FLAT PANEL DISPLAYS

A flat panel display (FPD) is an electronic component used to convert a visual image coded in an electrical signal into a visual image suitable for reading directly by a human observer. It serves as the visual interface between computers, electronic cameras, videotape players, transducers, and other systems. Classical analog dials, meters, galvanometers, and gauges, which typically respond directly to an electrical, mechanical, or pneumatic transducer or servomechanism, are not considered flat panel displays, even though they may be flat and display information. The FPD responds to a coded electrical signal that is processed and formatted by an electronic processor and is usually refreshed typically 60 times per second using matrix addressing. In less technical terms, the FPD is often referred to as an electronic display, digital display, or glass display. A basic review of the flat-panel display may be found in Ref. 1.

In electronic displays, the adjective “flat” refers to the complete panel structure. Flat panel displays are important because they are flat like a pancake as opposed to flat like a flat iron. Flat cathode-ray tubes (CRT) are possible where the tube structure is flat like a pancake. To achieve this, the simple beam addressing of a conventional CRT is replaced with some form of the more complex matrix addressing. Typically, FPDs also have flat front surfaces. However, CRTs can also be made with flat faceplates for custom application, but at additional cost. Making only the front surface of a CRT flat does not make it an FPD. The whole structure must be flat. A basic review of the cathode-ray tube, including flat CRTs, may be found in Ref. 2.

When considering that the CRT has existed for over a hundred years, the FPD is a relatively new electronic component evolving along with microprocessors. The concept of an FPD may have first occurred when engineers were attempting to develop a picture telephone in the 1930s and, again, in the

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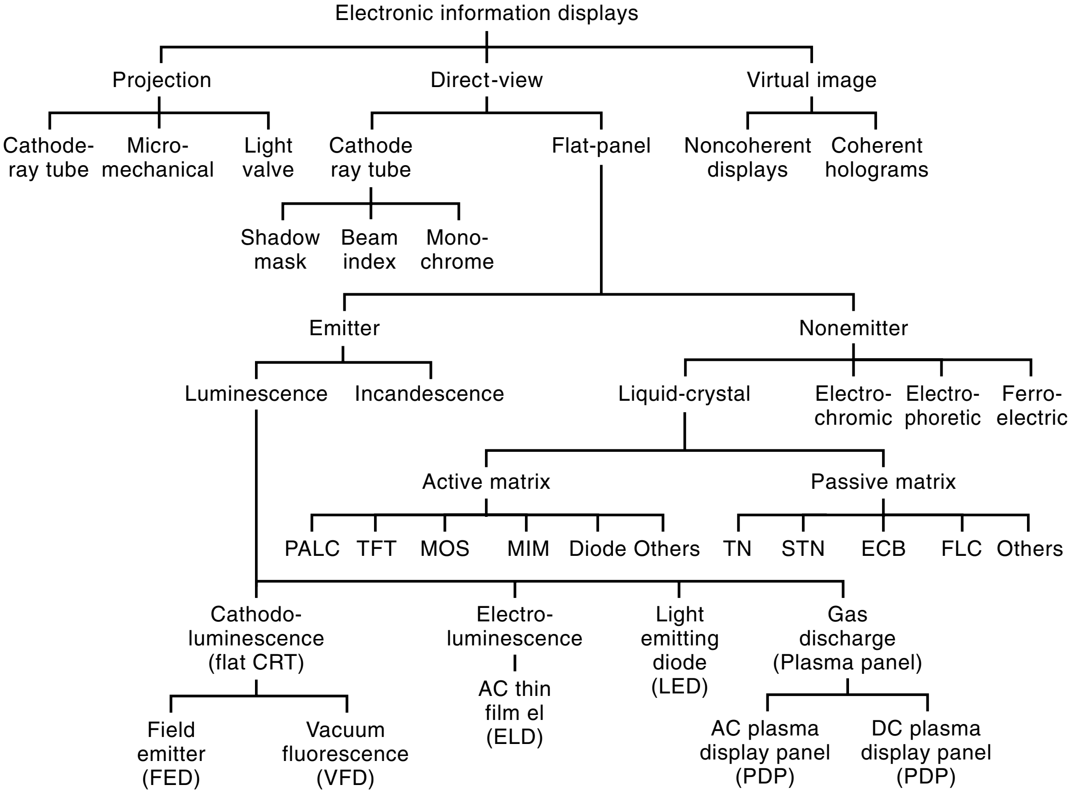

Figure 1. Organization of all major FPD technologies shown by categories commonly used in the display industry.

1950s when engineers were attempting to create a television set that could hang on the wall. The first functional FPDs were developed for hand-held calculators, televisions, wristwatches, and computer terminals in the 1970s. In the 1980s they were perfected for portable notebook computers and developed further in the 1990s with full color and high resolution for video and computer graphics. The first FPD technology seriously considered a contender to replace the TV on the wall was the electroluminescent display (ELD), with demonstration models made by Sharp shown at the Consumer Electronics Show in Chicago in 1979. Good reviews of ELDs are provided in Refs. 1 and 3.

FLAT PANEL DISPLAY MAJOR TECHNOLOGIES

An FPD is much like an electronic memory device. Both use some form of matrix addressing and can be made from different technologies. However, FPDs are much more complex because they must be scaled for the human observer and read in variable ambient lighting.

A diagram outlining the most commonly used FPD technologies is shown in Fig. 1. The diagram shows FPD technologies relative to all the electronic display technologies. As can be seen, all electronic displays can be divided into three broad categories. In the "direct view" category the image is generated directly on the viewed surface of the CRT or FPD. The other two broad categories require a projection of the image as in projection displays, virtual displays, or holograms. The CRT was the first electronic display. Because of cost, its use today dominates television and computer monitor applications. However, FPDs are expected to replace CRTs if and when the price becomes more competitive. Currently, FPDs are nearly ten times more expensive than comparable CRTs. In avionic and industrial applications, however, the prices are more favorable to the FPD due to the cost of mechanically ruggedizing a CRT, shielding it electromagnetically and electrostatically, and filtering it for readability in high ambient lighting. The FPDs are new product enablers, used where CRTs do not fit easily or at all.

The concept of an FPD is a simple extension of a printed picture with a time-varying dimension. The technical requirements to achieve this, however, are immense. Just how does one create an image so that it portrays a time-varying likeness to a real-life action scene yet remains thin like paper?

A short description of each FPD technology phenomenon is given in Table 1. There has been a long and extensive effort to invent a cost-effective high-resolution, color FPD. Displays engineers have divided flat panel technologies into two classes: emitters and nonemitters. In emitters the visible photons are generated to create the display image. With nonemitters an optical effect is used to create an image that cannot be seen unless illuminated with an external, independent light source. Table 2 gives an outline comparing the two. Nonemissive displays were imported early in the evolution of FPDs. The concepts of nonemissive electrooptic displays were reviewed thoroughly at the Brown Boveri Symposia in 1975 (4).

Electronic display applications fall into four broad categories as shown in Table 3. The categories are separated by the number of picture elements used in the display. The picture element, called a "pixel" in the electronic FPD industry, is the

Table 1. Flat-Panel Display Technologies

Technology	Advantages	Problem Areas	Phenomena
Active matrix liquid crystal display (AMLCD)	Quality image, full color, video speed, bright and dimmable	High cost, limited viewing angle	Twisted nematic mode, filters for color
Vacuum fluorescent display (flat CRT) (VFD)	Long life, high brightness	Complexity, small size	Cathodoluminescence, low voltage phosphors
Light emitting diode (LED)	Long life, high efficiency in color, any size	Low resolution	Solid state diode that emits visible photons at junction transition
Electroluminescent display (ac thin film) (ELD)	Fast response time, no flicker or smear, wide viewing angle	Low efficiency, phosphors complicate full color design, high voltage	Phosphor with dielectric electron tunneling, excited with ac high electric field
Plasma display panel (dc and ac) (PDP)	Large size, bright, fast response, wide viewing angle	Low efficiency, phosphors complicate full color design, high voltage	Classical gas discharge with light from excited gas mixture or uv-excited phosphors
Super twisted nematic liquid crystal display (passive matrix) (STN LCD)	Low cost, flexible in application, color	Slow response, limited viewing angle	Birefringence with polarizer and analyzer; retarder, compensating film used to get white
Twisted nematic liquid crystal display (passive matrix) (TN LCD)	Low cost, simple construction	Slow response, small size FPD	Birefringence with polarizer and analyzer
Plasma addressed liquid crystal (PALC)	Large size	Viewing angle	Gas discharge switch at each pixel row
Field emitter display (Flat CRT) (FED)	Low cost expectation	Still in development	Electrons emitted from tips and accelerated as in VFD
Electrochromic	Reflective, low power	Research, life	Charge and discharge with color change
Electrophoretic	Reflective, low power	Research, life	Bright particle electrostaticly moved in dark suspension
Ferroelectric	Reflective or transmissive	Research	Ferromagnetic material with electrooptic effect

building block of an FPD. The pixel area is the smallest spatial area of information. The complexity and cost of an FPD are in proportion to the number of pixels used.

