Project - LCD FAQs

Autor:
Data de publicació: 06-03-2017

LCD Frequently Asked Questions
from wayback machine: http://www.ee.washington.edu/circuit_archive/text/LCD.html

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Liquid Crystal Display (FAQ) Frequently Asked Question

Fundamental Liquid Crystal Display Technology: a multi-part introduction for the basic understanding of Liquid Crystal Displays

Version 1.00 August 18, 1993 By Scott M. Bruck

This FAQ should be printed in 9 POINT MONACO FONT

Since the introduction, rapid decline in price, and increased availability of notebook computers capable of operating Graphical User Interfaces (GUIs--MacOS and Windows), there has been an increased interest in flat panel display technology. A notebook/palmtop computer requires a light weight, durable, and reliable display. Liquid Crystal Display technology has met these requirements and as a result, virtually all notebook computers are equipped with some form of LCD. This FAQ is intended to address the general confusion concerning LCDs that has arisen recently by explaining the technology, operation, and characteristics of this important display device.

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2) A list of TFT display manufacturers is summarized and a list of what notebook computers use what TFT display.

3) Solutions to questions proposed on Internet news groups not covered in the body of the LCD FAQ text.

LCD FAQ Part I: Liquid Crystal Display Fundamentals

1.0 General Characteristics and LCD Modes

Liquid Crystal Displays (LCDs) are categorized as non- emissive display devices, in that respect, they do not produce any form of light like a Cathode Ray Tube (CRT). LCDs either pass or block light that is reflected from an external light source or provided by a back/side lighting system. There are two modes of operation for LCDs during the absence of an electric field (applied Power); a mode describes the transmittance state of the liquid crystal elements. Normal White mode: the display is white or clear and allows light to pass through and Normal Black Mode: the display is dark and all light is diffused. Virtually all displays in production for PC/Workstation use are normal white mode to optimize contrast and speed.

1.1 LCD Cell Switching and Fundamentals

A simplified description of how a dot matrix LCD display works is as follows: A twisted nematic (TN) LC display consists of two polarizers, two pieces of glass, some form of switching element or electrode to define pixels, and driver Integrated Circuits (ICs) to address the rows and columns of pixels. To define a pixel (or subpixel element for a color display), a rectangle is constructed out of Indium Tin Oxide -- a semi-transparent metal oxide (ITO) and charge is applied to this area in order to change the orientation of the LC material (change from a white pixel to a dark pixel). The method utilized to form a pixel in passive and active matrix displays differs and will be described in later sections. Figure 1 illustrates a cross sectional view of a simple TN LC display. Figure 2 depicts a dot matrix display as viewed without its metal module/case exposing the IC drivers. Looking directly at the display the gate or row drivers are located either on the left or the right side of the display while the data or column drivers are located on the top (and or bottom) of the display. New thin display module technology mounts the ICs on conductive tape that allows them to be folded behind the display further reducing the size of the finished module. An IC will address a number of rows or columns, not just 1 as pictured in figure 2.

Figure 1: Cross Section of a Simple LC Display

```
      viewer
////////////////////////////////////  Polarizer
_________________________________________ glass
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ Liquid Crystal
_________________________________________ glass
\\\\  Polarizer
      backlight
```

Figure 2: LCD panel and IC driver locations

```
____________________________________________
|    |
|  IC IC | Source/Column ICs
|  |  |
|  |  |
|IC---------------------Pixel  |
|    |
|IC <---- Gate Line/Row IC  |
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

* An IC driver will address a number of row/column lines and

not just the single pixel in the diagram above

Polarizers are an integral part of a LCD display, possessing the unique property of only passing light if it is oriented in a specific (oriented) direction. To utilize this phenomena in TN LC displays, the bottom polarizer orients incoming light in one direction. The oriented light passes through the LC material and is either unaltered or "bent" 90 degrees. Depending on the orientation of the top polarizer, this light will either pass through or be diffused. If the light is diffused, it will appear as a dark area. Figure 3 is a simple illustration of the sequence of events that occur when light passes through a simple twisted nematic LC display.

Figure 3: Polarized Light and its use in a TN LC display

Light (unoriented) will be defined as: !#$%&|-
Polarizer Orientation is defined by: ($ or #)
($ polarizer will only pass $ light)
(# polarizer will only pass # light) THEREFORE:

```
Light  Polarizer   result   LC (90   result  Polarizer   Image
Input  type        passed   degree   passed  type        output
       twist)

