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# LIQUID CRYSTAL DISPLAY TECHNOLOGY

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## INTRODUCTION

As the display in most imaging systems is the final medium through which an image is rendered for manipulation and verification, an understanding of display technologies is essential to the imaging process. Because individuals

flexibility, the display could be closely matched to a specific application because user requirements were well defined. This custom design approach enabled optimizing the graphics controller, system software, and user interface for the display, user, and application requirements. Despite the positive attributes of this "black-box" approach, such as high performance and superior application specific image quality, closed architecture platforms tend to be more expensive and suffer from incompatibility with peripheral add-ons and software packages not supported by the system manufacturer.

Today, the situation is dramatically different due to the continual evolution of the graphics controller interface. By mixing images with text and graphics, software developers require more from the display to support moving images without diminishing display performance for static images. The graphical capability of today's standard computer platforms has now made it unprofitable for vendors of imaging systems to develop their own displays for system-specific tasks. End users now typically purchase a computer platform, display, and a variety of other peripherals from multiple vendors and integrate them with ease (i.e., a plug-and-play philosophy). In such a marketplace, one must be well educated to match display technology to application needs. This article provides the reader with a fundamental knowledge of working principles of liquid crystal displays (LCDs), their capabilities, and their limitations.

## ADDRESSING DISPLAYS

Before we delve into the operation of a LCD, it is important to understand how these displays are addressed and their impact on resolution, refresh rates, and image fidelity. Many treatises begin with material and device configurations, but we will first develop a basic understanding of electrical addressing schemes that apply to all LCDs. Our hope is that the reader will be better prepared to recognize the capabilities and limitations of the various display configurations presented afterward.

A LCD with high-information content (e.g., computer or television screen) consists of a two-dimensional array of pixels, where a pixel is defined as the smallest switching element of the array. If the two-dimensional array has a total of $N$ rows and $M$ columns ($N \times M$ pixels), then in principle, there can be $N \times M$ electrical connections to control each pixel independently. This is known as *direct addressing* and is practical only for very low-resolution displays. For medium and higher resolution displays, and most commonly has units of candelas per squared meter (cd/m$^2$), nits, or footlamberts (fL). The two measurable quantities from the luminance–voltage curve that have the greatest impact on display addressing are the threshold voltage $V_{TH}$ (the voltage at which the luminance begins to increase) and a parameter $\Delta$ (the additional voltage beyond $V_{TH}$ needed to cause the display to approach or reach its highest luminance). If a liquid crystal (LC) material does not start to respond to an electronic stimulus until it has reached a well-defined voltage, then it is said to have a threshold; otherwise, if the display material responds to all voltages, then it is said to be thresholdless (1).

For simple direct addressing schemes, like the seven-segment digit electrodes shown in Fig. 2, the threshold(less) nature of the material is irrelevant because the segmented electrodes (or pixels) are independent of each other. The appropriate combinations of segments are addressed by dedicated logic circuitry (i.e., every pixel is independently driven by its own external voltage source), and the screen refresh rate is only as long as needed for a single pixel to switch. Direct addressing is practical only for low-resolution displays (<50 pixels).

In a passive addressing scheme (also known as multiplexing), one substrate has row electrodes, and the other substrate has column electrodes, as shown in Fig. 3.

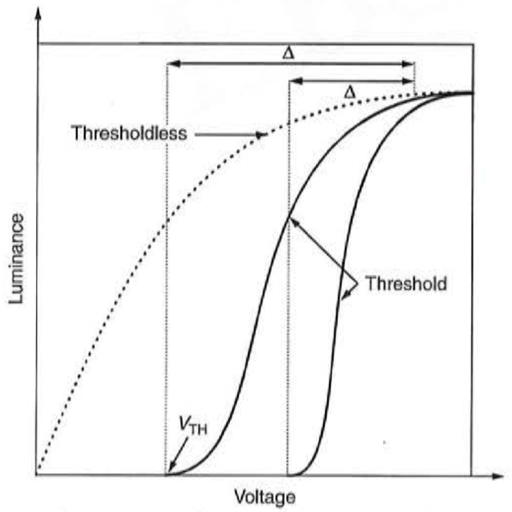

**Figure 1.** Luminance–voltage graph depicting the difference between materials that have well-defined thresholds and those materials that have no threshold (thresholdless). $V_{TH}$ is defined as the voltage at which the luminance begins to increase, and a parameter $\Delta$ is defined as the additional voltage beyond $V_{TH}$ needed to cause the display to approach or reach its highest luminance.