Vectorgraphic and video displays, which offer performance comparable to the CRT, are significantly more complex electronic components than pseudoanalog and alphanumeric displays. The pixel count ranges from 50,000 to two million and greater in monochrome or full-color versions. This corresponds to products from low-end video games, portable televisions, and personal computers up to full-color SXGA (1024 × 1280 pixel matrix) for computers and HDTV.

Lower pixel count displays have a very wide and diverse variety of markets and display technologies. The history of pseudoanalog and alphanumeric class of display is often traced to the first production of NIXIE Tubes by Burroughs (circa 1954), inventor unknown.

Typical low-pixel-count displays include handheld calculators, clocks, marquees, and signs. In addition, low-pixel-count displays do not suffer from the perplexing matrix addressing cross-coupling problem (to be discussed later) that is proportional to the number of matrix rows.

Table 2. Comparison of Flat Panel Display Technologies

Emitters	Nonemitters
Self-luminous	Need ambient light or backlight
High power dissipated in display panel	Minor power in display panel
Bright, high-quality image	Can look like emitter technology with backlight
Power always a disadvantage	Lowest power display in reflective mode
Color limited in display phosphor or emissive technology	Color attributed to backlight

NEW REALITY IN FLAT PANEL DISPLAY

The original market objective, starting circa 1950, to replace the CRT with FPDs has not been achieved. Instead, a whole new family of products that could not easily use CRTs has been created. Examples of these first new major products include briefcase- and notebook-style personal computers and handheld color television displays.

In the FPD technology spectra for vectorgraphics and video, which include ELDs, plasma display panels (PDP), light-emitting diode (LED) displays, flat CRTs, VFDs, LCDs, and so on, liquid crystal display (LCD) technology has emerged as the clear leader. This was first observed during a Japanese Technology Evaluation Center (JTEC) study of the FPD industry in Japan in 1991 (5). The production volume of LCDs is now more than 100 times greater than all other high-pixel count FPD technologies combined.

The FPD using liquid crystal technology for high information content displays is proving to be one of the greatest product-enabling components of the century. The liquid crystal display (LCD) form of FPD has a visual quality that is better, in many ways, than a CRT and has superior utilitarian features of less volume, weight, and power. Liquid-crystal displays can be used almost anywhere and constitute over 90% of the FPD dollar market. The only remaining obstacle for LCDs and other FPDs is cost. Because of the cost of LCDs, other technologies that may have a cost advantage are always

Table 3. Electronic Display Spectrum of Applications

Classification	Characteristics	Applications	Electronic Technologies
Pseudoanalog	Dedicated arrangement of discrete pixels used to present analog or qualitative information, 1 to 50 pixels	Meter-like presentations, go/no-go messages, legends and alerts, analog-like (watch dial), auto panel	Liquid crystal, light-emitting diodes, vacuum fluorescence, gas discharge
Alphanumeric	Dedicated alphanumeric pixel font of normally fewer than 480 characters; most common is 4- and 8-character numeric displays; 10 to 4000 pixels	Digital watches, calculators, digital multimeters, message terminals, games	Liquid crystal, LED, vacuum fluorescent, gas discharge
Vectorgraphic	Large orthogonal uniform array of pixels, which are addressable at medium to high speeds; color and monochromatic; normally, over 480 characters and simple graphics; 1000 to 100,000 pixels	Computer terminals, arrivals and departures, scheduling, advertising terminals, games	Liquid crystal, LED, plasma panels, electroluminescence
Video	Large orthogonal array of pixels, which are addressed at video rates; full color; standardized addressing interface; 50,000 to two million pixels	Entertainment television, graphic arts, video repeater, medical electronics; aircraft flight instruments, computer terminals, command and control, games	Active matrix liquid crystal, plasma panels, large LED array

being pursued. The LCDs are continuously improving and decreasing in price, and it is going to be very difficult for any other FPD technology to catch up.

There are many reasons for the acceleration of LCD technology, including: (a) highest immunity to ambient illumination; (b) thinnest profile; (c) lightest weight; (d) lowest power requirement; (e) color performance comparable to CRTs; and (f) lowest cost when compared to other FPD technologies. The LCD limitations are diminishing and becoming more acceptable to consumers. They include: (a) very high cost when compared to CRTs; (b) limited viewing angle; (c) slow speed of response (less than 200 ms in passive LCDs and 50 ms in active matrix LCDs); and (d) narrow temperature operating range (as wide as −30°C to +85°C).

The cost issue will prevail indefinitely due to the high content of LSI electronics required for the row and column drivers and buffering electronics. Active-matrix liquid-crystal displays (AMLCD), which are the highest performing FPDs with performance comparable to CRTs, are approximately ten times more expensive than CRTs. This major price difference between AMLCDs and CRTs will prevail through the beginning of the twenty-first century and will inhibit AMLCDs from replacing CRTs any time in the foreseeable future. Nearly half the cost of the AMLCD is in the large set of LSI circuits needed to control and drive the display. Furthermore, the photolithographic manufacturing process requires a high level of capital equipment and large amounts of process materials. The yield is above 80%. Further improvements in manufacturing costs are going to come slowly as the industry matures and capacity meets demand.

The speed of response of all LCDs is slower than for other FPDs and the CRT. Basically, most display technologies can create a new full-intensity, viewable image in one complete scan. An AMLCD, the fastest responding LCD configuration, takes approximately three complete scans of the image at 60 Hz. The slow response of the twisted nematic (TN) mode used in AMLCDs is due to the high viscosity and low restoring forces of the LC molecules. The response is fast enough for consumer video and games, and for preventing image flicker and smear. The lower-cost LCD configurations, such as passive TN and super TN (STN) LCD, take longer but, in general, are suitable for nonvideo imagery such as PC word processing, spreadsheets, graphics, and other items.

DISPLAY SIZE

The physical size of the FPD and its image quality are limited by manufacturing techniques and by the FPD technology used to create the image. The manufacturing technique dictates the size of the substrate that can be processed. For LCDs, the third-generation machinery used since 1996 can process glass in sizes of 550 mm × 650 mm and larger. Due to process yield and manufacturing considerations, LCD manufacturers prefer making four or more displays per substrate. Nine displays measuring 0.25 m (10 in.) diagonally or four displays measuring 0.38 m (15 in.) diagonally can be made on a 550 mm × 650 mm glass substrate.

It has been the worldwide custom to describe the size of an electronic display by its diagonal measurement in inches (SI conversion is in meters). It is assumed that the display has a 3 : 4 aspect ratio, which has been the case in television and most computer monitors. The custom is to quote the size of a CRT from the outside corners of the glass envelope, which is 10 to 20% larger than the size of the display image inside the tube. However, for an FPD the custom is to quote its size from the outside corners of the display image, which is smaller than the actual glass size. The general size characterization by the display diagonal dimension can become confusing and may be more confusing with high definition television (HDTV) display, which has an aspect ratio of 9 : 16.

The image display's size and quality are dictated by the number and size of the pixels and by the viewing distance. The quantizing of spatial area by the pixel is the basic building block of an FPD being called a "digital display" as opposed to a CRT, which uses the analog electron beam spot size to define spatial resolution. The FPD pixel size is defined by the circuitry etched on the glass substrate, whereas the CRT pixel size is defined by the focus adjustment of the electron beam.

