Thin-film-transistor/liquid crystal display technology—An introduction

by W. E. Howard

Liquid crystals are simple and very efficient electro-optic transducers, or light valves. Thin-film transistors are simple electronic control devices which can be fabricated on large transparent substrates. These two technologies, when combined, allow the fabrication of electronic displays which challenge the dominance of the cathode ray tube (CRT). This paper reviews the history of this important development, presents the current status in comparison to the color CRT, and describes the remaining challenges to be overcome if the color CRT is truly to be displaced.

Introduction

Two classes of electronic display have greatly changed the way we live and work—television receivers and computer display monitors. Until recently, both of these have been based upon one technology, the cathode ray tube (CRT), which dates from the 19th century. Over the years, CRT technology has been refined and extended until, today, one can buy high-definition television monitors with 40-in.-diagonal screens which can display images rivaling those projected from 35-mm slides. Nevertheless, this marvelous technology is losing its dominance to relatively new flat-panel technologies, principally because you cannot fit a color CRT in your pocket, nor can you fit one in a notebook computer.

The tremendous progress in integrated electronics has brought us to the point where the electronics of a television receiver is indeed pocketable, and where significant computing capability can be packaged in a notebook-sized product. This has created a huge and rapidly growing demand for light, thin flat-panel displays which can provide the images needed for these applications.

Display engineers have, of course, been dreaming of thin, flat screens since the advent of television. The dreams have spawned many inventions over the decades, but most of these have never attracted any significant interest or investment, either because they could not match the performance of a CRT or because they could not compete in cost. In the latter case, it has always been felt that thinness alone would not support much of a cost premium, and since new technologies typically have high initial costs, there was a very major barrier to innovation. The market for portables has transformed this situation, because the CRT is no longer a competitor.

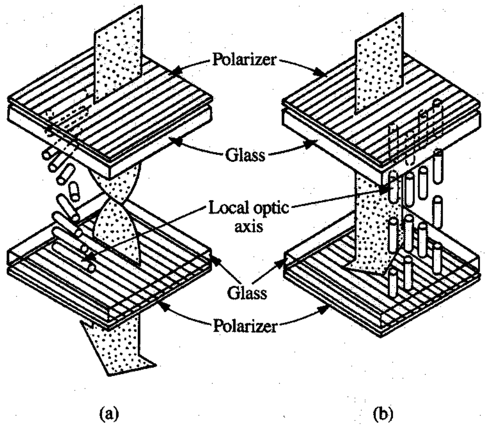

Figure 1

Schematic view of the operation of a twisted nematic (TN) liquid crystal cell. When no voltage is applied (a), the polarization of the transmitted light is rotated, and transmission of the cell is a maximum; with voltage applied (b), the polarization is unchanged, and there is no transmission (see text).

The first successful high-information-content flat panels were plasma panels, which emitted orange light from neon-based gas mixtures. These are still widely used, but full-color versions have been difficult to develop and tend to be limited in resolution, so that they are more suitable for group viewing than for personal use. They also tend to be power-hungry, with efficiencies typically in the range of 0.2–0.4 lumens per watt.

Electroluminescent (EL) displays, which are all solid-state, use the direct production of light in thin films and powders to provide mostly yellow displays of good appearance and moderate cost. These compete successfully with plasma displays in some applications, but they also tend to be too power-hungry for battery-powered portable products. In addition, a full-color display has been elusive because of the unavailability of a good blue EL phosphor.

The problems of these two technologies have caused more and more product designers to turn to liquid crystal (LC) displays, which have consequently experienced phenomenal growth. The success of liquid crystal displays has fostered continued development, to the point where full-color video displays have been realized which can rival and even surpass the CRT in appearance. It is this fact, coupled with relatively good efficiency and the potential for ultimate costs competitive with those of CRTs, which has led IBM to invest in the technology, in partnership with Toshiba, and which has provided the motivation for the work described in the papers of this special issue.

Liquid crystal displays

Liquid crystals (see for example [1]) are materials which exhibit many of the properties of liquids but which differ in having less symmetry than simple liquids, which are isotropic in their properties. Among liquid crystals, the simplest type is called *nematic*; it is characterized by having a preferred direction or axis, for asymmetrical mechanical and optical properties. Such asymmetrical optical properties are at the root of all display applications.

