Plenary Lecture. New challenges for dot-matrix liquid-crystal displays

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Plenary Lecture

New challenges for dot-matrix liquid-crystal displays

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Commercially available high-information liquid-crystal display panels are based on both multiplexed twisted nematics or compensated supertwist nematics and on switching arrays of TFTs or MIMs. The corresponding applications are monochrome screens for portable computers and word processors and pocket colour TV sets. The most recent achievements in research and development using multiplexed technologies such as supertwist nematics or electrically controlled birefringence will make possible the fabrication of larger-size colour panels for colour graphics terminals (14 in. diagonal, 8 colours or even full colour). The cost will be reduced by using driving circuits with a large number of outputs and cheaper interconnection techniques (e.g. chip-on-glass, TAB). The main problem of active addressing is the low fabrication yield and the reduced size. Innovations have therefore been proposed to solve these difficulties—new architecture of the TFT matrix, introduction of redundancy, reduction of the critical steps—these will lead to valuable TV applications in the near future. Regarding the emerging technology of ferroelectric liquid crystals, progress has been observed in size, response time, colour and even the capability of grey scales, but all of these possibilities have not yet been demonstrated together. The future challenge for liquid-crystal displays will be without any doubt the feasibility of large colour panels with about four million dots for HDTV. For such metre-sized screens different solutions can be imagined—direct view or projection devices—but in both cases major difficulties remain to be overcome, ranging from cell technology, electrical attenuation and crosstalk to lighting conditions.

1. Introduction

The purpose of this paper is to try to outline the potentialities of the different liquid-crystal display (LCD) technologies for some of the major application markets of the near future as well as in the medium and longer term. We start from the market requirements, the question being what is the best LCD for what application? Then we shall review all of the current candidates, and the basic operating principle of each technology will be described briefly. Starting from the current state of the art, we shall try to establish a comparison between the potential performances of these LCD technologies. Finally, we shall define the new challenge to be faced in order to succeed in the most exciting consumer market for displays in five to ten years; that is, high-definition television (HDTV).

2. Future specifications for LCD flat panels

From market surveys, we can see that computers and TV will be the major application markets for LCDs for some years. Consequently only these two specific

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applications will be considered. Both require large-size LC panels with colour capability, a large number of pixels and the best possible viewing quality.

2.1. *Computers*

The predictable evolution of computers is shown in table 1. Flat-panel specifications will follow the progresses of microprocessor power and also the related software development. Starting from the popular 640 × 200 or 640 × 400 monochrome monitors that are commerically available on portable personal computers, the next step will be multicolour panels, and ultimately full colour panels will be developed. The definition will increase continuously—probably up to the 1000 × 1000 range. At most, the need for sophisticated colour graphics with picture motion will make video-rate compatibility necessary.

Table 1. Probable evolution of flat panels for computers and office automation.

	1987	1988	1989	1990	1991
MPU system	lap-top computers 8 bits/16 bits			lap-top and desk-top computers 32 bits	
Resolution	640 × 200	640 × 400	640 × 480	720 × 512	1240 × 1024
Grey scale and colour	Monochrome black & white	Grey scale		Multicolour	Full colour
Size/in.	12	12		14	> 14
Required contrast	CR ⩾ 5:1	CR ⩾ 10:1			CR ⩾ 20:1
Response time/ms	200	100			50

From these general specifications, we can define the detailed characteristics required for colour LCDs for the next generation of portable microcomputers (see figure 1). We take here the example of a multiplexed LCD, which seems more realistic for a 14 in. diagonal panel. To keep the duty ratio as low as possible in order to obtain better contrast, it is usual to divide the matrix into upper and lower submatrices.

