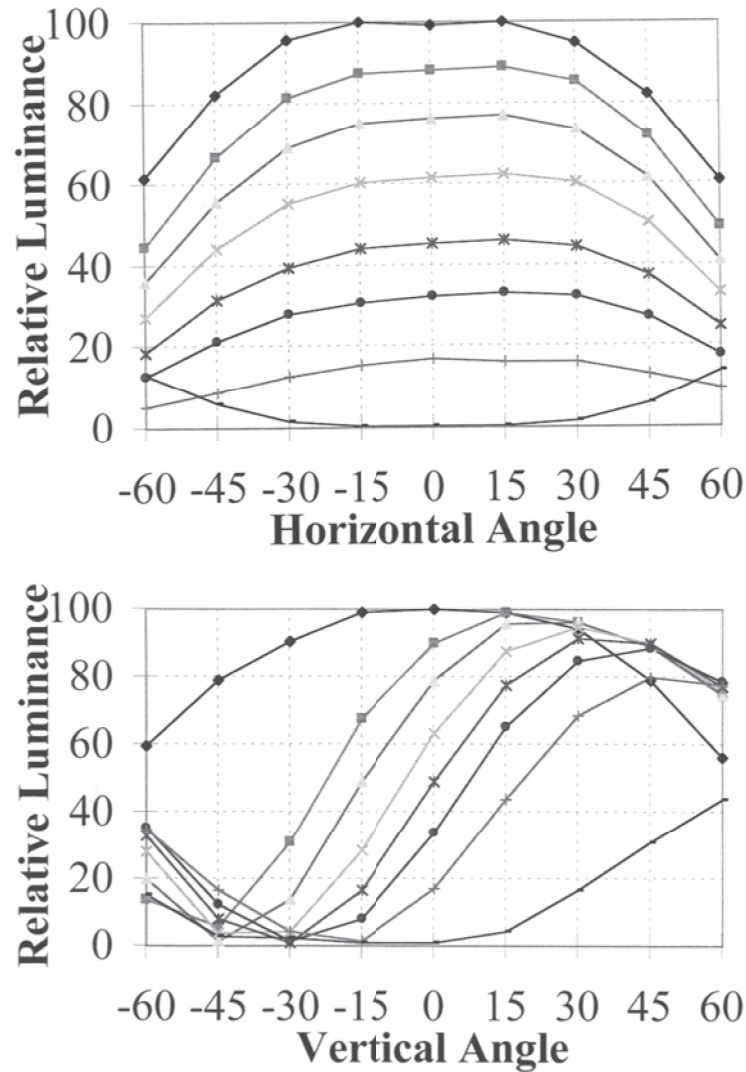


Figure 14. Graylevel luminance stability as function of horizontal and vertical viewing angles.

glass is being considered for future displays. For a 10.4" dia. display, replacing the 1.1 mm glass with 0.7 mm glass will reduce the display weight from 225 gms to 145 gms. Plastic substrates are also being developed as a replacement for glass substrates for further weight reduction and improved durability [37].

As discussed earlier, power consumption is a major factor for portable systems. Two major areas for reducing AMLCD power consumption are: 1) increasing the aperture ratio of the pixel and 2) use of a rear reflective polarizer [38, 39] instead of the absorptive polarizer. By using field shielding techniques [40, 41] and by use of smaller design rules the active area of the pixel can

be maximized by decreasing (or eliminating) the inactive space between the pixel electrodes and the gate and source buss lines. Sharp [41] has demonstrated 82% aperture ratio for 10.4" diagonal AMLCDs with SVGA resolution. Conventional absorptive linear polarizers reduce the optical efficiency by at least 50% by absorbing the light that is polarized perpendicular to the pass-axis of the polarizer. A reflective polarizer would reflect this light of wrong polarization for polarization rotation and re-imaging to potentially double the efficiency of the LCD. Two approaches [38, 39] have been reported for reflective polarizers. One approach is to use retro-reflective sheet polarizers [38].

This microprism based retroreflector performs satisfactorily at normal incidence but exhibits color shifts off-axis. The second approach for the reflecting polarizer is based on the use of a cholesteric LC film as a circular polarizer, and a quarter wave film to generate linearly polarized light. Using this approach Merck has reported 80% improvement in brightness for the same power consumption [39].