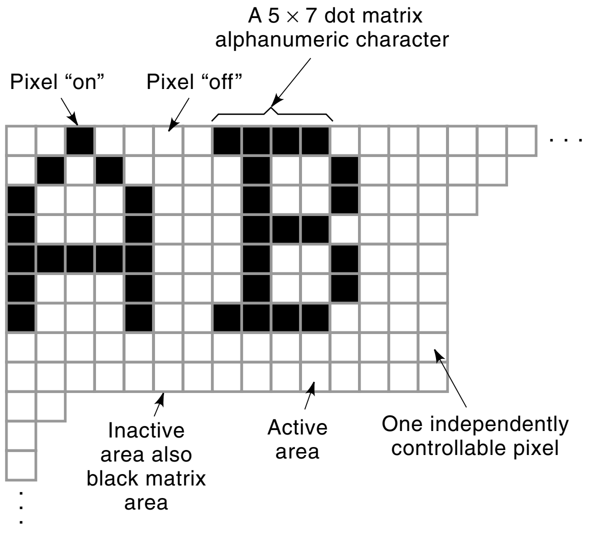

Figure 2. Nomenclature used to describe the details of a pixture element (pixel) matrix array.

The display is made of one pixel or millions of pixels, depending upon the application (Table 3). Each pixel is electronically and independently controllable. The controlled set of pixels makes the image. Each pixel is like a tile in a picture. Each tile dictates a quantized spatial area but can be of any luminance or reflectance and of any color. The pixel location is defined by its matrix address of row number and column number. Figure 2 shows the nomenclature for several pixels in a typical monochrome FPD.

Because the cost of an FPD is in proportion to the number of pixels, the pixels are made as large as possible without impacting image quality. The viewing distance and visual acuity are used to compute the pixel size. The threshold of human visual acuity is one minute of arc for 20/20 vision, and, as a rule, the pixel size is typically designed to intercept one to two minutes of arc at the nominal viewing distance. The rationale here is that the users should be able to see every pixel they paid for. If the pixels are too small, then the users are not seeing all the pixels. If the pixels are too large or the viewer gets too close, then the edges and corners and spaces between the pixel-active area can be seen and the image will begin to look jagged and chunky. Using the design rule of two minutes of arc for a workstation viewing distance of 0.5 m (20 inches), the pixel pitch would be 300 μm .0118 (inches). This is the typical design rule used in designing a computer monitor. A computer monitor with a VGA resolution of 480 rows and 640 columns of pixels at a pitch of 300 μm would require a display size of approximately 0.15 m × 0.20 m (6″ × 8″) or a ten-inch diagonal, which is a typical size found in the marketplace. Displays that are to be read from the same distance with the same image quality but with more pixels must be larger.

The relationship between size and resolution of all electronic displays for popular computer and television applications is shown in Fig. 3. The horizontal resolution (pixels or lines per mm) of broadcast television is usually less than the vertical resolution. The relative size of each display format in Fig. 3 is the same as shown regardless of the viewing distance. The LCDs dominate the market for sizes up to 0.5 m (20 inches) diagonal, PDPs for sizes 0.5 m (20 in.) to 1.52 m (60 in.), and LEDs for very large and very small sizes.

THREE WAYS TO DO COLOR

Since the early 1990s, color has become a major performance requirement in FPDs. It is relatively easy for CRTs to display full color with the shadow mask technique invented at RCA around 1950. Full color is technically difficult for almost all FPD technologies except LCDs, for which color has a major cost impact. Flat-panel displays over the 0.5 m (20 in.) size are made in color by using PDPs and LEDs. Other FPD technologies such as ELD, VFD cannot do full color except at low luminance and/or low efficiency.

A wide spectrum of color is achieved by electronically adding components of the red, green, and blue primary colors. The primary color components are added in accordance with the color additive technique adapted internationally by the CIE committee on color and presented in the CIE 1931 xy or CIE 1976 u'v' color space coordinate systems. The two are algebraically interchangeable. The newer u'v' color space is preferred because the graphically spatial differences are perceptually more uniform.

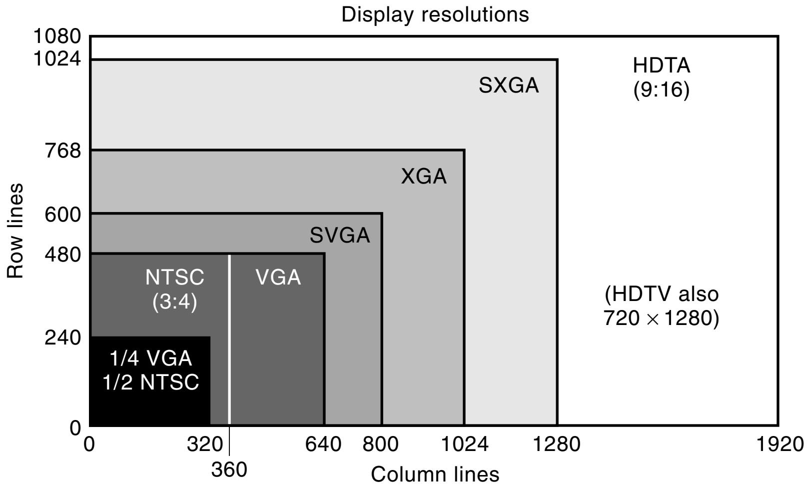

Figure 3. Relative size and row and column matrix size for the major PC graphic adapter cards. Note that the NTSC area is not to scale as the NTSC pixels are not square.

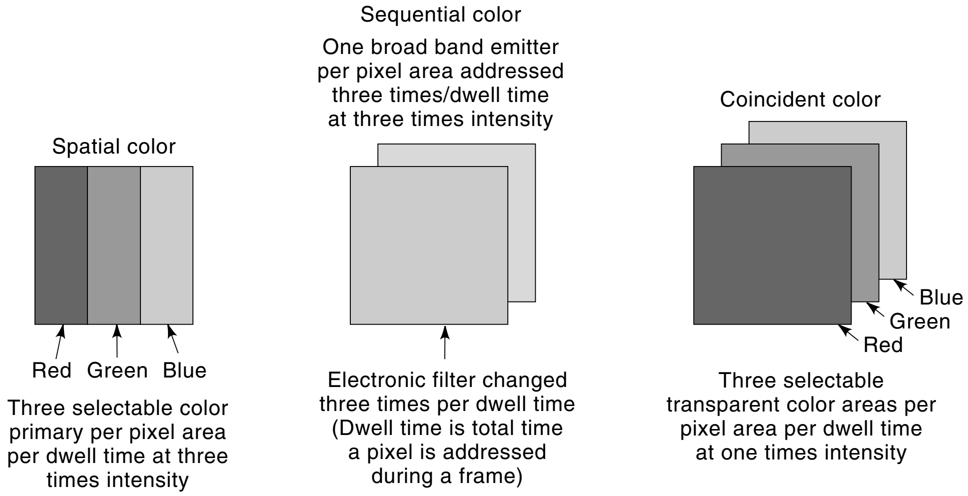

Figure 4. All of the known techniques for generating color in an FPD falls into one of these three categories.

Three techniques are used for electrically combining primary colors in FPDs as shown in Fig. 4. The one most commonly used is the spatial color technique in which the pixel area is subdivided into three or more subpixels, each being independently controllable and dedicated to a primary color. The subpixels are below the resolving power of the eye and merge as they are focused on the retina. The sequential color technique displays the pixel color primaries in sequence at high speed above the flicker frequency. The primaries are then merged in the retina of the eye to a single color signal. The merging occurs due to the persistence in the response of the primary color cone detectors in the retina of the eye.

In the coincident color technique, the color primaries are displayed simultaneously and merged in the display at each pixel. The color-emitting surfaces must be sufficiently spectrally transparent to allow the primary colors in the back to be seen. There are examples in the literature for almost all of the major FPD technologies used in all three color techniques.