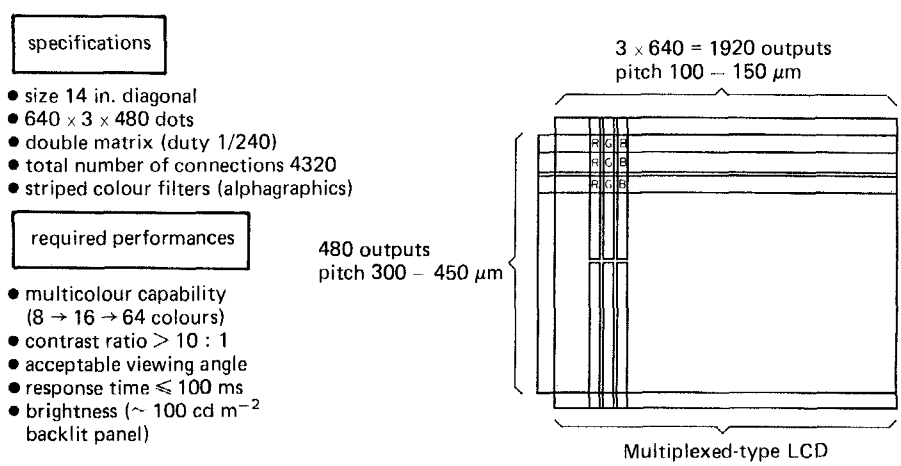


Figure 1. Specifications for a colour-graphics LCD panel for a portable PC.

In this case the number of external connections will be more than 4000 and the horizontal pitch of each of the R, G, B dots will be in the 100 μm range. We shall see that solutions are already under development and perfectly compatible with this specification.

2.2. *Television*

As for the second very important application, television (see table 2), we shall only discuss the future requirements for HDTV. Two approaches are generally considered for HDTV:

(*a*) one with a direct-view large screen (e.g. 40 in. diagonal);
(*b*) the other using projection from either a small-size colour liquid crystal cell or three monochrome cells (indeed the transmission of a colour LCD is only 5 per cent, while it reaches 30 per cent for a monochrome cell).

The main requirements in this latter case are

(i) a high resolution needed, leading to a very small pixel pitch (some tenths of a micrometre);
(ii) large number of connections (3 × 2400).

But, whatever the technology, the visual result on the screen must have the characteristics shown in table 2. These include contrast, extensive grey scales, high brightness (meaning very high input luminous power), and wide viewing angle (because of the recommended distance to watch HDTV). To ensure that the visual quality will be the best, the screen must be scanned with a 1/1200 duty ratio. In fact, there are only a few LCD solutions potentially able to reach this level.

Table 2. Tentative specifications of LC–TV for HDTV application.

Geometrical specifications			
		Projection type	
	Direct-view type	1 × colour cell	3 × monochrome cells
Size (diagonal)/in. (aspect ratio 16:9)	40	2–4	2–4
Number of lines	1200 (H) 3 × 1200 (V)	1200 (H) 3 × 1200 (V)	1200 (H) 1200 (V)
Horizontal pitch/μm	~250	10–30	30–50
Number of connections	4800	4800	7200

Required characteristics
Single matrix for visual quality (duty 1/1200) Contrast ratio $\approx 60:1$ Very wide viewing angle Full colour (64 → 256 grey scales) Brightness 300–500 cd m^{-2} Response time $\leqslant 20$ ms

3. The different LCD technologies

It is usual to classify these different technologies into *direct addressing*, which means that each pixel is defined by the crossing of two transparent conductive electrodes, and *active matrix addressing*, with an extra switching element at each pixel: it can be either two-terminal or transistor (see figure 2).

In the first case two-terminal devices may be classified by

back-to-back amorphous silicon diodes;
amorphous–silicon ring diodes;
metal–insulator–metal devices (Ta_2O_5);
metal–semi-insulator–metal devices (SiNx).

The most widely used transistor matrices are thin-film transistors made from either polysilicon or amorphous silicon (a-Si : H).

The case of ferroelectric smectic liquid crystals is special in that the intrinsic bistability leads to a multiplexed display without the usual limitations result when the number of scanning lines is increased. For the past few years, there have been