The first liquid crystal displays were described by Heilmeier et al. in 1968 [2]. They were based upon a phenomenon known as dynamic scattering, wherein the passage of current through a nematic liquid crystal causes the material to break up into domains having randomly directed axes. Since the domains are optically asymmetrical, they scatter light, rendering the material reflective or cloudy. This was recognized as offering a potential for electronic displays, even though the voltage for saturation was fairly large in relation to the threshold voltage for change, implying that efficient x-y addressing would not be practical for large matrices.

In 1971, a new type of liquid crystal display was described by Schadt and Helfrich [3]: the twisted nematic (TN) display. In this display, a nematic liquid crystal is contained by two closely spaced (5–20 μm apart) glass plates which have been coated with a polymer and rubbed in such a way that the nematic LC is aligned parallel to the rubbing direction. If the two plates are rubbed at 90° angles to one another, the liquid crystal deforms into a twisted structure (see **Figure 1**). If polarized light is incident on such a cell, the plane of polarization follows the twist of the LC; i.e., it is rotated by 90° in passing through the cell. If a second exit polarizer (Figure 1) is also rotated 90° with respect to the input polarizer, the light passes through undisturbed. When a strong electric field is applied across the cell, the liquid crystal molecules rotate so as to align themselves with the electric field, overcoming the influence of the rubbing alignment. This leads to a disruption of the twist and consequently the rotation of polarization. The incident light now sees crossed polarizers, and there is no transmission. The transition from full transmission to no transmission takes place over a voltage range of 1–3 V, so shades of gray can be achieved. This device was widely adopted for use in calculators, watches, and numerical readout displays. Twenty years later it is still dominant in these applications.

From the earliest days of liquid crystal displays, however, there has existed a desire to make complex matrix displays which could be used, for example, to display television images. The simplest structure is an x-y matrix in which one plate carries row electrodes and the other column electrodes. The object is to have a set of voltage waveforms for the rows and columns such that any set of intersections can be activated without turning on unselected intersections. Since there is a threshold voltage below which no change in transmission takes place, this x-y selection should be achievable, provided the matrix is not too large. It soon became apparent, however, that for typical TN characteristics, matrices with more than about ten rows showed reduced contrast; that is, the unselected intersections were being partially turned on.

This problem received a general treatment in 1974, in a classic paper by Alt and Pleshko [4]. Because the TN cell is known to respond to the square of the applied voltage, averaged over a time shorter than the transition time, they showed that the achievable ratio of RMS voltage at a selected point relative to the RMS voltage at an unselected point was a simple decreasing function of the number of rows N being multiplexed. Specifically,

$$\frac{\langle V_{\text{on}}^2 \rangle}{\langle V_{\text{off}}^2 \rangle} = \frac{1 + N^{-1/2}}{1 - N^{-1/2}}.$$

Figure 2 shows the transmission vs. voltage (T-V) characteristics for a typical TN cell, for various viewing angles. It is clear that, even for normal viewing, a $V_{\text{on}}/V_{\text{off}}$ ratio of at least 1.4:1 would be required, corresponding to a limit of about nine rows in a matrix. Maintaining good contrast over a wide range of viewing angles would reduce further the number of rows allowed.

Great efforts were made in the '70s and early '80s to develop liquid crystal formulations for which the transition was more abrupt (i.e., for which the T-V curve was steeper), so that larger matrix displays could be produced. Indeed, considerable progress was made, so that by 1983 multiplex ratios of 100:1 were being achieved, with contrasts of 10:1 or more [5].

Just when it appeared that improvements in 90° TN cells had leveled off, the prospects for high-information-content matrixes were given a tremendous boost with the introduction, in 1984, of the supertwisted birefringent effect (SBE) display, in which the twist of the LC was increased to 270°. While such a twist is not stable in a purely nematic LC, since it prefers to twist 90° in the opposite direction, with the addition of cholesteric components (that is, LC materials with a built-in twist) a 270° twist can be stabilized. The T-V transition in such a cell can be extremely steep; indeed, it can be bistable, i.e., with no stable intermediate states. The optical behavior of SBE displays is more complex than that of TN displays and involves the birefringence of the LC, as suggested by the name. SBE displays also are not easy to fabricate, since they require an expensive alignment process and very tight gap control. Nevertheless, they offered the prospect of matrix displays with more than 100 rows with good contrast.