**Figure 2.** An example of direct addressing, where the segments are independently driven to create low-resolution information.

Every pixel is uniquely determined by the region of overlap of a row and a column electrode, making it possible to access $N \times M$ pixels with only $N + M$ connections. A display that has a passive matrix is driven one line at a time; that is, one row is selected for addressing, and all of the columns are addressed using voltages associated with the image for that row. At some time interval later, the next row receives an appropriate voltage pulse, and the columns again are addressed using the information required for that row. The net result is that a pixel is influenced only sufficiently to produce an optical effect when the time-averaged voltage [called the root-mean-square (rms)] across the row and column electrodes is beyond the threshold ($V_{ON} \geq V_{TH}$). All of the rows not being updated are driven by row voltages that will not affect the image information already present. The catch is that there will always be a voltage on the non selected rows, and therefore that voltage must satisfy the relationship $V_{OFF} \leq V_{TH}$ so as not to induce an optical change. Therefore, a well-defined threshold in the luminance–voltage characteristic of the LCD material is necessary to prevent the non selected rows from being addressed (i.e., cross talk). LC materials typically exhibit threshold behavior, which many displays to be multiplexed; display materials that are thresholdless, such as electrophoretics (2) and gyricon (3), cannot.

An expression can be derived that completely specifies the maximum number of rows $N_{MAX}$ that can be addressed in terms of the voltage threshold and the parameter $\Delta$, a measure of the nonlinearity of the LC material:

$$\frac{\Delta}{V_{TH}} \leq \frac{1}{\sqrt{N_{MAX}}}. \qquad (1)$$

To maximize the number of addressable rows for higher resolution, one usually uses a material that has a very non-linear and steep luminance–voltage response, small $\Delta$, rather than using materials that have a large $V_{TH}$ (which increases power consumption).

Another important equation relates the rms voltages of the ON-state $V_{ON}$, and the OFF-state, $V_{OFF}$, to the maximum number of rows that is given by (for $N_{MAX} \gg 1$):

$$\frac{V_{ON}}{V_{OFF}} \cong 1 + \frac{1}{\sqrt{N_{MAX}}}. \qquad (2)$$

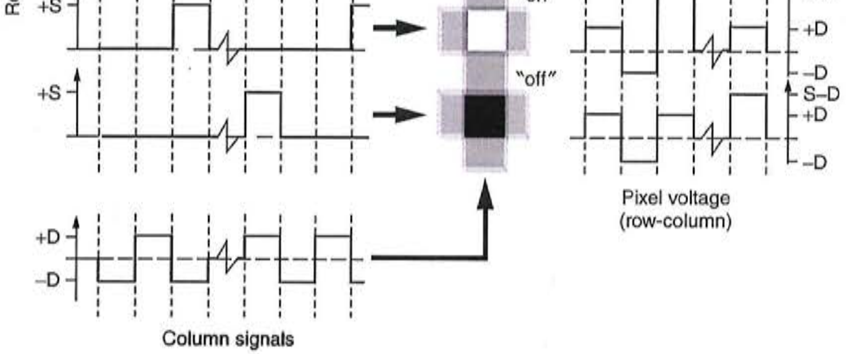

**Figure 3.** A simple example of multiplexing on an $N$-row matrix showing the row addressing waveforms, column addressing waveforms, and the corresponding pixel waveforms. This type of multiplexing, known as amplitude modulation, varies the amplitude of the pixel waveform to achieve the desired image. The normally black pixel is "ON" if the rms average pixel voltage exceeds $V_{\mathrm{TH}}$. See color insert.