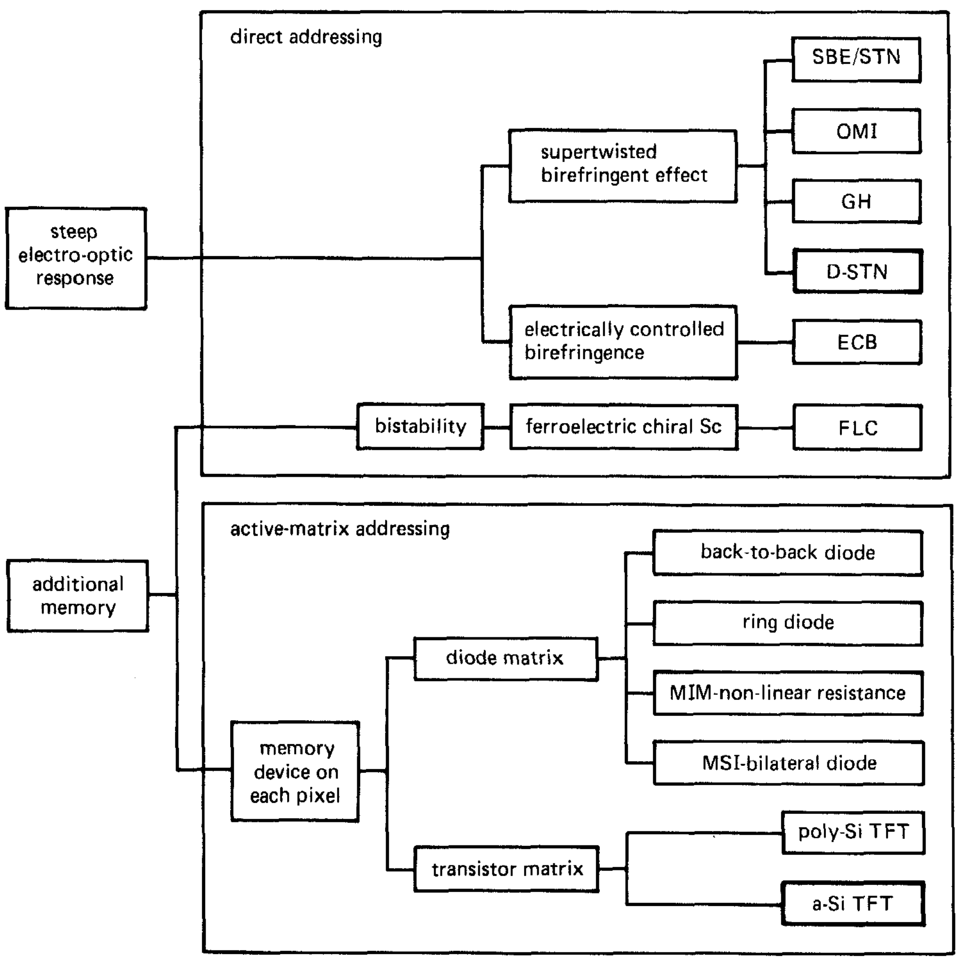


Figure 2. LCD technologies for large-size dot-matrix panels.

interesting innovations in *supertwisted structures* (STN) leading to the black and white compensated STN that is now replacing to an increasing extent the other LCDs in portable computers.

Different modifications have been introduced, which will be described in more detail; these include

SBE	super birefringence effect;
STN	super twist nematics;
OMI	optical-mode interference;
GH	guest–host;
D–STN	double super twist nematics;

Under research and development there are now two new technologies: electrically controlled birefringence (ECB) and ferroelectric liquid crystals (FLC). Both have shown very promising results during the past year. Even though their technology is different from the main stream of twisted LCDs, they will have great potential in the future.

3.1. *Supertwist nematics*

The TN (see figure 3) that is most widely used in commercial products is the standard 90° twisted nematic [1]. A large improvement in contrast and viewing angle has been obtained through the super birefringence effect (SBE) in a 270° twisted structure with a high surface tilt [2].

Unfortunately, in the beginning there were two disadvantages. These were

(i) a colouration in both on and off states (due to a residual birefringence, the polarizers being in an uncrossed position);
(ii) the impossibility of mass producing high-tilt surfaces.

A practical solution has been found by reducing the twist angle with a low-tilt surface. This is now used in all practical STN cells [3].