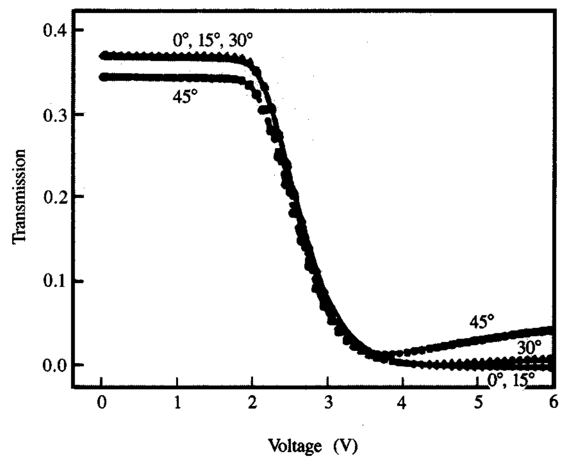

Figure 2

Transmission vs. voltage for a twisted nematic liquid crystal cell, for different horizontal viewing directions, measured from normal incidence.

The SBE concept was soon exploited in a flood of new displays with twist angles less than 270° and greater than 180°. These are generically referred to as supertwisted nematic, or STN, displays. Providing rather steep T-V curves, at least for normal incidence viewing, these displays have allowed multiplex ratios to be pushed to the vicinity of 400. The contrast of such displays falls off rapidly as the viewing angle is changed from normal incidence, but continued improvements based upon the use of compensating filters and new LC materials have maintained this technology as the leading low-cost high-information-content display.

Thin-film transistors

Thin-film transistors (TFTs), or, more precisely, insulated-gate thin-film transistors, date back to the early '60s, when P. K. Weimer [7] reported devices using CdS as the active material (the concept is even older, dating back to 1934). **Figure 3** shows a schematic view of one common type of TFT, a so-called inverted staggered TFT. In such a device there is a gate electrode on the bottom, which is covered with an insulator, followed by the active semiconductor material and a top passivation insulator. The passivation insulator is etched back to allow source and drain contacts to be made to the semiconductor, completing the device. When a voltage is applied to the gate, charge is induced in the normally resistive active layer, making it conducting. The source–drain resistance may thus vary by a factor of 10^6 or more, providing a good switch.

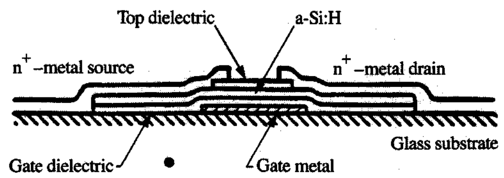

Figure 3

Schematic cross section of an inverted-staggered a-Si:H thin-film transistor (TFT), characterized by a bottom gate electrode and top source–drain contacts.

Thin-film transistors were initially viewed as low-cost alternatives to single-crystal transistors, but they were soon found to suffer from significant performance drawbacks, especially in terms of their stability and their switching speed. This was largely due to the immature technology of deposited insulators and the large density of traps in the CdS and, later, CdSe films.

Various active materials have been used in addition to CdS: CdSe, Te, polysilicon, amorphous silicon (a-Si), amorphous germanium, etc. Among these, the most widely used today are a-Si and polySi, with CdSe a somewhat distant third.

From a practical standpoint, the report of an amorphous silicon TFT by LeComber et al. [8] in 1979 must be considered a major milestone. As they recognized, the characteristics of a-Si TFTs are remarkably well matched to the requirements of liquid crystal driving, since they combine low OFF current with good ON/OFF ratios. Moreover, it was recognized immediately that they could benefit from the tremendous investment in a-Si solar cell technology, which could provide uniform, reproducible film quality over large areas using plasma-enhanced chemical vapor deposition (PECVD). The same PECVD processes could also be used to deposit the gate insulator material, in the same system, so that contamination of the critical interface could be avoided. Perhaps even more important, a-Si TFTs can be made at low temperatures (250–350°C), thus allowing the use of inexpensive glass substrates.

TFT/LC displays

It was recognized early in the history of liquid crystal displays, even before the work of Alt and Pleshko, that simple matrix multiplexing of liquid crystals would not permit high-information-content displays, especially television displays, to be made with acceptable contrast. Thus, there arose the idea of using thin-film devices to make an active matrix which would provide either an improved threshold characteristic, as in the case of putting a nonlinear resistor in series with each LC element, or direct control of the LC voltage, as can be achieved by using a TFT.