!##$%%&|-> |  #  | -> #### -> ~~~~~ -> $$$$ ->| # | ------> Black

!##$%%&|-> |  #  | -> #### -> ~~~~~ -> $$$$ ->| $ | ------> White
```

1.2 Liquid Crystal Material

1.21 Fundamentals

Please note, I am not a chemist, so I will keep this section as simple and concise as possible. Liquid crystals encompass a broad group of materials that posses the properties of both a solid and a liquid. More specifically, they are a liquid with molecules oriented in one common direction (having a long range and repeating pattern-- definition of a crystal), but have no long range order in the other two directions. For example, in figure 4 all the lines are oriented in the Y direction (up and down), but they posses no common ordering in the x direction (disorder is assumed in the Z direction). To more easily visualize this, think of figure 4 as one thin slice (one layer of molecules to be exact) of a block of material. If you examined another slice, the molecules would still be oriented in the Y direction, but they would be in different positions along the X-axis. By stacking millions of these thin slices, the Z direction is built up and as a result of the change in relative position on the x-axis, the Z direction has no long range order.

```
^ Y
|           Figure 4
|
|
|
|   ||||   |||    ||     |      |||||
|
|      ||||||||    ||||||||||||     ||||    |
|
|   ||||||      |||||       ||||    ||||
|  |||||||
|
|----------------------------------------------------> X
```

* The Z direction is coming out of the page toward the reader

The liquid crystals used for display technology are thermotropic liquid crystals; they exhibit desired characteristics over a specific temperature range. This is the primary reason why LCDs do not operate properly when they are too cold or too warm. If liquid crystals are too cold, they will not twist and the display will not form an image. If the display is too warm, the resistance of the liquid crystal material changes and this alters the properties of the display and performance suffers. Liquid crystal material for display use is normally referred to as TN (STN, DSTN, MSTN, and etc.) or Twisted Nematic--sometimes known as TNFE or Twisted Nematic Field Effect. It is called TWISTED since the crystals are twisted 90 degrees (or more for STN) from the top piece of glass to the bottom piece of glass. (TN usually refers only to a 90 degree twist.) Field Effect (a direct correlation is the semiconductor MOSFET), refers to the LC material's ability to align parallel or perpendicular to an applied electric field. As a result, using twisted or untwisted liquid crystal and two polarizers; an applied electric field can force the LC material into a particular alignment effectively diffusing or passing light through the top polarizer.

As a note of interest, polarizers are also one of the major reasons that LC displays require bright back lighting. The polarizers and liquid crystal materials absorb more than 50% of the incident light. As a result, even though the actual display is a very low power device, the power hungry back lighting makes a LCD module one of the primary causes of short battery life in notebook computers. Due to the fact that the LC material has optical properties and effectively bends light, the problem of viewing angle effects occur. When the user is not directly in front of the display the image can disappear or seem to invert (dark images become light and light images become dark). However, LC material and polarizer technology is rapidly improving and that improvement is showing up in brighter displays with greater viewing angles.

1.22 Liquid Crystal Alignment

Liquid crystals must be aligned to the top and bottom pieces of glass in order to obtain the desired twist. In other words, the 90 degree twist is formed by anchoring the liquid crystal on one glass plate and forcing it to twist across the cell gap (the distance between the two glass plates) when contacting the second plate. Furthermore, The actual image quality of the display will be dependent on the surface alignment of the LC material. The method currently used for aligning liquid crystals was developed by the Dai-Nippon Screening (English= Big Japan Screening) Company. The process consists of coating the top and bottom sheets of glass with a Polyimide based film. The top piece of glass is coated and rubbed in a particular orientation; the bottom panel/polyimide is rubbed perpendicular (90 degrees for TN displays) with respect to the top panel. It was discovered that by rubbing the polyimide with a cloth, nanometer (1 X 10 - 9 meters) size grooves are formed and the liquid crystals align with the direction of the grooves. It is common that when assembling a TN LC cell, it will be necessary to eliminate patches of non- uniform areas. The two parameters required to eliminate the nonuniformities and complete the TN LC display are pretilt angle and cholesteric impurities. TN LC cells commonly have two problems that affect uniformity following assembly: reverse tilt and reverse twist. Reverse tilt is a function of the applied electrical field and reverse twist is common when no electrical field is applied. Reverse twist is eliminated by the introduction of cholesteric additives and reverse tilt is eliminated by introducing a pre-tilt angle to the LC material. The pre-tilt angle also determines what direction the LC molecules will rotate when an electrical field is applied. Pre-tilt angle can be visualized by considering the normal position of the LC molecule to be flat against the glass plate, by anchoring one edge and forcing the other upward by a specific number of degrees, a pretilt angle is established.

1.23 Liquid Crystal Display Names and classes

Before discussing the different types of LC displays the topic of Birefringence must be explained. When a light ray strikes a crystal (or crystal-like material), it will be split into two separate light beams; with one beam perpendicular (offset by 90 degrees) from the other. Since the beams travel different paths, they reach the viewer's eyes at slightly different times. This is an essential point, it may cause the color or polarity of the display to change when viewed at angles where the viewer may see both rays.

For active matrix displays, in order to maximize contrast and gray scale reproducibility, Twisted Nematic (TN) is utilized. This material is twisted 90 degrees from the top to bottom glass panels. STN or Super Twisted Nematic is chemically distinct from TN and the twist angle is usually greater than 200 degrees. Furthermore, due to the large twist angle, the actual alignment of the polarizers for STN LCDs are not perpendicular, but adjusted to find the best direction (rotation) for optimum display characteristics. The STN material is rotated in a way so the change from transmission to dispersion is very abrupt and therefore can respond quickly to small changes in voltage. Figure 5 illustrates the response characteristics of a TN curve and Figure 6 shows the response characteristics of a STN curve which will further clarify these points.

100% | Figure 5
| Typical Response of a Normal White TN Display