Several options are available and being developed to enhance the viewing angle of a display. The various viewing angle enhancement techniques include: halftone grayscale [21], dual domain technique [42], compensation films [32], SpectraVue™ backlight collimation and front viewing screen method [43], OCB (optically compensated bend) mode [44], and IPS (in-plane switching) mode [45]. Some of these approaches may not be suitable for use in portable systems due to their impact on the display transmission and thus its power consumption. For example, the IPS mode may not be suitable for portable systems because of its very low transmission, even though it provides excellent viewing angle and image quality. Based on the rapid progress being made on the viewing angle enhancement methods driven by the workstation display market, it is expected that AMLCD viewing angle will not be a major limitation for its use in the future high performance portable systems.

Reflective displays offer the most potential for reducing the power consumption. Unlike selectively modulating the transmitted light in a backlit LCD, reflective LCDs selectively reflect the ambient light, eliminating the need for backlight power. When ambient light is not adequate, front lighting can be provided to make these displays viewable [46]. Reflective color displays using guest-host mode [47], and PDLC mode [48, 49] have been reported. One of the major requirements for a high quality reflective display is a high level of spectral reflectance, to achieve good color selectivity and acceptable reflected luminance. Conventional polarizer and color filter based LCD approaches described above are not suitable for a reflective mode, because of the very low transmitted light intensity (typically less than 5%) that is available for reflection. Both the guest host mode and PDLC mode do not require polarizers, and thus can provide brighter reflective displays. Recently, a holographically formed [49] liquid crystal polymer reflective display has been reported. It consists of a liquid crystal (LC) and polymer multi-layer structure that reflects light at specific wavelength and transmit the light at other wavelengths.

The reflection intensity can be controlled electrically. This device does not use either polarizers or color filters, and hence, can provide bright color images.

Monochrome, reflective LCDs have also been developed using cholesteric liquid crystal materials [50]. Polymer stabilized cholesteric texture (PSCT) type reflective LCDs show a potential for use in electronic book, electronic newspaper and document viewing applications. PSCT-LCDs are bistable, the stable states being reflecting planar state and non-reflecting focal conic state. The bistability allows the display to retain the image without consuming any power. A 14" diagonal high information content, monochrome, passive matrix reflective cholesteric display has been demonstrated [50] with a resolution of 200 dpi, and a pixel matrix of 2240×1728 pixels. These displays can be bright because no polarizer is needed and the pixel aperture ratio can be very high. The present major drawbacks of the reflective cholesteric liquid crystal technology are lack of full color and video speed.

The current development efforts in reflective LCDs are focused on achieving improved color performance, resolution, grayscale, viewing angle, and brightness.

6. Field Emitter Display Technology

The field emitter display (FED) is essentially a flat CRT. It consists of a two-dimensional array of matrix-addressable electron sources that is proximity focused on another two-dimensional array of phosphor dots. The FED is an emissive flat panel display based on cathodoluminescence-similar to the CRT; however, unlike the CRT which relies on the sequential addressing of phosphor dots by a single electron source, the FED uses multiple electron sources per pixel which are proximity focused on the phosphor dots. In one respect it bears some similarity with AMLCD because the two-dimensional array of electron sources are matrix addressed. The electron sources are on a base-plate while the phosphor dots are on a face-plate. The face-plate is separated from the base-plate by a vacuum gap using physical standoffs or spacers [51–56].

A typical field emitter display is shown in Fig. 15. The electron sources are sharp cones that emit electrons by quantum mechanical tunneling in the presence of a high electric field. The application of a positive voltage to the gate electrode with respect to the emitter results in an intense electric field at the emitter surface leading to electron tunneling or cold cathode electron emission. The electrons are emitted normal to the base-plate and

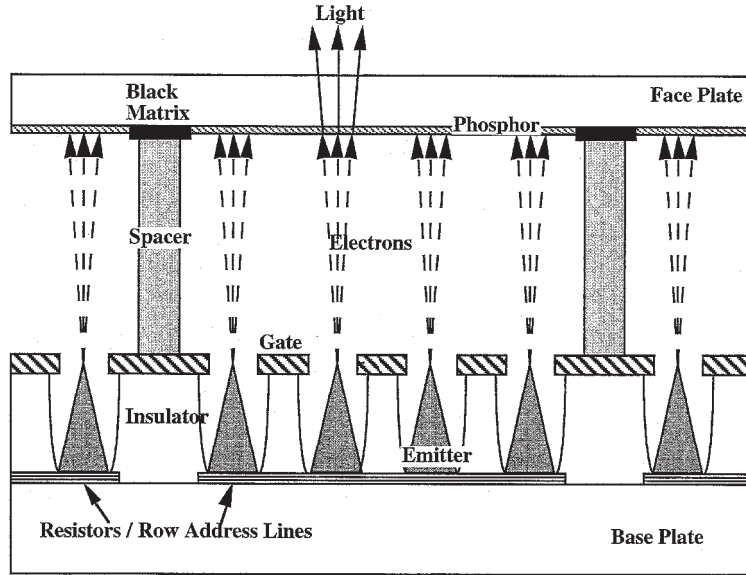


Figure 15. Device structure and operating principles of a field emitter display (FED).

travel to the face-plate which is biased at a voltage higher than the base-plate. The electrons bombard the phosphor and create a luminous image which is seen by the viewer.