The performance parameters of each display technology dictate which of the three color-generating techniques is best. A comparison can be made assuming that the dwell time for addressing the pixel area and the luminance is the same for each color generating technique (Fig. 4). In the spatial color technique example, each primary subpixel must be three times more luminous than for coincident color. In the sequential color technique example, each primary must be three times faster and three times more luminous than for coincident color. In the coincident color case, the emitter must be transparent or projected from three or more sources onto the pixel area. The coincident color technique requires more addressing electronics as both the row and column pixel address must be duplicated for each primary. In spatial addressing only the column addressing must be duplicated for each primary. With sequential addressing the pixel addressing is not duplicated, but the addressing speed is increased in proportion to the number of primaries. The electronic filter is used in sequential color to eliminate unwanted color wavelengths for each primary. The filter may need to be sequenced in the vertical direction. High-speed LC pie cells have been made by Kaiser, Tektronix, and others for two and three primaries. Filters are used in all three techniques to make the primaries more saturated or to select the desired primary from a broadband back light as in the case of the spatial color technique. Coincident color has been used with the transparent thin-film phosphors used in ELDs. Sequential color and high-speed LC pie cells have been used with cathodoluminescent displays. The LCDs use spatial color quite successfully.

To achieve full color, the luminance of the primaries is mixed by the electronics. Full color is achieved when the shading across the image of the human face or across all other parts of the image is continuous. In standard television video over 64 gray shades, or six bits per pixel, are needed in each primary. In the highest quality of high resolution images, 256 gray shades, or eight bits per pixel, are used per primary. To save bandwidth, the number of gray shades in the blue primary may be reduced because the human visual system is less sensitive to blue. A common economical design is to use six bits in red and green and four bits in blue.

The common technique for generating gray shades is shown in Fig. 5. Spatial gray shades can be achieved by turning on colored subpixels in pattern sets or by dithering randomly. The advantage of spatial gray shade is that the subpixel is either full “on” or full “off.” The disadvantage is that extra subpixels are needed for primary color gray shades, which could be used as pixels for resolution. Spatial color resolution is sacrificed for gray shades. Time subdivision (temporal dithering) and amplitude modulation are the most common techniques for generating gray shades. There is no loss in resolution with these modulation techniques as there is with spatial gray shades.

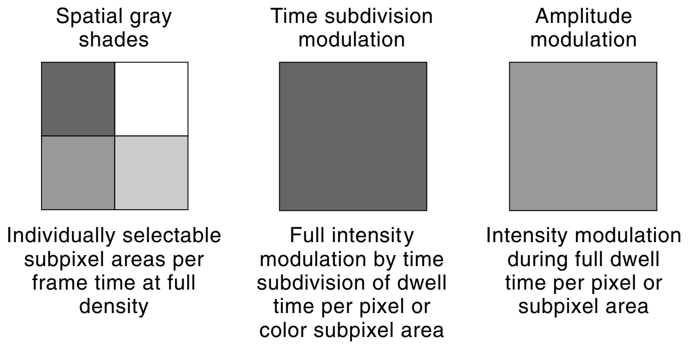

Figure 5. All of the known techniques for generating a monochrome gray shade in an FPD fall into one of these three categories.

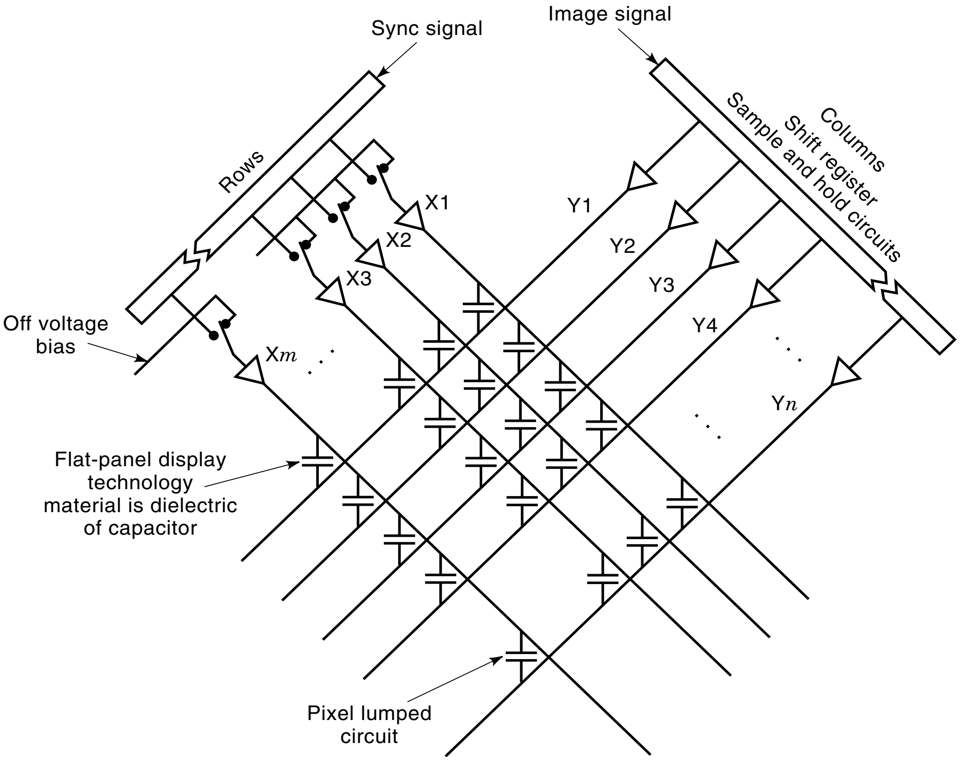

Figure 6. The equivalent electronic circuit of a typical FPD showing the pixel matrix array. Electrical cross-coupling between the pixels exists because of the row and column conductor interconnections.

The gray shades should vary exponentially in intensity due to the fact that the human eye responds exponentially. This is done at the electronic input to the column drivers. A gain correction is used to compensate for the natural response of the display pixel or subpixel and causes it to change exponentially as the input signal is increased. This is often called a gamma correction because it is analogous to the gamma correction used in the CRT video amplifier gain correction for television.

MATRIX ADDRESSING PROBLEM

The electrical signal to all electronic displays is a serial time sequence of the image organized in a raster format of rows, which for viewing must be converted to a rectilinear image. In all FPDs this is done by some form of matrix addressing. An electric circuit of an array of m rows and n columns is shown in Fig. 6. For most FPD technologies each pixel can be represented as a leaky capacitor. In Fig. 6 a resistor is not shown in the equivalent circuit of a pixel because the impedance of the resistor is significantly less than that of the capacitor. Pixels for FPDs using the LED technology are unique in that they are diodes instead of capacitors. A list of the equivalent circuit for each of the major FPD technologies is given in Table 4.

The display is addressed by electrically charging each pixel capacitor in proportion to its image intensity. The charge is conducted through the row and column lines as shown in Fig. 6. To save scanning time, the FPD capacitor array is addressed in parallel "row at a time," which is consistent with the raster formatting convention of the incoming electrical signal. A shift register is included with the column drivers to format the signal. After a row of data for row X2 is shifted into the column shift register, the signal is applied in parallel to all the columns at the same time that row X2 is enabled to receive the data. While the capacitors of row X2 are being charged, the signal for row X3 is being shifted into the shift register. This process is repeated until the entire matrix array of capacitors is charged up to the signal level appropriate for the image transmitted. When complete, the matrix array is scanned again to refresh the image, or change the image, as dictated by the signal. To minimize flicker, the image is typically refreshed 60 times per s.

The image is created by the response of the dielectric material in the pixel capacitor to the electric field impressed on it from the capacitor charge. If the dielectric is EL phosphor, such as ZnS doped with Mn, then, at sufficient field strength, electrons will tunnel through the ZnS and excite the Mn atoms, which then emit a yellow-orange light. If the dielectric is an argon/neon gas, then, at sufficient field strength, the gas ionizes and emits an orange-yellow light. If the dielectric is a birefringent LC compound, then the LC molecules rotate, thus changing the optical retardation of the cell gap, which controls the passage of light between a polarizer and analyzer located, respectively, on the top and bottom of the cell. If the

Table 4. Matrix Pixel Equivalent Circuits

Leaky Capacitor	Diode	Three or More Terminal Pixels	Switch with Memory
LCD (all types)	LED	VFD	AMLCD
EL	MIM LCD	FED	FLCD
PDP	VFP	AMLCD	Active matrix ELD
	FED	Flat CRT	—

pixel is an LED, then light is emitted in proportion to the current passing through the diode.