A classic paper on this subject is by Lechner et al. [9], who in 1971 analyzed the requirements of an active-matrix LC display and proposed numerous possible approaches, including the use of TFTs. It is a tribute to these authors that almost every one of their schemes has since been implemented in working high-information-content LC displays. These include a two-diode approach, currently being pursued by Philips [10], a ring diode approach, employed by Citizen [11], and a gas-discharge switch, used by Tektronix [12] (although not in quite the same way).

Also in 1971, T. P. Brody and others at Westinghouse, whose TFTs had been in development for some years, received a U.S. Air Force contract to build a TFT/LC display. By 1973, a 6-in. × 6-in. display had been built [14], although most of the effort of the group at that time was in fact focused on TFT/electroluminescent displays.

T. P. Brody is without doubt the principal pioneer of TFT/LC display technology. He had an unshakable vision of the potential of TFT technology to parallel the development of integrated circuits, with ever-increasing complexity and perfection. He and his colleagues initially focused on Te as the active material for their TFTs, but later they switched to CdSe, which offered good mobility and which fitted well their fabrication strategy of patterning devices with evaporation shadow masks.

By 1979, Westinghouse had decided not to continue the TFT work. Brody, however, had not given up, and in 1981 he founded Panelvision in order to pursue the development of TFT/LC displays. Panelvision ultimately became the first company to produce a commercial TFT/LC product, in 1984, but by that time there had been a major upsurge in TFT/LC activity in Japan. The work in Japan was heavily focused on a-Si:H TFTs, although the first product, a 1-in. pocket TV from Seiko-Epson, employed polysilicon TFTs.

In a TFT/LC display, each cell of a matrix has a TFT, the gate of which is attached to a horizontal row electrode and the drain of which is attached to a vertical column electrode. The source of the TFT is attached to the liquid crystal electrode (see **Figure 4**). The display is activated a row at a time, by activating the gate lines. The column electrodes carry the data voltages, synchronized to the gate pulses, so that when a given TFT is turned on, the data line charges up the liquid crystal capacitor, formed between the liquid crystal picture element electrode and an opposing ground plane electrode, to the appropriate voltage on the data line at that time. Then the TFT is turned off, so that the charge is held on the capacitor until the next refresh cycle. To avoid any flicker in the image, typical refresh rates are 60–70 Hz. The data voltage is isolated from the other rows of the display by the TFTs,