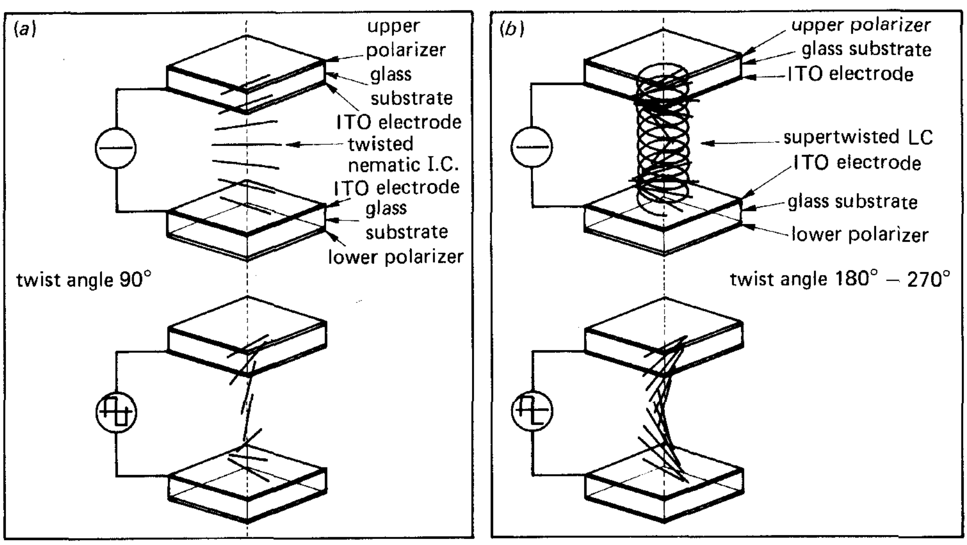


Figure 3. (*a*) Conventional twisted nematic (TN). (*b*) Supertwist nematic STN (SBE, OMI, GH).

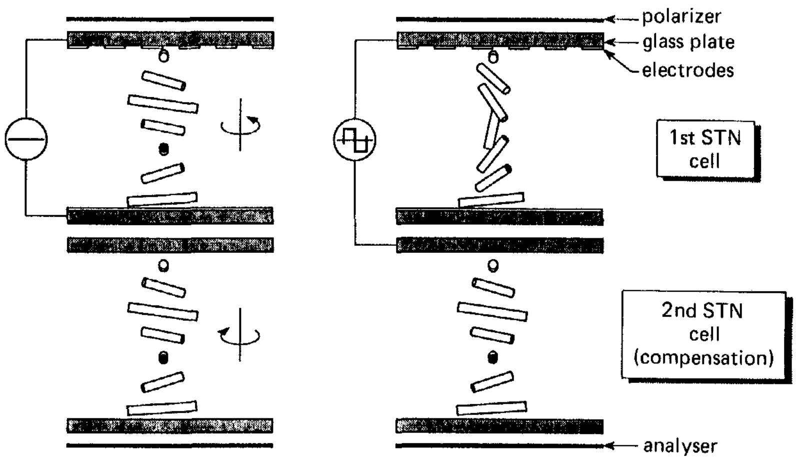


Figure 4. A double supertwist LCD cell (D–STN).

In order to obtain almost black and white STN panels, different innovations have been introduced. These include

(1) decreasing the optical thickness of the birefringent medium (so-called optical mode interference (OMI) [4, 5];
(2) dissolving dye molecules in the liquid crystal in order to obtain a smaller wavelength dependence (G–H) [6];
(3) the most effective innovation—because it retains both brightness and contrast is the double STN or neutralized TN (see figure 4).

In addition to the operating dot-matrix STN cell, an extra STN compensation cell is stacked, the sense of twist being opposite. This cell acts as an optical compensator. In fact, it is possible to compensate for both on and off states. Some trade-off can be obtained by adjusting the relative optical thicknesses of both cells.

At SID 88 [7, 8] it was shown that it was also possible to incorporate colour filters in such a neutral double-layer STN cell in order to realize a multicolour and even full-colour panel. More recently, the compensating LC cell has been replaced by a retardation plate made from a polymer film. Such a technology is well placed to satisfy the specifications for a full-colour panel for portable computers if it is compatible with mass production.

3.2. *Electrically controlled birefringence effect* (*ECB*)

Even though the ECB effect (see figure 5) has been well known for a long time [9, 10], it has only recently shown its capability for full-colour panels with a wide viewing angle and a high multiplexing capability [11, 12]. This electro-optic effect shows an intrinsically steep transmission-versus-voltage response curve because a small variation in the director tilt across the cell produces a large change in the transmission of light between crossed polarizers. Consequently, high multiplexing ratios are possible while retaining good contrast ratio and a wide viewing angle.