```
T |
R |************
A |           *
N |             *
S |<-- Zone I->     *
M |                  *
I |                  *
T |                    *
T |                      *
A |                        *
N |           <----Zone II--- * --------->
C |                            *
E |                              *      <--Zone III-->
 |                               *
 |                                 *
 |                                   *************
0% |______________________________________________________________>
              Vt (Threshold Voltage)
 Applied Voltage
```

1.24 The TN Liquid Crystal Response Curve

The most prominent feature of the TN response curve is the central linear region between the two flat areas (Zone II). Zone I describes the white color of the display when no electric field is applied. In other words, the display will transmit virtually all the introduced light. On the other hand, in Zone III, the display will diffuse light and appear dark. The middle region can display gray scale or an image somewhere between White and Black. The key point here is that you must be able to very carefully control the voltage applied to the LC cell and maintain it for one duty cycle (before that pixel is addressed again) in order to produce accurate colors. For this reason, this type of LC material is primarily used for active matrix LCDs.

COMMONLY ASKED QUESTION NOTE: because the LC material is partially twisted in the gray scale area, when looking at a display at an off angle the colors tend to shift and sometimes invert due to birefringence.

COMPUTER APPLICATION NOTE: The TN response curve does not have to be utilized for gray scale, in order to make a simpler display, improve viewing angle, and use cheaper IC drivers; the Apple Powerbook 170's TFTs (thin film transistors) drive the TN response curve directly into region 3. This gives all the speed/contrast advantages of a TFT display and cheaper manufacturing cost, but provides no gray scale.

1.25 The STN Liquid Crystal Response Curve

The Key to understanding the STN curve is simply that due to the addressing method applied, only a small amount of voltage is available to change the LC material from transmittance to a dispersion state. For this reason, the shape of the curve has nearly a 90 degree shift between Zone I and Zone II regions; in other words, it goes ballistic and nearly straight up ! This property allows the LC material to shift from white to black at its threshold voltage (VT) without being concerned with partial transmission (gray scale). Furthermore, the 90 Degree curve shape means that gray scale is not available from the LC material itself and the driving circuits must provide the necessary fixes for levels of gray.

STN displays inherently have a yellow on blue appearance (anyone remember the old Zenith Laptops ?). Because many individuals found the yellow and blue appearance undesirable, a number of techniques were developed to convert the STN image to a black on white scheme. DSTN, developed by Sharp Corporation, was the first commercial black and white conversion of the STN display and refers to Double Super Twisted Nematic. DSTN displays are actually two distinct STN filled glass cells glued together. The first is a LCD display as described previously, the second is a glass cell without electrodes or polarizers filled with LC material for use as a compensator which increases contrast and gives the black on white appearance. The drawbacks are a heavier module, a more expensive manufacturing process, and a more powerful backlighting system.

FCSTN is Film Compensated STN and is now the most commonly used STN display technology on the market. FSTN, monochrome STN, and Polymer film STN are all standard STN displays with a polymer film applied to the glass as a compensation layer instead of the second cell as in the case of the DSTN. This simpler and more importantly cost effective method provides the preferred black on white image for this display technology. However, once again, this design lowers the transmittance of light and requires a more powerful back lighting system.

COMMONLY ASKED QUESTION NOTE: Why are STN displays slow ? Due to the method used to address passive matrix (STN/DSTN) displays and the high density of pixels required for standard VGA displays, the liquid crystal material must respond to an extremely small change in voltage. In developing these materials for this voltage characteristic, there was a reduction in the switching speed. A slow display can best be illustrated by the tendency of the cursor to "submerge" or disappear when rapidly moved across the screen. Another common example is the blurring of images when they quickly move across the display as in the case of high speed games. A fast display is less than 40 milliseconds, most STN type displays are between 200 and 250 milliseconds. However, some new LC mixtures are reaching 150 millisecond speeds.

COMMONLY ASKED QUESTION NOTE: What is Contrast ? Contrast is defined as the ratio of black to white, more simply put, how black is black when next to a white or clear pixel. In terms of numbers, passive matrix LCDs are usually able to produce a contrast ratio of approximately 13 - 20:1; in real terms you get a set of different grays and blues but no true blacks.