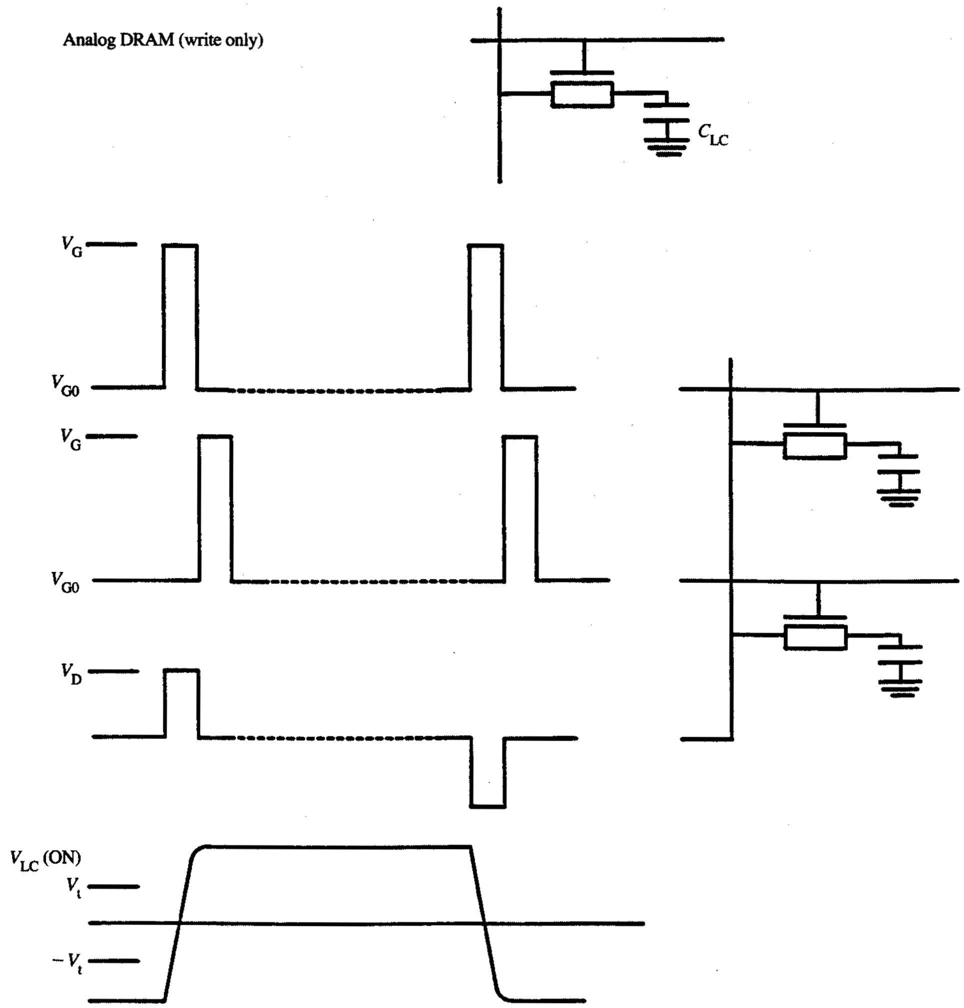

Figure 4

Typical waveforms for a thin-film-transistor/liquid crystal display (TFT/LCD), illustrating an ON cell (first row) and an OFF cell (second row). The voltage V_{cc} (ON) for the ON cell is also shown.

which are turned off, so that crosstalk is very low, even when the number of rows in the matrix is very large, more than one thousand.

The overall effect is almost the same as being able to control, individually and independently, the voltage at each liquid crystal element. Thus, any point on the transmission voltage curve is accessible, leading to good ON/OFF contrast and good gray-scale control.

Full-color liquid crystal displays

Not all liquid crystal development was directed toward the addressing problem. T. Uchida of Tohoku University [15] reported in 1981 an approach to color LC displays using micro color filters incorporated *inside* the display, to avoid any problems of parallax. He argued that by putting a white light behind the display and having red, green, and blue filters on separate electrodes within each picture element (pixel), a color display could be made which would be analogous to a color CRT (see **Figure 5**).

This approach was adopted by Morozumi et al. [16] of Seiko-Epson when, in 1983, they captured the imagination of the display community with a 1-in. TFT/LC color TV. For anyone with doubts about what liquid crystal displays could do, the Morozumi demonstration was persuasive. It