The LC material in TN and STN displays is slightly nonlinear. The STN LCD is more nonlinear than a TN LCD due to the extra twisting of the molecules in the cell. The rotation of the molecules inside the pixel capacitor of Fig. 6 responds to the rms value of the voltage. The rotation of the molecules changes the optical retardation, which gives the contrast change when viewed between cross polarizers. The limitations in this effect can be computed from equations derived by Alt and Pleshko (6) known in matrix-addressing passive LCDs as the "Iron Law." Cross-coupling critically hampers the TN mode of LCDs. The STN mode of LCDs was invented to minimize cross-coupling. In AMLCD with TFTs, the TFTs act as a switch to prevent cross-coupling. Other forms of AMLCD, as shown in Fig. 1, provide a nonlinear barrier to inhibit cross-coupling effects. The TFT AMLCD has the best performance of all the other FPDs. The advantage of the other forms of AMLCD is lower cost but with lower performance than TFT AMLCDs.

Problem with Matrix Addressing

An FPD operates basically in the manner already described here. However, it is far more complex due to the electrical cross-coupling that occurs in the matrix array of pixel equivalent circuits. Due to sneak circuits that occur inside the matrix array of capacitors shown in Fig. 6, the charge at each capacitor cannot be maintained in proportion to the data signal. If a voltage is applied to pixel capacitor 11, then a fraction of the voltage will be applied to pixel capacitors 12, 22, and 21 due to the electrical circuit interconnecting the capacitors. If pixel 11 was intended to be at high voltage and pixels 12, 22, and 21 were intended to be at zero voltage, the interconnecting circuit would inhibit this from happening in accordance with Kirchhoff's law for circuit analysis. Similar cross-coupling occurs for all the pixel capacitors in the array.

A detailed discussion of FPD matrix addressing can be found in Chapter 5, Ref. 1. The ELD, PDP and LED displays can operate in a matrix of the type shown in Fig. 6 due to strong nonlinear properties.

THE EMERGENCE OF LCDS

Since circa 1963 LCDs have been vigorously pursued as a replacement for the CRT, but only recently have they emerged as a major industry electronic component surpassing one billion U.S. dollars in 1989. No other FPD technology has come close to annual sales that high. The LCD industry annual sales are in the tens of billions of U.S. dollars. Before 1990 (a somewhat arbitrary point in time) all FPDs were niche-market components implemented by numerous technologies. Most never got out of the research and development laboratory. Thus far, the TN LCDs, LEDs, ELDs, VFDs, and PDPs have been successful as low- and medium-information content displays. Only LCDs have been successful in the marketplace as high-performance, high-information-content color FPDs.

Today the leading FPD technology is the LC technology. The AMLCD is the benchmark by which all FPDs are rated. Any new technology, such as field emitter displays (FED) or organic LEDs, must be evaluated relative to AMLCDs and other forms of LCDs. The infrastructure for LCDs in Japan and around the world is now so immense that it is difficult to conceive of a technology that could possibly displace it in the near future. The next FPD will probably evolve from the present infrastructure. It is the only FPD in volume production with full color in video and PC sizes. Its emergence has been due to two technical solutions to the complex matrix addressing problem. One is the STN LCD configuration, which has sufficient nonlinearity for large arrays to be matrix addressed. This configuration falls into the "passive LCD" classification because there are no active components internal to the display panel for addressing the array of pixels. The other solution is the AMLCD (Fig. 7), which utilizes an active component or switch at each pixel or color subpixel to provide sufficient nonlinearity for matrix-addressing the linear TN mode of LCD. The first demonstration of a TFT AMLCD by Morozumi in 1983 (7), convinced most observers that AMLCDs would win the FPD technology race during the 1980s. Thus far, the most widely used active element has been a thin film transistor (TFT) in which the semiconductor is amorphous silicon. Polysilicon TFTs and single-crystal silicon metallic oxide semiconductor (MOS) are also used in matrix addressing LCDs.

Polysilicon is used primarily in small-size, high-resolution AMLCDs for projector and helmet-mounted displays. In these applications, the row and column drivers are made monolithically on the display substrate at the same time the pixel transistors are made. This approach always has the promise of integrating other system electronics on the same substrate.

New modes of reflective color LCDs have been developed for very low-power applications using STN mode with retardation films. These are for personal portable product displays where some color capability is desirable and where there is not sufficient power for a backlight. These reflective modes always suffer from low luminance but with significantly reduced product system weight due to lower power requirement.

Plastic LCD substrates have also been developed for TN LCD personal portable product displays to reduce weight and improve ruggedness but at an increased cost.

Very high resolution color AMLCD microdisplays have been developed for small helmet-mounted displays using a silicon wafer as the backplane. Conventional LSI processing is used to make the row, column, and pixel drivers with system electronics on the periphery. These are the most compact and most expensive FPDs. The markets for miniature handheld and helmet-mounted displays are emerging. Optics are needed to magnify the image. They are used to create a vertical image in most applications.

The viewing angle of AMLCDs has been improved significantly with compensation films. In the conventional TN mode, the LC molecules are aligned to be horizontal to the substrates and progressively twist 90° from layer to layer, going from the back substrate to the front substrate. The electrooptic effect is achieved by partially rotating the long cigar-shaped LC molecules vertically. The retardation now changes due to the birefringence of the LC molecules. The partial rotation causes a nonuniform contrast between different viewing angles due to variations in optical thickness. The optical thickness variations can be partially compensated for with optical retardation films placed inside the polarizers. Good results have been achieved by many manufacturers and this technique is used where a moderately wide viewing angle is

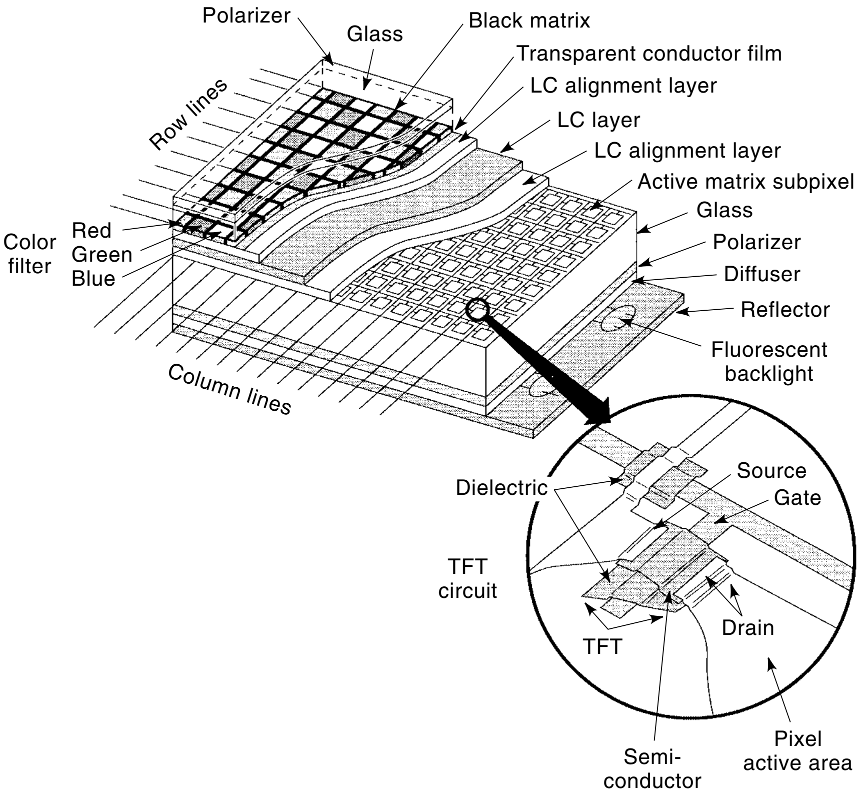

Figure 7. The cross section of a color AMLCD showing the complexity of the highest-performing flat-panel display.

needed. It is not generally considered to be needed on notebook PCs as the narrow viewing angle gives the single user a degree of privacy. However, with multiple viewers of television displays, for example, it is needed and is achievable.