The key features of a field emitter display are:

- Two-dimensional array of electron sources on a base plate
- Two dimensional array of phosphor dots on a face-plate
- Proximity focusing of emitted electrons on phosphor
- Redundant electron sources per pixel.

6.1. FED Operating Principles

The base plate of the FED consists of a two-dimensional array matrix-addressable electron sources. There are several approaches to generating electron emission and addressing the electron emitters. Similar to all matrix addressing schemes, the FED relies on the non-linear current voltage characteristics of field emitters. Figure 16 shows the current-voltage characteristics of a typical field emitter array. One approach to addressing the field emitter arrays for a video-display application is to use the following scheme: Each pixel consists of multiple field emitters. Each field emitter has an emitter and a gate (extraction) electrode. Rows of pixels consisting of multiple field emitters are electrically connected and are placed in parallel with other

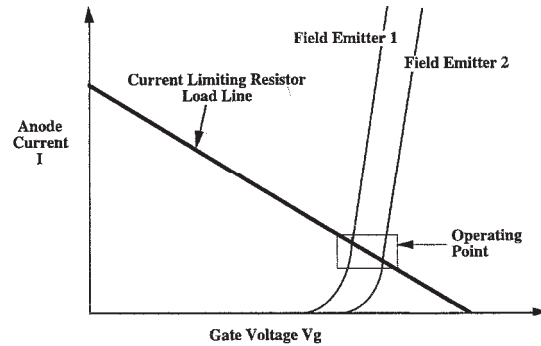


Figure 16. Current-Voltage characteristics of a field emitter display. The figure indicates the role of a resistive load line in established an operating point.

rows of pixels. On the other hand, the gates (extraction grids) of the field emitters in each pixel are electrically connected in parallel columns which are orthogonal to the rows of emitters. In this configuration, the emitter array associated with each pixel is uniquely defined by the intersection of a specific emitter row and a specific gate (extraction) grid column. The pixel is selected by electrically addressing the row corresponding to the pixel while simultaneously addressing the corresponding column [57].

Gray scale and color rendition are two important issues for video-display applications. The brightness of a pixel is proportional to the total electron charge delivered by the field emitter array to the phosphor of an

individual pixel within a frame. The charge delivered by the electron sources to the phosphor within a given frame can be varied by changing the time period within the frame at the activated site or changing the emission current produced during the activation. These two techniques are referred to as time division multiplexing or analog voltage gray scale methods. Cathodoluminescence also has the property that phosphor continues to emit photons after electron excitation has stopped. This is the key property that allows sequential addressing of phosphors in a CRT. Photon emission persists for a duration of the frame period even though the phosphor is only addressed for a brief portion of the frame period. Another factor is the nature of the human visual system. The human visual system allows the eye to perceive color by either spatially integrating the photons from the sub-pixels or temporally integrating the photons from the sub-pixels.

6.2. Field Emission

The electron sources in FEDs are field emitter arrays. Field emitters work on the principle of electron tunneling from a metal or semiconductor surface into vacuum when a high electric field is applied [58, 59]. Field emission occurs when the energy barrier width at the surface is of the order of the electron wavelength ($\sim 10\text{--}20 \text{ \AA}$). Typical metal and semiconductor surfaces have an energy barrier height of about 4.5 eV that prevents the electrons from escaping into vacuum. This implies a field of about $4.5 \times 10^7 \text{ V/cm}$ is required on the emitting surface. Obviously, this high electric field will be difficult to generate with reasonable voltage using a parallel plate capacitor. However, from electrostatics we know that high electric fields can be generated on surfaces with reasonable voltages if the surface has a small radius of curvature. The electric field at the tip of the curvature is

$$F_{\text{tip}} = \frac{V_g}{kr_0}$$

where F is the electric field, V_g is the applied gate (extraction) voltage, r_0 is the radius of curvature and k is constant that depends on the aperture width and cone height. “ k ” has a typical value of 2–5. For example, a field emitter with a radius of curvature of $50 \text{ \AA}$ will be able to generate a field of $4.5 \times 10^7 \text{ V/cm}$ with an applied gate voltage of about 20 to 100 V.