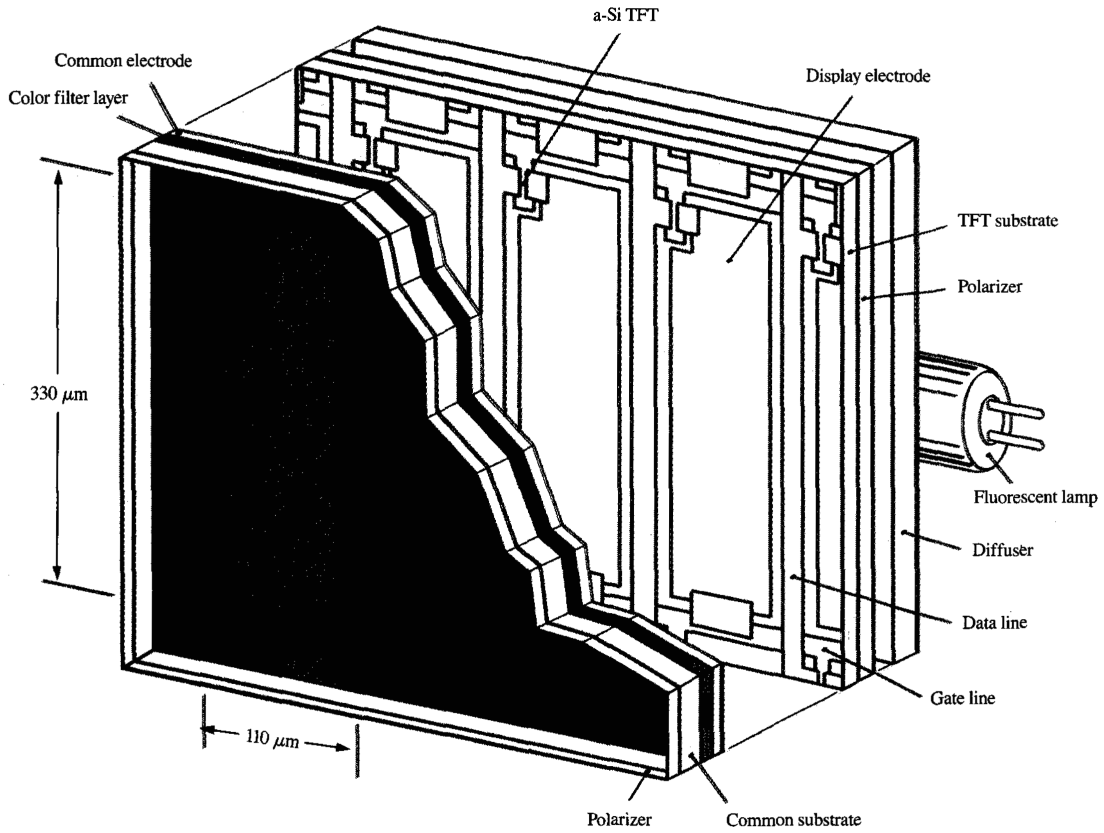

Figure 5

Schematic rendering of a portion of the structure of a complete TFT/LCD panel. Light from a fluorescent lamp passes through individual liquid crystal cells, each of which is controlled by a thin-film transistor and each of which has associated with it a color filter. The overall result is an array of individually controlled red, green, and blue light sources which can reproduce an arbitrary image, in analogy with a color cathode ray tube.

probably triggered more interest and more investment than any display prototype in recent memory. In the last eight years, more than twenty companies have demonstrated TFT/LCD prototypes, with the list including all of the major electronics companies in Japan, as well as a few companies (or laboratories) in the U.S. and Europe.

The principal drawback to this approach to color displays is the reduction of efficiency caused by absorption in the color filters. Even for ideal filters, only one third of the lamp spectrum is transmitted by each filter, and since ideal polarizers only transmit one half of the light, the theoretical efficiency is less than one sixth the efficiency of the lamp. In practical terms, the filters only transmit about 25% of white light and polarizers about 40%, and the useful area of a cell is 50% or so, leading to an overall transmission of about 5%. Fortunately, fluorescent lamps are very efficient, with efficiencies of 50–70 lumens per watt, even for small lamps. On the other hand, backlight diffusing systems are only 30–50% efficient, so that overall efficiencies are in the range of 1–2 lumens per watt for color TFT/LC displays. This is still more efficient than most color CRT displays.

The fluorescent lamps which are used in backlighting are of the three-band type; that is, they emit predominantly in red, green, and blue spectral regions. Without this fortunate circumstance, color filter efficiency would be considerably lower than 20%.

The penalty in efficiency in achieving color is analogous to the situation in color CRTs, where 80–90% of the electron-beam current is intercepted by the shadow mask.

In addition to the loss of efficiency, there is a loss of resolution in color displays, in comparison to monochrome

Table 1 Comparison of color CRTs and color LCDs.

	CCRT	*TFT/LCD*
Resolution	4/mm	5/mm
Contrast	50:1	>200:1
Color gamut	Equal	
Response time	<1 ms	<20 ms
Shading	Analog	Analog
Total content	4×10^6 pixels (low luminance)	$>1 \times 10^6$ pixels
Luminance	400 nits (cd/m^2) ($<1 \times 10^6$ pixels)	>400 nits
Efficiency	0.5 (high res.) –3.0 (low res.) lumen/W	1–2 lumen/W
Cost (10-in.-diag. image)	\$100–300	\$1500
Viewing angle	±90°	±50° (horiz.) ±30° (vert.)

displays, since three cells and three thin-film transistors must be used for each full-color picture element, or pixel. Moreover, the lateral displacement of the three color arrays with respect to one another introduces a visual error in the image. Finally, the color filter plates are currently quite expensive, so that there is a significant cost premium for color.

Replacing the color CRT

For any color display technology to replace the color CRT, it is essential that all of the key characteristics be matched or exceeded. Resolution and contrast are the most basic. Resolution must exceed 4/mm in reasonably large displays, with contrast greater than 50:1. TFT/LC displays have exceeded these characteristics, especially when one considers contrast in high ambient illumination, e.g., in direct sunlight. In a CRT, the phosphor strongly reflects ambient light, whereas in a TFT/LCD the color filters absorb most of the ambient light.