where $V_{\mathrm{ON}}/V_{\mathrm{OFF}}$ is referred to as the selection ratio. When $N_{\mathrm{MAX}}$ is large, this ratio approaches unity, leading to poor contrast because the difference would decrease between the luminance in the ON- and OFF-states. Therefore, Eq. (2) dictates the optical contrast ratio (CR) of the display, which is defined as the ratio of the luminance in the ON-state and the luminance in the OFF-state ($\mathrm{CR} = L_{\mathrm{ON}}/L_{\mathrm{OFF}}$). Equations (1) and (2) were first derived by Alt and Pleshko in 1974 and remain the fundamental expressions governing multiplexing (4). To increase resolution using passive addressing techniques, a technique known as "dual" scan can be implemented. In the dual-scan approach, two column drivers are used to address the upper $N/2$ rows and lower $N/2$ rows. Examination of Eq. (1) shows that the dual-scan approach improves the ratio $\Delta/V_{\mathrm{TH}}$ by a factor of $\sqrt{2}$ (5).

Although some LC configurations that use the multiplexing technique have reasonable contrast for large values of $N$, other limitations enter into consideration such as response time (the time taken for a pixel to be switched to the fully ON-state plus the time needed to relax to a completely OFF-state), viewing angle (the maximum polar angle for which a display maintains reasonable contrast and minimal color degradation), and gray-scale issues (those that involve the operation of a pixel at a luminance which is intermediate between the ON- and OFF-states). The frame rate in a passively addressed display is severely limited by the time it takes for a single row to switch, as well as the number of rows in the display, because the frame rate must be greater or equal to the product of the two. In only a few exceptions, displays that use passive addressing will not support full video frame rates. However, this problem can be essentially eliminated using an active-matrix addressing scheme, where a nonlinear element is used for pixel isolation.

Active-matrix addressing is recognized by the display industry as the ultimate solution for high fidelity, high information content, full color, and significant gray-scale applications. Additionally, this addressing approach can be used with thresholdless and large $\Delta$ materials because a discrete nonlinear switch is integrated into each pixel structure. An active-matrix LCD incorporates a two-dimensional circuit array (or matrix) to provide the electrical addressing of individual pixels (6). This matrix incorporates an active device in each pixel, usually a thin-film-transistor (TFT), positioned at one of the corners. Almost all LCD pixels are essentially dielectric capacitors whose leakage is minimal when a charge is placed on the electrodes through the transistor. And due to the electrical isolation afforded by the transistor, the voltage on one pixel remains constant while other pixel elements are subsequently addressed; therefore, the Alt–Pleshko limitation expressed by Eq. (2) does not constrain the contrast ratio, as it does in passive-addressing schemes.

A schematic diagram of an active-matrix circuit is shown in Fig. 4, where each pixel element is defined by the overlap of row and column bus lines. The circuit diagram shows that each pixel has one TFT and a LC capacitor formed between a top conducting surface, (typically indium tin oxide (ITO)), and the active-matrix substrate. This approach is significantly more complex than passive addressing, as can be seen from the cross section of an active-matrix TFT display also shown in Fig. 4. The intricate underpinnings of active-matrix addressing and the complex processing required to create one are beyond our scope, but the basic operation can be understood as follows. The display is addressed one line at a time, as in passive addressing. When a row (called the scan or gate line) is addressed, a positive voltage pulse of duration $T/N$ (where $N$ is again the number of rows and $T$ is the frame time) is applied to the line and turns on all transistors in the row. The transistors act as switches that transfer electrical charges to the LC cells from the columns (called data or source lines). When subsequent