```
100% ^
 |                  Figure 6
T |
R |    ********
A |           *
N |            *
S |<-Zone I----> *<-----------Zone II--------------------->
M |             *
I |            *
T |             *
T |             *
A |            *
N |           *
C |          *
E |         *
 |        *
 |        *
 |        *
 |         *
 |      *************************
0% ----------------------------------------------------->
  Vt Threshold Voltage
 Applied Voltage
```

1.3 Liquid Crystal Display Assembly

Once the switching devices or electrodes have been fabricated on the glass halves and the polyimide film has been applied & rubbed, spacer balls (usually 4 to 8 micrometers [1 X 10 - 6 meters] in diameter) are sprayed on one half of the display. Spacer balls are used to insure that the glass plates remain a certain distance apart over the entire area of the display; this is also known as cell gap. If the cell gap is not uniform, an image will appear different from one end of the display to the other. If the spacer balls are not applied correctly, they will collect and the user will be able see them as strange areas of non-uniform dust or distortion. (Single spacer balls are too small to see and they are not black dots.) If the Display has a very large cell gap, when you apply slight pressure to the display by touching it with your finger, you will see the image change and the LC material shift under the glass. Doing this does not damage the display, but take care when bringing any sharp objects, such as pen or pencils, near the screen; it is very easy to damage the polymer film and or polarizers on the display.

The two glass panels are then aligned and glued together with an epoxy. During panel assembly, if dirt is trapped between the two glass plates, you most likely will see these as annoying spots on the display. During the application of the glue, one corner is left open. In a vacuum chamber, the liquid crystal material is drawn into the display through the open corner. Upon completion, the remaining hole is filled with another epoxy. The LC material will align itself to the grooves in the polyimide and spread out around the spacer balls.

After final assembly, excess glass is cut and driver ICs are mounted. The finished display is mounted onto a backlight assembly (also known as an inverter assembly) and encased in metal. There are a number of methods for backlighting a LC display. STN displays usually have a side, top, or bottom lighting system. In simple terms, this is where the fluorescent tube is mounted. For example, in a side-lit display one or two fluorescent tubes will be located at the left and or right edges of the display. A fluorescent tube normally 4 mm in diameter is used. This is dispersed by a plastic plate around the entire area of the display. A dispersion plate looks like a white sheet with small holes; each of the holes provides a small point of light. On top of the dispersion plate, a diffuser is placed. A diffuser takes the numerous points of light and uniformly spreads it out over the entire area of the display. The net effect is providing a backlighting source around 4 or 5 mm thick !

An Active matrix display, especially color modules, transmit much less of the incident light and require more elaborate backlighting systems. An active matrix TFT display has a matrix fabricated on one piece of glass; the metal lines and transistor elements are not transparent and block a significant percentage of light. In order to obtain higher contrast, newer displays incorporate what is called a black matrix. This is a black film that surrounds the pixel elements (this can be on the matrix, but is usually around the color filters); although this yields higher contrast, it also reduces brightness. Further complicating this, the polarizers and the color filters reduce the output to less than 5% of the incident light. As a result, most backlighting systems designed for active matrix based displays usually consist of 4 or 5 four mm tubes placed directly behind the display with a diffuser plate to insure uniform irradiation. Therefore, they are called backlit. This method of lighting makes the display slightly larger, heavier, and greatly increases power consumption. The final metal encased display is called a display module or sub-assembly and this is what the end user or notebook manufacturer receives.

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Acknowledgments:
I would like to thank Mike Schuster (SCHUSTER@PANIX.COM) for commenting on clearness and general understanding while compiling this FAQ.

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LCD FAQ Part II: Addressing and Color Technology (Passive and Active Matrix Displays)

2.0 General Overview:

Addressing describes the method employed to transfer charge (data or the display image) from the outside world to the display. Unlike a CRT, which is just a surface of phosphors scanned with a beam of electrons in a vacuum, a liquid crystal display is an array of conductors with metal (or metal like) lines running in both horizontal and vertical directions. For the case of a CRT, the electrons travel through a resistance free medium (vacuum) and deliver a clear consistent signal. The charge traveling through the metal lines of a LCD matrix is affected by the properties of the metal. As a result, the magnitude and waveform of the applied charge can vary from one end of the display to the other. This variation imposes limitations on display quality and capabilities.

2.1 Addressing: Passive and Active Matrix Displays