Wider viewing angles in both the horizontal and vertical planes have been achieved with "in-plane" twist as demonstrated by Hitachi and NEC of Japan. In the configuration of AMLCDs, the LC molecules are electrostatically rotated in the horizontal plane as the name suggests. Good contrast is achieved as with TN vertical rotation without the variations in optical thickness, thus giving very little change in viewing angle contrast. However, the in-plane electrodes reduce the transmittance from approximately 7% to 5% and therefore lower overall efficiency.

A wide viewing angle becomes very important in 20-inch diagonal AMLCD monitors due to the variation in viewing angles across the screen from a fixed eye position. Active-matrix LCD manufacturers are exploring other LC modes to yield a viewing angle comparable to that of a CRT without increasing the cost or decreasing the utility of the display.

Liquid Crystal Display Evolving Technology

The LCD technology is still evolving. Several configurations are in high-volume production:

1. Twisted nematic (TN) LCD—matrix addressability limited to approximately 64 rows, lowest cost, twist angle of 90°, limited viewing angle and response speed. The TN mode is the highest unit volume production of LCD. Due to limited matrix addressability, it is used mostly in small- to medium-size displays.
2. Super-twisted nematic (STN) LCD—matrix addressable up to 512 rows, ideal for low-end PCs, color, lowest cost PC LCD, twist angle of 145° to 200°, limited in viewing angle and response time. The speed of STN LCD is not fast enough for quality video presentation. Improved matrix addressability is achieved from the nonlinearity resulting from the higher twist angle.
3. Metal-insulator-metal (MIM) AMLCD—used in addressing a TN LCD to increase pixel nonlinearity for improving matrix addressing. As the MIM thin films of, typically, Ta/TaO_x/Cr are placed at each addressable pixel internal to the display panel, an MIM-augmented display is called an AMLCD. However, the individual pixel is a two-terminal element. (The addressable pixels or subpixels of most AMLCDs are three-terminal elements.) Seiko Epson produces this configuration, which is used primarily in handheld LCD TVs. The price and performance puts MIM LCD TV products between STN LCD and TFT AMLCD portable televisions.
4. Dual-addressed LCD—used in addressing color STN LCDs to reduce the effects of cross coupling in matrix-addressed FPDs. The column electrodes are opened in the center of the display to render it electrically two separate displays. Column drivers are placed at the top and bottom of each pixel or subpixel column line. The matrix addressing requirements are reduced by a factor of two because the number of row lines are reduced by half in each half. The increase in cost for the extra column drivers is justified by the improved overall performance as required by portable PCs.
5. TFT AMLCD—uses a full switch at each pixel or subpixel to stop cross-coupling. The TFT semiconductor is

typically a-Si : H, but may be a poly-Si : H or single-crystal Si. CdSe has also been used as a TFT semiconductor. Of all of the LCD configurations, the full switch gives the fastest speed, widest viewing angle, and best color and gray scale.

6. Others—there are numerous other versions of LCDs being developed and in limited production. Examples include ferroelectric (FLC) LCDs by Canon, electronically controllable birefringence (ECB) LCDs by Seiko Instruments, and plasma-addressed LCDs (PALC) by Sharp, Sony, Tektronix, and others.
7. Multiple row or active addressing—a very clever technique for improving the speed performance of an STN display promoted by Scheffer and Clifton in 1992 (8). The technique simultaneously addresses all the rows and columns of the display, letting the response of the LC material integrate the effect. The rows are enabled with orthogonal functions, and the data are applied to the columns after being preprocessed with the mathematical orthogonal row functions. Extra electronic processing is via LSI custom electronics to preprocess the signal to perform multiple row addressing. This configuration has been demonstrated by In Focus, Optrex, and Sharp and is commercialized to a limited degree. As always, the columns are addressed in parallel. The cost for full implementation of the preprocessing outweighs the improvements for most market applications. Active addressing has fundamental advantages and may be used more extensively in the future.

These LCD configurations cover a wide spectrum, and all seem to be finding markets that best fit their individual performance-to-cost ratio and features. It is important to note that the commercial market is utilizing all these configurations in consumer products because of the price and performance differences and the unique features of each. Detailed discussion of LCD modes of operation may be found in Ref. 9.

Within the LCD community of display developers and users, there has been an ongoing debate regarding whether STN LCDs or TFT AMLCDs will dominate in the major markets. Because of clear price and performance differences, it appears that both will hold a significant segment with their prospective market advantages. Instead of dominance by one, the spectrum is expanding with price and performance characteristics between the two major configurations, STN LCDs and TFT AMLCDs.

The separation in price and performance between STN and TFT LCDs is fundamental to the technology of the respective approaches. The STN LCD is a passive display utilizing single row and column electrodes for addressing. This approach depends upon the nonlinear response of the STN mode to make the display matrix addressable. The TFT forms a transistor switch at each pixel or subpixel; therefore, it can use the more linear-responding TN mode and still be matrix-addressable. The TN mode has faster response and more uniform gray scales than the STN mode. Only the TFT LCD is fast enough for video and has enough gray scale for full color. The TFT, however, greatly complicates the pixel or subpixel structure and makes it a three-terminal device (Figs. 7 and 8). The manufacturing of TFT AMLCDs is highly machine-intensive and requires several photolithographic steps to be performed at, typically, a 2 μm design rule.

THE LIQUID CRYSTAL DISPLAY ADVANTAGE

As a group, LCD technologies have several unique technical advantages that underscore why, since the late 1980s, they have advanced so far beyond the other FPD technologies:

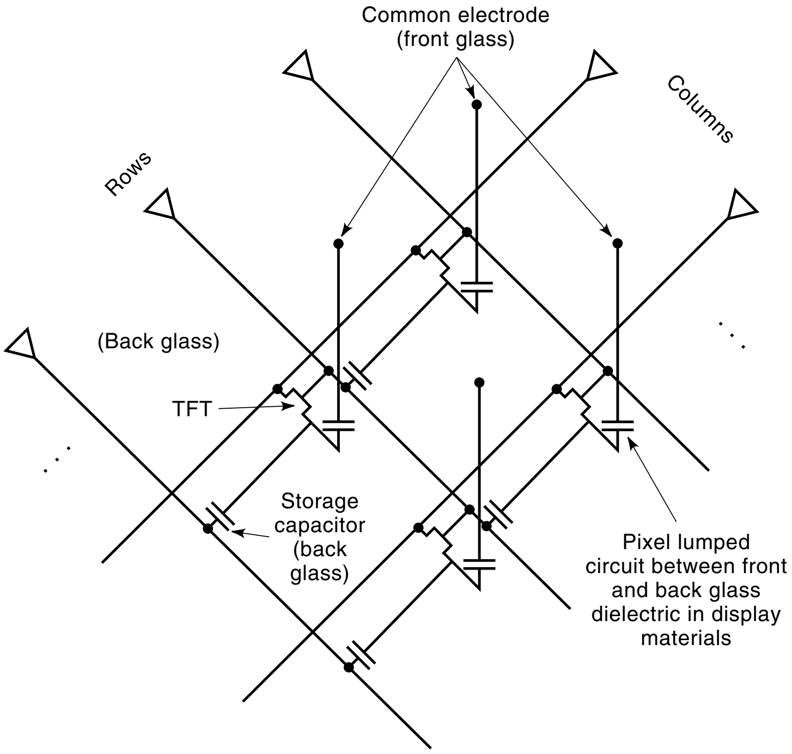

Figure 8. The equivalent electrical circuit of a typical AMLCD using TFTs and a storage capacitor at each addressable pixel.