Advances in integrated circuit technology and micro-machining technology have made the fabrication

of small field emitter structures with nanometer-range radius of curvature (1–10 nm) feasible. There are several approaches to fabricating these microstructures with small radius of curvature. They fall into the following broad categories:

- Point Emitters (Cone Field Emitter Arrays [60, 61])
- Line Emitters (Vertical Edge [62], Ridge [63], Lateral Thin-Film-Edge Field Emitter Arrays [64, 65])
- Micro-textured broad area emitters (Amorphous Diamond Field Emitters [66]).

In general, they are three terminal devices; however, two terminal and four-terminal devices are possible. Electrons are emitted from the cathode (emitter) by the application of a positive voltage to the gate (extraction) electrode with respect to the emitter. Emitted electrons are collected by the anode or phosphor screen.

In the simplest form, the terminal I-V characteristics are given by

$$I_s \sim I_e = a_{\text{FN}}(V_G)^2 \exp\left[-\frac{b_{\text{FN}}}{V_G}\right]$$

where a_{FN} and b_{FN} are constants that depend on the material properties and geometry [60], I_s and I_e are the screen and emitter currents respectively, and V_G is the applied gate voltage. The non-linear and essentially exponential I-V characteristics makes the field emitter array suitable for matrix addressing, without having to use a non-linear switching element such as a TFT in AMLCD.

6.3. Phosphor Screen

The faceplate of the FED is the phosphor screen. It is patterned into stripes or dots of red, green and blue phosphors. Two types of phosphors are used in FEDs. The majority of FEDs currently use low voltage phosphors. These phosphor screens have transparent conductor backing between the glass and the phosphors [51, 56]. Low voltage phosphors are used for two reasons: (i) the need to keep the beam size small requires that the distance between the base plate and the faceplate be kept to a minimum, and (ii) the concern about dielectric breakdown in the vacuum envelope when the distance between the faceplate and the base plate is too small, requires that the screen voltage be kept low. Typical separation between the face-plate and the base-plate is $200 \mu\text{m}$ and the screen voltage is 500 V. Low voltage phosphors have moderate luminous efficiency of about 5 lumen/watt.

Some FEDs use high voltage aluminized phosphors as in a CRT [67–70]. This requires an increase in the distance between the face-plate and the base-plate, due to dielectric breakdown considerations. Typical anode voltage bias is about 10,000 V for a typical base-plate to face-plate spacing. The phosphor is covered on the vacuum side by a thin Al film. High voltages allow the electrons accelerated toward the screen to penetrate the thin Al layer. High voltage phosphors have higher luminous efficiency (~ 25 lumen/watt).

For a given brightness, low voltage phosphors require higher cathode current density than high voltage phosphors. Phosphor lifetime is determined by total Coulomb charge build up. As a result of this high voltage phosphors have a longer life than low voltage phosphors because they (i) require lower cathode current densities for a given brightness and (ii) have higher luminous efficiency.

6.4. *FED Demonstrations*

PixTech of France has demonstrated a 6-in dia. FED with a brightness >100 fL, an intrinsic contrast ratio $>100:1$ and a response time of 2 ms. The average screen power was 0.01 W/cm^2 , and the display had viewing angle characteristics of a CRT [Vaudaine 1991]. The display uses a low voltage phosphor and demonstrated a luminous efficiency of about 5 lumen/watt. Variants of the PixTech technology have been adapted for high brightness application [68] and low power application. These FEDs are based on Mo-cones fabricated by e-beam evaporation.

Micron Display Technology demonstrated an 0.7-in diagonal full color display for Camcorder and head mounted applications. The power consumption of the display is a factor five lower than an equivalent AMLCD display operating at 15 fL. The luminous efficiency is greater than 3 lumen/watt. The Micron FED display is based on Si-cone technology. It was fabricated using reactive ion-etching and chemical-mechanical polishing. A 14" diagonal display is under development [58].

Raytheon adapted the classical cone emitter developed by LETI for high brightness displays by using high voltage phosphors. This was accomplished by increasing the base-plate/face-plate separation and adding a focus grid between the face plate and the base plate. The grid focuses electrons emanating from the emitter on the phosphor. This reduces the spot size and improves resolution. This approach allows

Raytheon to use 10 KV screens and attain very high brightness and luminous efficiency. Brightness of up to 4200 fL flat field and 3500 fL video have been demonstrated with a luminous efficiency of 20 lumen/watt with P53 phosphor. The display is 512×512 , 4" per side monochrome display. They are working on a 512×512 , 6" per side color version [68].