There are distinct differences between active and passive matrix displays, but two factors make the greatest impact on potential customers. Active matrix displays can cost twice as much as an equivalent passive matrix display and add more than $1000 to the cost of a notebook form-factor computer. However, active matrix displays produce a stunning and bright image without ghosting or artifacts that rivals the quality of CRTs. Furthermore, even with the price differential, manufacturers are able to sell every active matrix color notebook they can produce.

2.11 Liquid Crystal Cell Charging

In general terms (regardless of display type), in order to protect the liquid crystal material from deteriorating, cells are addressed by alternating current (AC), not direct current (DC). There is no resultant charge in the LC material following two addressing cycles; build up of charge in the LC material will permanently damage it. In other words, a positive and then an equal but opposite negative charge is applied to the LC material every other frame. By applying dual polarity addressing, the LC material changes twist direction every other cycle and the net charge is zero. Furthermore, since the liquid crystal material is changing twist directions every other cycle, screen savers or screen inverters are not required and in reality do absolutely nothing. Passive matrix displays utilize DIRECT ADDRESSING; the charge is applied directly from the drivers to the pixel element. Active matrix displays utilize INDIRECT ADDRESSING; the charge is "filtered" through a switch before reaching the pixel element.

2.12 Driving Methods: Passive Matrix Displays

Passive matrix displays have rows of electrodes on one half of the display glass and columns of electrodes on the other. The electrodes are usually fabricated out of Indium Tin Oxide (ITO), which is a semi-transparent metal oxide. When the two pieces of glass are assembled into a display, the intersection of a row and column form a pixel element. Furthermore, if a pulse is sent down one row and a specific column is grounded, the established electric field can change the state of liquid crystal(from white to black). By repeating this process (display scanning) an image can be formed on the display. Problems arise as the number of rows and columns increase. With higher pixel density, the electrode size must be reduced and the amount of voltage necessary to drive the display rapidly increases. Furthermore, higher driving voltage creates a secondary problem; charging effects. Even though only one row and column are selected, the liquid crystal material near the row and column being charged are affected by the pulse. The net result is the pixel selected is active (dark), but the areas surrounding the addressed point are also partially active (grays). The partially active pixels reduce the display contrast and degrade image quality. A final problem is the speed of the STN material, a display must be able to react in less than 40 milliseconds for performance similar to a CRT. Most STN materials are between 150 and 250 milliseconds and can not switch from black to a white image that quickly. This problem results in disappearing cursors and blurred images when high speed graphics are utilized

COMMONLY ASKED QUESTION NOTE: What is STN Gray Scale ? As discussed in part I section 1.24, the STN curve does not possess an intrinsic gray scale capability like the TN curve, therefore driving methods have been developed to create the illusion of true gray scale. Gray scale can be derived from frame-rate control and dithering/space modulation. Frame-rate control quickly switches on and off a pixel, the eye perceives this as gray. Dithering or space modulation is accomplished by alternately keeping some pixels black and some white in a checkerboard layout; when using this method, the layout is in a random order. If dithering is in a regular (repeating) pattern, it is detectable by the human eye. In real world applications, combinations of both technologies are applied to commercial displays. The result, however, is sometimes wavy or moving grays. (The image appears to be moving in waves or a solid color appears to be in motion when a large area is set to a specific gray level.)

RECENT TECHNOLOGY NOTE: What are Dual Scan STN Displays ? This is simply taking currently made color STN displays and applying some previously developed technology. Back in the late 1970's and early 1980's liquid crystal chemistry was not as advanced and in order to build high data content displays, manufacturers were forced to build two displays on one glass plate. A dual scan display utilizes similar technology. Instead of running the columns down the entire display, they are terminated in the center of the display, a small gap is left, and the line is continued to the bottom of the display. In reality, you now have two 640 X 240 displays on one glass plate. Therefore, if IC drivers are mounted on the top and the bottom of the display, the charge must only travel half the distance of a normal display. As a result, the effects of the contrast limitations discussed in section 2.12 can be reduced. The end result appears to be a brighter display, but in reality it is only improved contrast (the blacks appear darker). The dual scan STN display still suffers from the ghosting and artifact problems inherent in all slow STN displays.

2.13 Driving Methods: Active Matrix Displays