The fabrication technology is slightly different from that of twisted nematic cells because a perpendicular (homeotropic) alignment of the director is needed at the cell

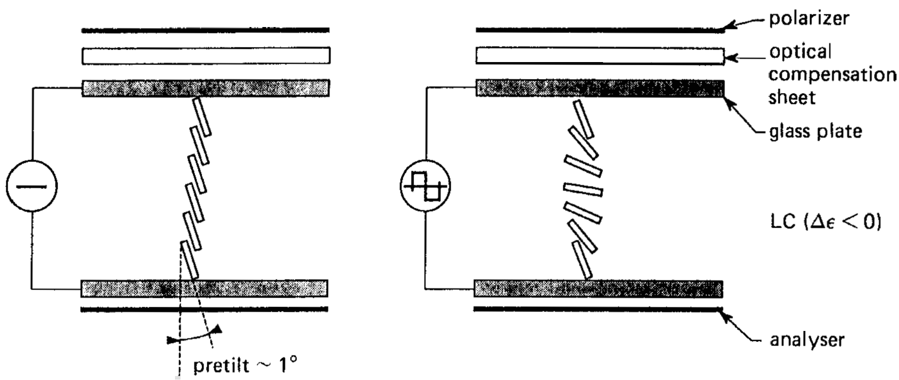


Figure 5. Electrically controlled birefringence (ECB).

boundaries. The major, specific ECB requirements are

(1) perpendicular alignment of the director (with a small pretilt to avoid domain formation);
(2) negative dielectric anisotropy of the nematic;
(3) an optical compensation plate, whose purpose is to widen the viewing angle (it acts as a negative birefringent medium).

Multicolour and even full-colour panels have been realized with ECB technology.

3.3. *Ferroelectric liquid crystals (FLC)*

The discovery of ferroelectricity in chiral smectic C phases and the practical achievement of a surface-stabilized FLC cell have opened a new field of interest in bistable LC displays [13]. Figure 6 shows the basic principle of operation of an FLC cell. In thin cells (1–2 μm) the helical structure of the smectic C phase can be suppressed and so it is possible to switch between two uniformly aligned up and down states with a pulsed electric field of both polarities. Stabilization of both states can also be obtained by applying an a.c. bias field after the writing pulse in thicker cells (5 μm).

If the angle of the tilted smectic phase is such that $2\theta = 45°$ then the optical transmission can be switched between crossed polarizers by reversing the voltage polarity. In practice, such displays have been operated as multiplexed devices. Multiplexing is no longer obtained by the amplitude-selection method but by inverting the polarity of the writing pulse during the scanning time.

Ferroelectric LCD devices are still at the laboratory stage and several problems must be solved before the technology can enter the development phase [14–17]. One of the major initial problems was the difficulty in obtaining grey scales, but it has been shown very recently that this problem could be solved. The main difficulties are as follows.

(1) Obtaining the two up and down (which are the directions of the polarization vector) bistabilities. This corresponds to two different positions of the director in the smectic layers, as shown on the schematic drawing (figure 6). Now, the angle currently observed is only 15–20°, while the required value is 45°, corresponding to that required for the maximum theoretical contrast and brightness.