The technologies described above rely on lithography technologies that have $1\text{--}1.5 \mu\text{m}$ gate aperture and require gate voltages of 100 V for device operation. The dynamic power consumed by the addressing circuitry for the display is proportional to the square of the voltage. Furthermore, the high voltage ICs required for driving the FEDs are expensive. The cost of FEDs and driver circuitry can significantly be reduced if the gate operating voltage is reduced. Silicon Video Corporation [69] and FED Corporation [70] have recently demonstrated small displays based on ultra-small gate aperture FEAs which require low gate operating voltage. Furthermore, they use high screen voltage.

The Silicon Video demonstrated a full color 2.4" dia., 1/4 VGA display with 80 lines/inch resolution, and a 120×140 pixel matrix. This display demonstrated a brightness of 20 fL (all white, 50% filter), 20% brightness uniformity, and 16 gray level operation. It uses high voltage aluminized phosphors (P22) operated at 4 kV to achieve high quality color, low power operation and long life. Ion tracking lithography technique has been used to define molybdenum cone emitters with 200 nm gate apertures [69].

The FED Corporation has demonstrated a 2.54" dia., 1/4 VGA display using interference lithography to fabricate ultra-small gate aperture Mo cones. Like the Silicon Video Corp. demonstration display, it uses high-voltage aluminized phosphors. It is a 512×512 -pixel, 256 level gray-scale, 700 cd/m^2 display consuming only 0.25 W. The luminous efficiency is over 30 lumen/watt [70].

6.5. *Research Activities in Field Emitter Displays*

Despite recent advances in FED technology, there are a number of issues that need to be resolved before the technology can reach the market or its full potential. These issues revolve around (i) gate operating voltage, (ii) current uniformity, reproducibility and reliability, (iii) emitter surface conditioning, (iv) luminous efficiency, (v) spacer technology, (vi) vacuum sealing and packaging, (vii) low voltage phosphors and (viii) obtaining high resolution with high voltage phosphors.

Bozler et al. demonstrated the reduction of gate operating voltage by reducing the gate aperture of FEAs [71]. The gate aperture of the devices was 160 nm and was defined using interference lithography (IL). Gate turn-on voltages of 25 V were demonstrated and this was reduced to about 10 V when the FEAs were flashed with Cs. Further reduction in gate operating voltage can be obtained if the aperture is decreased further.

There are several research groups that are developing high aspect ratio field emitter arrays to reduce the capacitance of the field emitters arrays and obtain the nearly ideal field emitter structure proposed by Utsumi [72]. Hori et al. demonstrated a high aspect ratio, tower structure field emitter array with large emission current and low gate voltage operation [73]. The device has high aspect ratio.

Other research activities focus on integrating a focusing electrode with the field emitter array. The purpose of the focus electrode is to reduce the spot size when high voltage phosphors are used and the faceplate-baseplate distance is increased [74–78]. The results of Palevsky et al. indicate that the integrated focusing electrode will be important for high resolution and high efficiency FEDs [68].

7. Summary and Conclusions

Advances in computing and communications are bringing about a paradigm shift in the direction of merging these technologies to provide anytime anywhere access to information, which is driving the development of high performance portable systems such as notebook computers, and wireless multi-media terminals such as InfoPad. These portable systems require thin, light weight, low power displays with a high image quality including high resolution, true color, and full motion video. The display is expected to handle a variety of data types such as text, graphics, and high resolution true color full motion video. Display is a critical subsystem of the portable system because it is the primary man-machine interface, and has a major impact on the system power consumption, and thus the battery life between charges. Currently, backlit AMLCD is the best display choice for a high performance portable system such as the present notebook computer, or the future wireless multi-media terminal. However, significant improvements in AMLCD performance are required to meet the requirements of the future portable systems. The areas of required improvements include power consumption, brightness, viewing angle,

grayscale, color rendition, cost etc. Meeting these future display requirements of reduced power consumption and cost, while significantly increasing the resolution, size, optical performance and functionality is challenging. Innovative light management techniques, reflective polarizers, reflective color filters, low voltage display driving, and integration of driver electronics on display glass are needed to address future performance requirements. Reflective LCDs offer a very low power display solution for portable systems where low power is of paramount importance. The current emphasis on the reflective color LCD development effort is expected to lead to improvement in the image quality of these displays, for application to certain niche applications. Reflective LCDs are not expected to match the image quality of the backlit TFT-LCD under a wide range of ambient lighting conditions.

Field emission display (FED) development is coming out of the research stage, and into the proto-type development phase. FED technology has made significant progress in recent years, and the performance of proto-type FEDs continues to improve rapidly. This technology continues to show potential for low power displays with high image quality which is required for the future portable systems. Longer term, FEDs may be an attractive alternative to LCDs for portable applications.

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