In order to eliminate the problems of the STN/passive matrix display, the active matrix display was developed. Active matrix displays have a thin film Transistor or diode on the glass substrate that indirectly addresses each pixel element. Depending on the display type, application, or manufacturer, the TFT may be comprised of amorphous silicon (a-Si) or polycrystalline silicon (p-Si), The TFT completely isolates one pixel element from the others in the display and eliminates the problem of partially active pixels. Simply put, the TFT acts as a switch ! When a row of TFTs are addressed the gate lines are active-- the switch is turned on, this allows charge to flow from the columns into the pixels and set the image for the frame cycle. Once a row has been addressed, the gate line is reversed biased (the switch is turned off) to insure that no charge can pass from the columns into the pixel element. Thus, the pixel is now completely isolated as the rest of the display is addressed. The LC material acts as a capacitor and stores charge. After a charge is placed on a liquid crystal cell (the defined pixel area), it begins draining similar to a discharging capacitor (an exponential function). As a result, unless the display can be written quickly (all 480 rows scanned and the return to the top of the display to rescan starting from row 1 for a VGA display) the image will not be uniform from the top to the bottom of the display as the LC material starts to untwist. In order to insure charge storage for one frame and carefully control charge on a pixel element, TFT displays incorporate a second capacitor in parallel with the LC material. The combined capacitance gives active matrix displays the essential capability to accurately maintain the amount of charge applied; thus reliable partial charges can be utilized and gray scale or full color displays are possible. With proper drivers and high quality TFTs, 256 gray scales have been obtained with quality that surpasses that of CRTs. TN material can also switch much faster than STN, thus 40 millisecond TFT displays are common yielding CRT like speed.

COMMONLY ASKED QUESTION NOTE: What is cross Talk ? Cross talk is best described as the effect when a dark image (box or widow shape) is placed in the middle of a white background. Faint vertical and horizontal lines will be seen from the edge of the window proceeding to the edges of the screen. This can be caused by poorly designed drivers or poorly made TFTs. The off selected TFTs are not completely off and some charge, very strong at the edge of a window, has leaked into the pixels creating the effect. This is a common problem and is being addressed by the manufacturers of TFT based displays.

2.2 Color Display Pixel Layout and Yields

In order to build a fully functional color VGA display, a TFT LCD must have 480 X 640 X 3 pixel elements. The 640 X 480 is the well understood VGA pixel layout (640 X 400 for the Apple Powerbook series and 640 X 480 for the 180c), except 640 red, 640 green, and 640 blue columns or stripes of color pixels are now required. This is a total of 921,600 TFTs that must work in order to build a perfect display. Using a semiconductor analogy, it is similar to building a 1 Megabit DRAM on a 10 inch glass plate; not an easy task considering a particle smaller than the diameter of the human hair can destroy a single TFT. Achieving a 100 % yield or a perfect display is virtually impossible, thus even though manufacturer yields are starting to reach 60% (for sellable devices) prices are very high. Furthermore, if 4 defective pixels are found on a color VGA screen, this already represents a 99.99 % pixel yield-- not bad for any process. For the most part, the most common pixel defect is caused by some form of contamination damaging a TFT and preventing it from turning the pixel off (seen as bright spots on a dark background). There are two layouts for pixels on TFT displays. The most common for computer applications is the STRIPE layout. A stripe layout has repeating stripes of red, green, and blue columns across the display. For multimedia and high density arrays (projection LCD modules), a triad pixel layout is used. A triad layout has the three color sub-pixels in a triangle shape.

Figure 7 illustrates the difference between the two layouts.

Figure 7: Color Pixel Layouts

Stripe Layout   Triad Layout

RGB RGB RGB   R   R   R
RGB RGB RGB   G B   G B   G B

Note: What is a color filter ? A color filter works by absorbing specific wavelengths of light and only passing light of a certain wavelengths (In other words, a red filter will remove all wavelengths of light except for red -- thus it looks red !). White light is made up of a spectrum of wavelengths, so it can yield the red, green, and blue for displays. However, when filtering out the unwanted wavelengths, the overall brightness is reduced.

COMMONLY ASKED QUESTION NOTE: What is a pixel ? Unfortunately, in most of the literature and magazines, there is not a clear definition as to what a pixel is. In its most basic form, a pixel is described as one element on a display screen. For a monochrome screen this is an adequate description. However a color pixel is actually made up of three subpixels: a red, green, and blue pixel. This is sometimes called a pixel triad. Therefore care must be taken in describing pixels. In terms of this document, a pixel is the entire element consisting of red, green, and blue sub-elements. A subpixel consists of the individual red, green, or blue elements. Gray scales for LC displays are always calculated as a function of subpixels.

2.3 Color Displays: Gray Scales and Bits