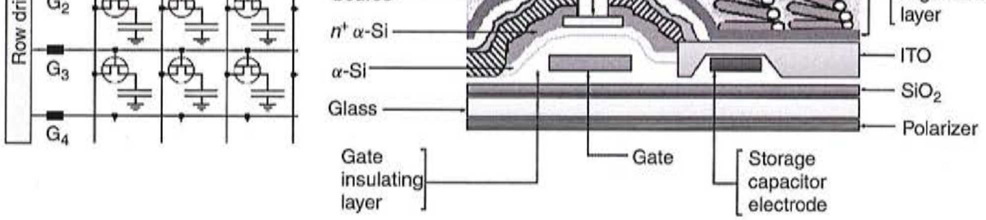

**Figure 4.** The driving circuit of an active-matrix thin-film transistor next to the cross section of an active-matrix pixel. As is apparent from the pixel structure becomes substantially more complex when active-matrix schemes are used. See color insert.

rows are addressed, a negative voltage is applied to the gate line that turns off all of the transistors in the row and holds the electrical charges in the LC capacitors for one frame until the line is addressed again. Alternating row-select voltages are required for most LCD materials, and the polarity of the data voltage is usually switched in alternate frames. The refresh rate in this addressing scheme is not limited by the number of rows but only by the response time of the LC.

A nonlinear pixel element can be implemented by a variety of approaches, but we will mention only the two most prominent active-matrix types: amorphous silicon (α-Si) and polycrystalline silicon (poly-Si). Both of these involve complex fabrication of thin films of silicon structures (<300 nm) on glass or quartz substrates. The details of active-matrix development are sufficiently complex to be far beyond the scope of this review, but we include a simple introduction to familiarize the reader with the basics.

Pioneering work on the active matrix began in the early 1970s (7), and the now conventional α-Si approach was first proposed in 1979 (8), where the deposited thin film of silicon has a small grain structure and is randomly configured (9). In this approach, inexpensive glass substrates are typically processed at ~300 °C, using well established processes, including sputtering, photolithography (typically 5–8 photomasks), plasma-enhanced chemical vapor deposition (PECVD), wet chemical etch, and reactive ion etching (REI). The resulting electron mobility is low (~0.5 $cm^2/V/s$), but it is more than adequate to form a useful switch for the pixel (9). However, there are two prominent limitations. First, the aperture ratio (the transmissive area of the pixel divided by the total pixel area) of the display is decreased to 50–75% due to the use of an absorbing light shield to overcome the photoconductivity of the α-Si TFT. Second, because the supporting row- and column-drivers must be mounted on additional IC chips bonded to the display substrate, the connections (>4,000) increase fabrication complexity and decrease reliability. Nonetheless, α-Si active-matrix displays have been made in all sizes and are most popular as laptop monitors and other large-area LCDs. Current research issues include reducing the number of photomasks (10), increasing display resolution (11), and increasing the aperture ratio (12).

In contrast, a poly-Si substrate can yield TFTs whose electron mobility is much higher (~440 $cm^2/V/s$), but must be processed at significantly higher temperatures (6). Fabrication typically involves the same α-Si process described before on a more expensive quartz substrate. Additional processing at the higher temperatures leads to recrystallization in a furnace or by laser annealing (13,14). An intriguing approach uses a laser ablation/annealing approach where CMOS-TFTs are fabricated at high temperatures using a quartz substrate and are subsequently transferred to flexible plastic substrates without any noticeable deterioration in poly-Si performance (15). In all approaches, the silicon grain becomes larger and more uniform and allows electrons to flow much more freely. The greatest benefits of these poly-Si substrates are the ability to fabricate row- and column-drivers directly on the periphery of the glass substrates and the reduction of the TFT size to ~5 × 5 μm. Additionally, the aperture ratio can be made substantially higher. Disadvantages include the high process temperature, increased fabrication complexity (higher accuracy required in photolithography and ion implantation), and the higher off-leakage current. Integration of driver electronics onto the substrate, increased display brightness, lower power consumption, and the ability to form smaller pixels at higher densities (>200 dpi) make these poly-Si displays particularly useful for microdisplays and medium size displays.

Display addressing directly impacts resolution and optical performance. Because most imaging applications require high resolution, active-matrix addressing is the most prominent addressing approach in the imaging field. Because of the complexity of the substrate, active-matrix

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