The range of colors is another important characteristic, and in this area the TFT/LCD is at least as good as a color CRT. Both displays allow continuous shading or gray scale, with the range being defined by the maximum contrast. Some early TFT/LC data displays are deficient in the number of gray shades allowed only because they employ digital data drivers with 3 or 4 bits, but this is a temporary limitation which does not apply, for example, to pocket TVs.

Since color CRTs are widely used to show television images, it is necessary to have a sufficiently fast response time or update time for an image, usually less than 30 milliseconds.

In several respects the TFT/LCD image is superior to that of a color CRT, as is shown in **Table 1**. Color CRTs suffer from defocusing and convergence errors at the edges of the screen, and from nonlinearity in beam positioning. They also show much lower contrast in fine patterns than in coarse ones; TFT/LCD contrast is preserved down to the single-pixel level.

This set of attributes basically ensures that TFT/LCDs will replace CRTs in large numbers provided that the cost can be reduced to be more competitive. Cost projections for TFT/LC technology predict that the costs will be competitive, in the important 10–14-in. sizes, certainly by the year 2000 and probably in the late 1990s.

Today, there are products in high-volume manufacture with 10-in.-diagonal screens and 640 × 480 formats. Prototypes have been shown of million-pixel workstation displays in sizes up to 16 in. diagonal.

The competition of TFT/LCD technology with CCRT technology goes beyond direct-view applications. There is a parallel competition in projection displays, which ultimately may have even greater economic impact, as projection displays with 40–50-in. screens are expected to be the most popular medium for high-definition television viewing in the late 1990s. Projection cells using TFT/LC technology, either a-Si:H or polysilicon-based, are already at the HDTV level in prototypes, and products are available which give excellent renderings of standard 525-line TV images. It appears that projection systems using TFT/LC technology will be lighter, cheaper, and more accurate than CRT-based systems.

Remaining challenges

In addition to cost, a number of challenges must be met if TFT/LC displays are to realize their potential fully. First, improvements to the array technology are needed if larger displays with higher content and higher resolution are to be achieved. Higher-conductivity metals and higher mobility in the semiconductor material will enable these improvements to be made, while at the same time increasing the aperture ratios, or percentages of active area, for such displays. This is important for decreasing power consumption. Since power is so critical for portable applications, significant improvements will also be needed in backlighting techniques. Flat fluorescent lamps, which are under development, are an example of an innovation which could reduce significantly not only the power consumption but also the thickness of TFT/LC displays.

Large areas are another challenge. While glass is readily available in large sheets, and thin-film deposition techniques are well developed for large areas, we need to develop patterning techniques which will be economical for large areas. Existing step-and-repeat exposure systems are relatively easily scaled to larger sizes, but they will result in proportionately higher costs. Also needed are better techniques for making large-area liquid crystal cells while maintaining the tight tolerances required on glass spacing.

The viewing angle of today's twisted nematic displays is not adequate for all applications. Although the viewing has been made quite uniform in the horizontal direction, the satisfactory viewing range in the vertical direction is limited. We need to develop new cell designs and perhaps even new liquid crystal modes to overcome this limitation, which is especially noticeable for video-image applications and for large screens. Further in the future, perhaps solid materials can be developed which could replace the liquid crystal as the electro-optic transducer. Then we could have an all-thin-film structure on a single sheet of glass. If such a device could also modulate unpolarized light, efficiency would be improved at the same time.

Finally, we must return to cost. The value of the raw materials in a TFT/LCD is rather low, so from the driver chips to the color filters to the transistor array, even the liquid crystal, most of the cost is in processing. As we continue to simplify and automate processes and reap the economies of scale, we have good prospects for reducing costs. However, experience suggests that such progress does not come easily, from a few brilliant insights, but rather requires the efforts of many engineers over many years.