Due to the overall poor performance of Passive Matrix color displays, only active matrix displays will be specifically discussed. However, major points are applicable to both display addressing technologies. Unlike an analog CRT, in a digital color TFT active matrix display, you literally get what you buy...forever. Even if you upgrade to a new video driver or display card, you will still have the same number of colors and gray scales. The number of colors is a direct result of the number of gray scales a display can reproduce. The standard VGA format is rated to display 256 colors, however it can select from a 18 BIT CLUT (color look up table) which means the choice of 262,144 colors(this calculation is based on a bit calculation for a pixel triad -- 2 ^ 18 --- see later section on calculations). Intrinsic gray scale reproducibility for TFT displays is a result of two factors: the quality of the driver ICs used on the display and the resistance of the gate metal(the rows of the display). The gate metal must carry a clear and undeformed pulse from one end of the display to the other(640 X 3 = 19200 lines). If the pulse is not maintained the TN curve will not charge to the desired level and the correct color can not be displayed. Therefore, the more gray scales required, the greater the control that must be exerted over the gate lines. For example, most displays sold today can display 256 colors out of 4092 or 512. The 256 colors is based on the VGA video controller, the 4092 is a display limitation. 4092 possible colors indicates that a display can reproduce 16 gray scales. This is derived from 16 (red) X 16 (blue) X 16 (green) = 4092 possible colors. Once again, dithering can be used to extend this, but there are displays in limited production that can reproduce 256 gray scales or more than 16 million colors ! Most current TFT color displays feature 3 bit drivers (where 2 raised to the third power yields 8); these drivers can produce a total of 512 colors. This is more than adequate unless later on you decide you wish to pursue some multimedia functions which require more than 32 levels of gray scale. Although the controller and the computer may be fast enough to handle the functions, 8 or 16 gray scales will be inadequate-- your image will not be what you expect (It will look like a collection of color shadows). Sharp has recently demonstrated 10 inch 640 X 480 displays running on Apple Macintoshes displaying 64 gray scales. These 6 bit drivers are supposedly entering production and will enter the commercial market shortly. The color reproduction of these displays is excellent.

2.4 Understanding Digital Color Pixels

4 Bits, 8 Bits, 16 Bits, 24 Bits Just how many colors can they actually generate ? Digital video divides the number of colors or gray scales into a distinct number of points. Based on these "POINTS" the system can generate a fixed number of colors or gray scales. Manufacturers tend to play games with numbers, so sometimes it is very difficult to understand "BIT" color talk. First of all, the bit system is based on the binary system so: 1 Bit color, which is 2 raised to the first power is 2. In other words a black & white display where the pixel has a state of being either on or off. This can currently be extended to 24 bits which (at 2 to the 24 power) yields more than 16 million gray scales. OK, now that

we understand how gray scales are calculated, lets convert this to a color display: Once again, manufacturers play a game with numbers and here we introduce bpp or BITS PER PIXEL. Now depending on manufacturer, a pixel can be made up of 1 subpixel (the individual Red, Green, and Blue pixels) or can be a composite of all three colors. If we examine a 16bpp system the following calculations are applicable: 2 raised to the 16th power is: 65536. So if the system is 16 bpp for the combined primary colors, the system can produce a total of 65536 colors. If the system produces 16 bpp for all three colors then 65536 X 65536 X 65536 = 2.8 X 10^14 colors. The small table below summarizes the Bits confusion. Triad Pixel refers to a combination of the RED/GREEN/BLUE pixels. Subpixel refers to the individual red, green, or blue pixel. The number of gray scales for a monochrome display is always the same as a triad calculation bpp display. The numbers listed down the columns refer to how many gray scales or colors that a system configuration can produce. CRT based color is usually calculated as the triad pixel calculation.

Bits/Colors	Mono or Triad Pixel	Subpixel (R/G/B)
1	2	8
4	16	4096
8	256	1.68X10^7
16	65536	2.81X10^14
24	1.68X10^7	4.72X10^21

COMMONLY ASKED QUESTION NOTE: What is analog video ? Unlike digital or bit based video analog video is based on a continuous flow of data. The wave form can be thought of as a continuous wave of points with the distance between points so small that it is impossible to differentiate between them. In other words, it can theoretically provide an infinite number of gray scales. VGA is an analog system and VGA CRTs are analog displays. The advantage of an analog display is that when you upgrade your video card and drivers to handle more colors, your existing monitor should be able to operate with the extended color ranges. NEC makes an analog XVGA TFT LCD, but due to power handling requirements, it is not suitable for battery based portable computers.