1. Use of low-voltage row and column CMOS electronic drivers—the drive electronics of a matrix-addressed FPD constitute almost half the cost. Because of low voltage and power requirements, the LCD drivers can be fabricated in LSI with up to approximately 240 drivers per chip. Of all FPD drivers, only LCDs can use CMOS drivers using 3v technology, which consumes the least power and costs the least.
2. Separation of luminous power from image signal—the row and column drivers do not have to deliver luminous power to the panel. When used, luminous power is applied as a separate backlight module. To conserve power or enhance viewability, such as in a high ambient illuminated environment, the luminous intensity is modulated independent of the image. These LCDs have been made for avionics with a dimming ratio of over 2000 : 1, exceeding the dimming performance of all other FPDs and CRTs. Furthermore, the luminous efficacy of the backlight can be optimized. Also, the spectral color of the backlight can be selected and optimized. High-efficacy fluorescent back lights are often used with the near optimum red, green, and blue color phosphor. As a consequence, LCDs have the highest luminous efficacy of any electronic display.
3. Color capability and flexibility—color filters are added in combination to the LCD panel and backlight to make possible a wide spectrum of highly saturated colors. The selection of the three primary colors is almost unlimited due to the wide variety of phosphors, pigments, and dyes available. The RGB color filters are typically added in front of the individual LCD subpixels inside the front glass substrate of the panel. Other FPD technologies—such as VFDs, ELDs, and PDPs—require a unique phosphor emission to achieve bright and efficient primary colors that, in general, have not yet been developed for all the colors.
4. Immunity to ambient illumination—through the use of polarizers the LCD is a nonreflecting, or black, display. As a consequence, when optimized, it is nearly immune to ambient illumination. Furthermore, the colors maintain their chromaticity coordinates in varying ambient lighting. To enhance this feature, an antireflecting coating is added to the first surface of the display, and a low-reflecting black matrix is added between all the active pixel areas to reduce reflections.

TECHNICAL CHALLENGE

Difficulties achieving a low-cost, general-purpose, high-information-content color FPD is due to several technical issues. First of all, an FPD is the most complex of all electronic components because it must interface with the human visual system in all environments. In addition to the usual functional parameters of electronic components, there are optical issues such as luminous efficacy, spectral emission, and human factors, which include photometry, size, color, readability, and dimmability. Ambient light is added to the list of environmental operating conditions of temperature, humidity, shock, vibration, EMI, and others.

There have always been markets that have been willing to pay premium prices for FPDs. In the 1970s the U.S. aerospace industry and military computer markets supported the early developments of high-information-content FPDs using ELD, PDP, and, to a lesser extent, LED technologies. Typically, these displays were monochrome, from 6 to 12 (.15–.30 m) diagonal inches in size with 512 × 512 lines of resolution.

Technical issues have limited the commercial development of FPDs. The primary issue has been the ability to address a large array of pixels at a suitable speed with appropriate optical contrast, luminance, resolution, power efficacy, color, and gray shades, all at an affordable cost.

Matrix Addressing

The design evolution process starts with a few rows of pixels and an electrooptical effect such as ELD, PDP, or LCD, and then expands the pixel array count until the display performance requirements can no longer be achieved.

In the 1960s and 1970s, shift addressing was very successfully applied to the Burroughs Selfscan product line of PDPs. Burroughs' gas shift register was successful in the past because the use of the gas shift register minimized the required number of high-voltage electronic row and column drivers and made the product cost-competitive then. After 1980, the electronic row drivers became less expensive than gas shift structure, and the VFD became less expensive and displaced PDP with gas shift registers.

Matrix addressing is used to save electronic driver cost, which becomes an issue at 30 or more pixels. A display with 30 pixels would require 30 drivers in direct drive, or 11 drivers in a 5 × 6 matrix addressing arrangement.

The direct addressing of each pixel in a display is an obvious approach and is used extensively for the lowest of low-information-content displays where fewer than 30 pixels are used. There are typically 7 pixels or segments for each numeric character, plus 1 for decimal or colon. In a typical computer display with 480 rows of 640 pixels, or 307,200 or more total pixels, it is technically impossible to connect electronically to each pixel individually.

Matrix addressing has been the most fruitful way to address a large array of pixels. Each pixel is in a row and a column that can be addressed by common electrodes. In the computer example given in the preceding, the 480 rows and 640 columns are each connected by an electrode for matrix addressing as shown in Fig. 6. In this technique, for a monochrome display, there are 480 row signal drivers and 640 column signal drivers connected to the edges of the display panel. A color display requires three times the columns for red, green, and blue subpixels, or 921,600 total subpixels.

Cross Coupling

Cross coupling in matrix addressing is difficult to describe and compute without resorting to writing all the loop and node equations based on Kirchhoff's Laws and solving the equations with matrix algebra. However, the equations are simplified by observing that all pixels have identical impedance and all the row and column electrodes can be assumed to have zero impedance. If the pixels did not have identical impedance and the electrodes had significant impedance, the displayed image would not be uniform.

In FPDs cross-coupling degrades the image directly. The image is seen by the viewer because there is a luminance contrast difference between the pixels. This is usually characterized as the contrast ratio of the luminance of the pixel commanded "on" to a neighboring pixel commanded "off." The maximum contrast ratio can be shown to be inversely proportional to the number of rows in the array, and independent of the number of columns, so long as the columns are addressed in parallel as discussed in Ref. 1.

Furthermore, it can be shown that there is nothing that can be done in the external circuit to minimize the cross-coupling beyond making the voltage apply to all "off" pixels, one-third that of the "on" pixels. This can best be seen by drawing a loop-and-node diagram of the entire matrix-addressed array and tying all the common nodes together (Ch. 5 of Ref. 1).

The minimum effect of cross-coupling is directly proportional to the response of the pixel intended to be "off" times the number of rows in the display panel when using line-at-a-time addressing and optimum voltages. The "off" pixel looks more and more like an "on" pixel as the number of rows increases; thus the contrast ratio becomes smaller and smaller, which directly degrades the quality of the image. To minimize the impact of cross-coupling, display material that has little or no response at the cross-coupled voltage is selected. This is why ELD, PDP, ferroelectric, and LED make good FPD materials. Other technologies, such as FED and VFD, use three-terminal pixels, and the third terminal acts like a filament switch as in a triode vacuum tube. The structure is now very complicated when compared to simple two-terminal matrix addressing.

The response of a cross-coupled ELD pixel is reduced by orders of magnitude. Gas mixes have no response due to a voltage threshold, ferroelectric materials have no response due to hysteresis, and LEDs have no response because cross-coupling is inhibited. At least one reverse-biased pixel occurs in every cross-coupling current loop in a diode matrix. Furthermore, TN LC, electrochromic, electrophoretic, incandescent, and many other technologies do not work well in matrix-addressed displays because these materials have a nearly linear optical response with applied voltage. For example, with such technologies a switch like a TFT or a nonlinearity like an MIM diode must be added at each pixel. Such additions always add significant complexity to matrix-addressed displays.

Over the years this cross-coupling problem has led to many false promises in the display device industry. Typically, a display breadboard of a small number of rows and columns is made and successfully operated with insignificant cross-coupling. The severity of cross-coupling only becomes apparent when the full-scale display with all rows operating is made and demonstrated. It cannot be overemphasized that the cross-coupling issue is the most difficult design problem in the development of an FPD.

Duty Cycle

The second major issue with FPDs is the duty cycle, which is the time spent turning "on" a pixel or a row of pixels.

For a CRT the duty cycle is the time during which the electron beam excites the area of the phosphor associated with one pixel. In a raster-scan CRT the pixels are addressed sequentially. The duty cycle is then the reciprocal of the product of the number of pixels in the raster. Thus, for a CRT displaying VGA format (480 × 640 pixel matrix) at 72 frames/s, the duty cycle is $1/(480 \times 640) = 3.26 \times 10^{-6}$ and the dwell time on each pixel is $(3.26 \times 10^{-6})/72 = 46$ ns. Fortunately, CRT phosphors can absorb sufficient energy during this short dwell time to emit sufficient light until the next scan cycle. The resulting light is actually emitted for several ms after the beam leaves the area during a period of time called "persistence." FPDs, in general, also respond with a delayed optical effect. One exception is LEDs, which only emit a photon when an electron transcends the diode junction. As a consequence, LEDs turn "on" and "off" in nanoseconds.

The duty cycle of FPDs is made significantly greater than that of CRTs by addressing the columns in parallel. As a consequence, the FPD dwell time for the forementioned VGA example is 480 times longer; 15 μs are needed to turn on ELD and PDP pixels. This is purely a materials issue and cannot be altered significantly by the electronics. The electrical drive signal in these two examples must be on the order of 200 V with a fast rise time that contributes to EMI.

Efficacy

Display materials efficacy is a major issue. It has been a continuous challenge to make displays as bright and efficient as possible. Only a few materials qualify that are also matrix-addressable. The material must also have a high response speed because of the duty cycle consideration.