References

1. P. G. de Gennes, *The Physics of Liquid Crystals*, Clarendon Press, Oxford, UK, 1974.
2. G. H. Heilmeier, L. A. Zanoni, and L. A. Barton, "Dynamic Scattering: A New Electrooptic Effect in Certain Classes of Nematic Liquid Crystals," *Proc. IEEE* **56**, 1162 (1968).
3. M. Schadt and W. Helfrich, "Voltage-Dependent Optical Activity of a Twisted Nematic Liquid Crystal," *Appl. Phys. Lett.* **18**, 127 (1971).
4. P. M. Alt and P. Pleshko, "Scanning Limitations in Liquid Crystal Displays," *IEEE Trans. Electron Devices* **ED-21**, 146 (1974).
5. Y. Ishii, S. Kozaki, F. Funada, M. Matsumura, and T. Wada, "Optimum Polarizer Condition in TN-LCD for High Level Multiplexing," *Japan Display '83, Proceedings of the 3rd International Display Research Conference*, Society for Information Display, 1983, p. 470.
6. T. J. Scheffer and J. Nehring, "A New, Highly Multiplexible Liquid Crystal Display," *Appl. Phys. Lett.* **45**, 1021 (1984).
7. P. K. Weimer, "The TFT, A New Thin-Film Transistor," *Proc. IRE* **50**, 1462 (1962).
8. P. G. LeComber, W. E. Spear, and A. Ghaith, "Amorphous Silicon Field-Effect Device and Possible Application," *Electron. Lett.* **15**, 179 (1979).
9. B. J. Lechner, F. J. Marlowe, E. O. Nester, and J. Tults, "Liquid Crystal Matrix Display," *Proc. IEEE* **59**, 1566 (1971).
10. K. E. Kuijk, "DR, a Versatile Diode Matrix Liquid Crystal Approach," *Eurodisplay '90, Proceedings of the 10th International Display Research Conference*, VDE Verlag, Berlin, 1990, p. 174.
11. S. Togashi, K. Sekiguchi, H. Tanabe, E. Yamamoto, K. Sorimachi, E. Tajima, H. Watanabe, and H. Shimizu, "A 210 × 228 Matrix LCD Controlled by Double Stage Diode Rings," *Eurodisplay '84, Proceedings of the 4th International Display Research Conference*, S.E.E. Paris, 1984, p. 141.
12. T. S. Buzak, "A New Active-Matrix Technique Using Plasma Addressing," *Digest of Technical Papers, 1990 SID International Symposium*, Society for Information Display, 1990, p. 420.
13. T. P. Brody, "The Thin Film Transistor—A Late Flowering Bloom," *IEEE Trans. Electron Devices* **ED-31**, 1614 (1984).
14. T. P. Brody, F. C. Luo, D. H. Davies, and E. W. Greeneich, "Operational Characteristics of a 6 in. by 6 in., TFT Matrix Array, Liquid Crystal Display," *Digest of Technical Papers, 1974 SID International Symposium*, Society for Information Display, 1974, p. 166.
15. T. Uchida, "A Liquid Crystal Multicolor Display Using Color Filters," *Eurodisplay '81, Proceedings of the 1st International Display Research Conference*, Society for Information Display, 1981, p. 39.
16. S. Morozumi, K. Oguchi, S. Yazawa, T. Kodaira, H. Oshima, and T. Mano, "B/W and Color LC Video Display Addressed by Polysilicon TFTs," *Digest of Technical Papers, 1983 SID International Symposium*, Society for Information Display, 1983, p. 156.

Received November 18, 1991; accepted for publication February 4, 1992

Webster E. Howard *IBM Research Division, Thomas J. Watson Research Center, P.O. Box 704, Yorktown Heights, New York 10598 (HOWARD at YKTVMV, howard@watson.ibm.com).* Dr. Howard received the B.S. degree in physics from Carnegie Mellon University in 1955 and the A.M. and Ph.D. degrees in physics from Harvard University in 1956 and 1962, respectively. At Harvard he was a National Science Foundation Predoctoral Fellow. He joined IBM in 1961, and since that time has worked at the Thomas J. Watson Research Center as a Research Staff Member. His activities have been primarily in the areas of semiconductor physics and display technology, including work on electron quantization in surfaces, semiconductor superlattices, heterojunctions, and the band structure of IV–VI compounds among the topics in physics, and including plasma technology, electrochromics, thin-film electroluminescence, and thin-film-transistor/liquid crystal technology among his areas of interest in displays. Currently, he is manager of the Flat Panel Display Technologies group. Dr. Howard is a Fellow of the American Physical Society, a Fellow of the Society for Information Display, a Senior Member of the IEEE, and a member of Sigma Xi. He is currently Secretary of the Society for Information Display. In 1981, he was a co-recipient of the Wetherill Medal of the Franklin Institute, and in 1989 he received an IBM Corporate Technical Award for his work on 2D electron gases. He holds seven U.S. patents in semiconductor and display technology.