COMMONLY ASKED QUESTION NOTE: Why are TFT Color Displays Expensive ? There are numerous reasons for this. As discussed above, displays with large numbers of defective pixels can not be sold and as a result, yield is usually thought to be the major problem. In reality, one should be aware that the largest cost of TFT displays are the materials utilized for production. Since Japanese manufacturers have not standardized the size of displays yet, each manufacturer has specific material needs (glass, holders for machines, robots, and etc.). This fact alone keeps display prices extremely high since material and machine suppliers can not make standard parts for an entire industry at this time.

COMMONLY ASKED QUESTION NOTE: How many gray scales are required for multimedia operations ? Usually 64 gray scales or more are required for true multimedia operations. TFT LCDs with 64 gray scales will probably be available in volume within a year.

COMMENT: Why are some color TFT displays much brighter than others ? The brightness of a screen is determined by two related factors; the size of the screen and the aperture ratio of the pixels. On the surface of an active matrix array there are both pixels and electronics, as a result of the opaque electronics, some of the area that light could pass through is blocked. The ratio of light passing through the pixel to the entire area of the pixel and associated electronics is called the aperture ratio. The larger the ratio is, the more light that can pass through the pixel and the brighter the image on the display will be. Furthermore, if the display itself is bigger, there is more room for the pixels and the result is more light passing through the individual pixels. For this reason, DTIs 10 inch display found in the IBM Thinkpad 700c is much brighter than some of the smaller 8.4 and 9.5 inch TFT displays.

2.4 Basic Principles of TFT Operation

For all intensive purposes, a TFT can simply be considered a switch; when selected (on) it allows charge to flow through it and when off it acts as an barrier preventing or at least restricting the flow of charge. As mentioned earlier, a TFT is a MOS FET device or a Metal Oxide Semiconductor Field Effect Transistor. The gate line can be considered the "switch" of the transistor, with this you turn it on, partially on, or off. The Source and drain are the entrance and exit, respectively, for the charge you want to pass through the switch. In the case of a display, this is the charge that you want to appear on the pixel. Looking at Figure 7, source and drain metal electrodes are separated by an amorphous silicon (a-Si) semiconductor layer; with the absence of charge the a-Si layer acts as an insulator or resistor and prevents the flow of charge from the source to drain; thus isolating the pixel from the rest of the display. SiNx or silicon Nitride is the gate insulator and forms the gate dielectric; electrons do not pass from the gate line into the transistor, but are used to influence the charge distribution in the semiconductor layer. A MOS FET that fits this description (you turn it on)is called an enhancement device. When a positive charge is placed on the gate line, electrons (or negatively charged particles) will begin to collect in the area above the gate, on the other side of the Silicon Nitride (SiNx) in the a-Si. When the charge on the gate is increased to a certain point, called the VT or threshold voltage, enough electrons will have collected in the a-Si to change it from an insulator to a conductor. In other words, you build up a channel of electrons, so if there are electrons at the source (high) and nothing at the drain (low), the electrons will begin to move through the electron filled channel until the charge is the same at both sides or you turn the transistor off. The result is a charging of the pixel and a change in the state of the liquid crystals. The unique aspect of this device is the nonlinear characteristics after the TFT passes through Vt. It exponentially moves to a conduction state (usually 6 to 8 orders of magnitude) and makes it very easy to turn a TFT on or off around the Vt value. For more information on MOS FET device operation, pick up a book on Semiconductor Physics or Solid State Physics. The above is only meant as a basic simplified description of MOS device operation.

2.5 TFT Connections

The gate line of the TFT determines whether or not the TFT will pass a charge into the pixel. These are controlled by the row bus-lines. On a standard VGA display, the gate lines would be the 480 horizontal lines. The source lines of the TFT are connected to the column or data bus-lines. These lines provide the charge for the pixel or contain the data for the image. The drain lines of the TFT are directly attached to the ITO pixel, this transfers the charge from the semiconductor region into the pixel.

Figure 7: Thin Film Transistor Cross Section

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^^^^^^^^^^^^^^^^^^^^^^^^^^^ ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
 Source Metal ^ ^ Drain Metal
   ^ ^
     $$$$$$$$$$$$$$$$$$$
     $ SiNx      $
 *******************************************
 *  a-Si Semiconductor  *
*********       *************
  ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  ~  SiNx     ~
  ~    ___________________      ~
~~~~~~~~~~~~~~~~~~  |        |    ~~~~~~~~~~~~~~~~~~~
     | gate       |
______________________________________________________________

   glass

______________________________________________________________
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Acknowledgments:
I would like to thank Mike Schuster (SCHUSTER@PANIX.COM) for commenting on clearness and general understanding while compiling this FAQ.

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