Thus far, in the case of ELDs, zinc sulfide activated with manganese has been one of the few successful thin-film EL materials in production. It has a basic material efficacy of approximately four lumens per watt in monochrome and luminance in a display of about 90 cd/m^2 with a yellow-orange color centered at 583 nm. However, the ultimate criteria for display efficacy are total lumens in a Lambertian distribution toward the viewer divided by total power consumed in the display. For the ELD described here, this efficacy is less than 1 lm/W. There is the promise of new materials because so many combinations and types of hosts and activators exist, but none have been found after over fifty years of research.

In this category PDP materials are not as good as ELD materials. The primary gas mixture used for monochrome displays has been neon, typically combined with 0.1% argon, called the "Penning Mixture." The efficacy is less than 1 lm/W, and luminance in a display application is less than 100 cd/m^2. The new large 20- and 40-inch (0.5 and 1.0 m) diagonal displays demonstrated by Fujitsu, Photonics, Plasmaco, and others have an efficacy of 0.7 lm/W and luminance of 35 cd/m^2 using a gas mixture designed for UV emission and fluorescent phosphors for color.

The color LCDs need a backlight due to the absorption of the pixel color filter black matrix and polarizers, which reduce the transmittance of an AMLCD to approximately 7%. Highly efficient fluorescent cold– and hot cathode lamps have a luminous efficacy of 40 and 80 lm/W, respectively. The brightness can be made at any level, independent of the LCD panel, by simply increasing the intensity of the backlight. A luminous efficacy of over two lm/W in color has been achieved with color AMLCD, which exceeds all other display technologies, including CRTs under similar performance conditions. The color CRT has an overall luminous efficacy of 1 lm/W or less.

If power is really at a premium and some sacrifice in readability can be tolerated, as is often the case in highly portable products, then the LCD can be used in the reflective mode. The luminous efficacy of LCDs in the reflective mode is orders of magnitude higher than with a backlight. A low-power backlight may be used for viewing the display in the dark. In this case the back reflector is made partially transmissive and is called a "transflector." The sacrifice in performance is in the brightness of the display, which is about one-fourth that of the surrounding ambient brightness. Compensation can be made for this by making the image larger. Comparing an LCD calculator and an LED calculator will give a good example of this discussion.

Ambient Illumination

To the electronic displays engineer, the most perplexing installation problem is the impact of the ambient illumination reflecting off the display surface. Ambient illumination can be very high when compared to the emitted luminance. At the display surface the reflected ambient illumination is added to the emitted luminance, which inevitably reduces the contrast ratio. In equation form,

$$\text{Contrast ratio} = (L_{\text{on}} + \text{Reflections})/(L_{\text{off}} + \text{Reflections})$$

where L_{on} is the display's emitted luminance of the "on" pixel and L_{off} is the luminance of the "off" pixel. The luminance of the "off" pixel is due to cross-coupling, internal light scattering, and/or light piping.

The reflections of the "on" and "off" pixels are the same for all electronic displays except for LCDs. The first surface reflections are typically 4% due to the mismatch of the indices of refraction between air and glass, which can be minimized with antireflective coatings using an index-tapered sequence of thin films. However, this is only the first of many surfaces in a typical display. In CRTs the major problem is the phosphor itself, which is an excellent Lambertian reflector with typical reflectivity of 80%. This is the principal reason CRTs cannot be used in the bright outdoors without special filters and significant additional power.

The displays engineer's classical technique to counteract high ambient illumination is to use antireflective coatings for the first surface and neutral density filters for internal reflections. The neutral density filter always helps the contrast ratio because the ambient illumination must pass through the filter twice—once going in and once when reflected back—whereas the emitted luminance need only pass through the neutral density filter once going out. The problem with this approach is that the display now becomes dimmer. The classical solution is to increase the emitted luminance. Consequences of this "solution" are a larger power requirement, shorter life, etc. The solution works, but at some point the display cannot produce enough luminance to be readable at the highest ambient illumination.

The second technique to obtain further contrast ratio improvement is to use narrowband-emission phosphors for the display and a notch filter to match the emission of the display. This technique, using narrowband phosphor, was a breakthrough necessary to make monochrome and color avionic CRTs readable in direct sunlight.

A third technique used often in LED, VFD, ELD, and PDP FPDs is to use a circular polarizer that traps much of the reflected ambient illumination due to a phase shift of 180° of the incoming light at the reflecting surface. Ideally, reflected light is fully absorbed by the polarizer if no scattering occurs. The emitted light is only 50% absorbed.

In general, a combination of antireflective coatings, neutral density filtering, notch filtering, and circular polarizers, plus first-surface frosting to defocus any first-surface reflections, is used. These techniques improve a display after it has been optically "cleaned up," that is, eliminate or minimize all reflections to the greatest extent possible inside the display. One of the most effective cleanups is a "black matrix," which is used to blacken all the nonemitting areas between the pixels. A black matrix is used on almost all displays. Techniques using, where appropriate, black phosphors, black dielectrics, and black electrodes have never been fully realized due to fundamental material properties of phosphors, dielectrics, and conductors.

The Liquid Crystal Display Advantage

When compared to all other emitting displays, backlit LCDs are unique. Liquid-crystal displays are black-absorbing displays because they use polarizers that absorb all the incident ambient light. They need the first surface reflections' antireflective coatings and/or first-surface frosting. These LCDs cannot benefit from neutral density filtering, notch filtering, or circular polarizers. Their contrast ratio is achieved through the difference between absorbed and transmitted light. The light is transmitted from a continuously emitting back light and reflected ambient illumination. Each of the color filters of an LCD acts like a switchable notch filter and renders an LCD highly immune to ambient illumination. A small portion of the ambient light entering the open or "on" pixel is reflected by the backlight back through the "on" pixel but not through the "off" pixel, thus enhancing the contrast ratio. This contribution to the contrast ratio is small due to the low transmittance of color LCDs. However, it is extremely important because it does not degrade the contrast as in all other electronic displays but improves it slightly.

Immunity to ambient illumination is the single most important performance advantage of LCDs over all other FPDs.

Final Considerations

Liquid crystal display may become analogous to FPD at the present rate of LCD technology evolution. The possibility of finding a new FPD technology is highly unlikely. Research in FPDs should continue, but it may be more productive if applied to LCDs or materials with similar electrooptic properties or to the applications of the LCD infrastructure, such as applying TFTs to other materials.

Scientists doing materials research for display applications often do not appreciate the subtle and complex engineering issues in electronic displays.

BIBLIOGRAPHY

1. L. E. Tannas, Jr., *Flat-Panel Displays and CRTs,* New York: Van Nostrand-Reinhold, 1985.
2. P. A. Keller, *The Cathode-Ray Tube: Technology, History, and Applications,* New York: Palisades Press, 1991.
3. Y. A. Ono, *Electroluminescent Displays,* Singapore: World Scientific, 1995.
4. A. R. Kmetz and F. K. von Willisen (eds.), *Nonemissive Electrooptic Displays,* New York: Plenum, 1976.

5. L. E. Tannas, Jr., et al., *Flat-Panel Display Technologies: Japan, Russia, Ukraine, and Belarus,* Park Ridge, NJ: Noyes Publications, 1995.
6. P. M. Alt and P. Pleshko, Scanning limitations of liquid-crystal displays, *IEEE Trans. Electron Devices,* **21**: 146–155, 1974.
7. S. Morozumi, et al., B/S and color LC video display addressed by poly-Si TFTs, *SID 83 Dig.,* 1983.
8. T. Scheffer and B. Clifton, Active addressing method for high-contrast video-rate STN display, *SID 92 Dig.,* 1992.
9. B. Bahadur (ed.), *Liquid Crystals: Applications and Uses,* Vols. 1–3, Singapore: World Scientific, 1990.
10. Y. A. Ono, *Electroluminescent Displays,* Singapore: World Scientific, 1995.
11. L. E. Tannas, Jr., et al., *Flat-Panel Technologies,* Park Ridge, NJ: Noyes Publications, 1995.
12. L. W. MacDonald and A. C. Lowe, *Display Systems,* New York: Wiley, 1997.

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