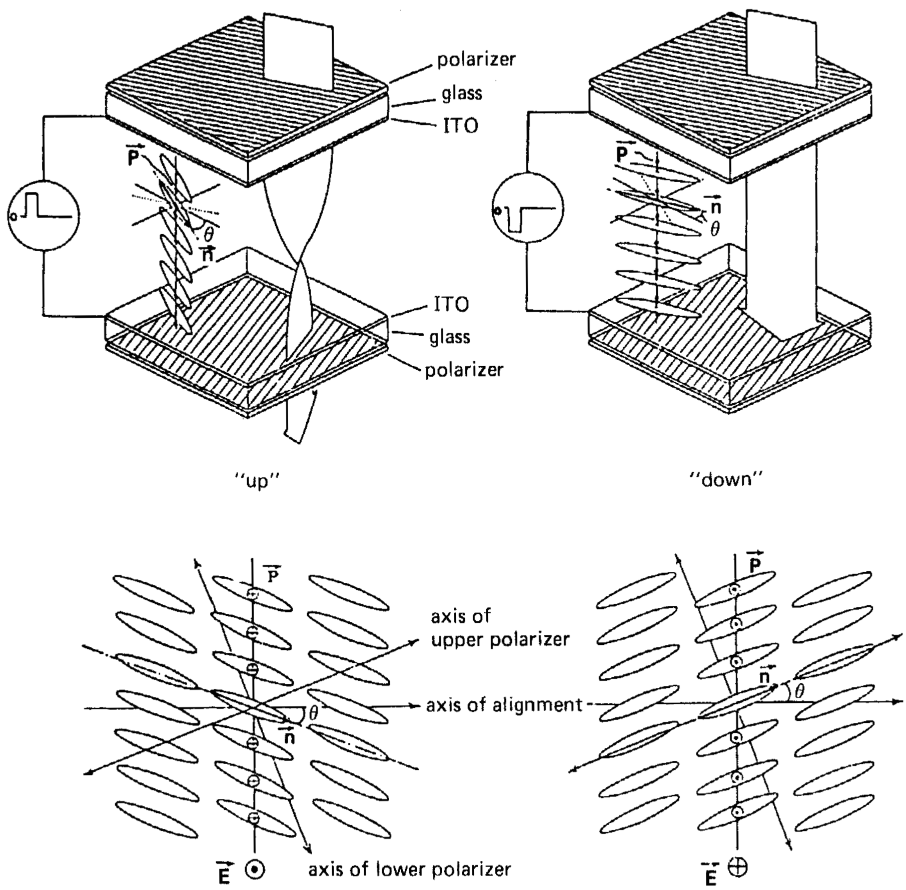


Figure 6. A ferroelectric liquid-crystal display (FLCD): schematic of the cell, showing bistability.

(2) To achieve very good cell technology: in particular, (i) a weak alignment of the director, allowing both states to remain stable after the application of a single pulse of the right polarity; and (ii) a narrow gap spacing (1·5–2 μm) with an accurate control of the gap dimension.

It has also been shown that colour panels could be realized.

The FLC technology is, without any doubt, the most promising one because of two unique advantages. These are the best angle of view of all the dot-matrix LCDs and an intrinsically short response time and the fact that the contrast does not depend on the number of scanning lines. Nevertheless, a complementary effort must be conducted in order to put this FLC effect into practical use.

3.4. *Active-matrix addressing*

The most developed technology for pocket TVs so far has been the 90° TN mode driven by an active matrix (even though most of the market uses multiplexed TN). The active matrices are either of the two-terminal type (see figure 7) or the well-known TFT addressing matrix (see figure 8).

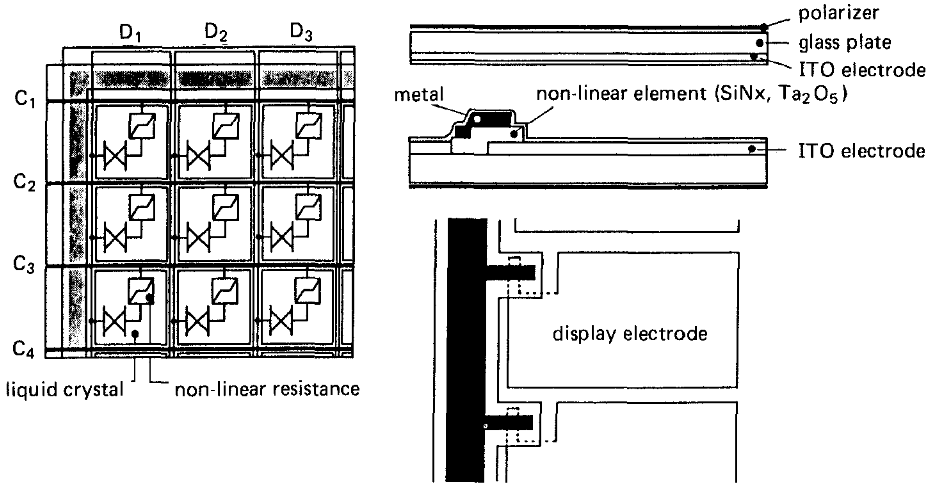


Figure 7. A diode matrix array—two-terminal active matrix.

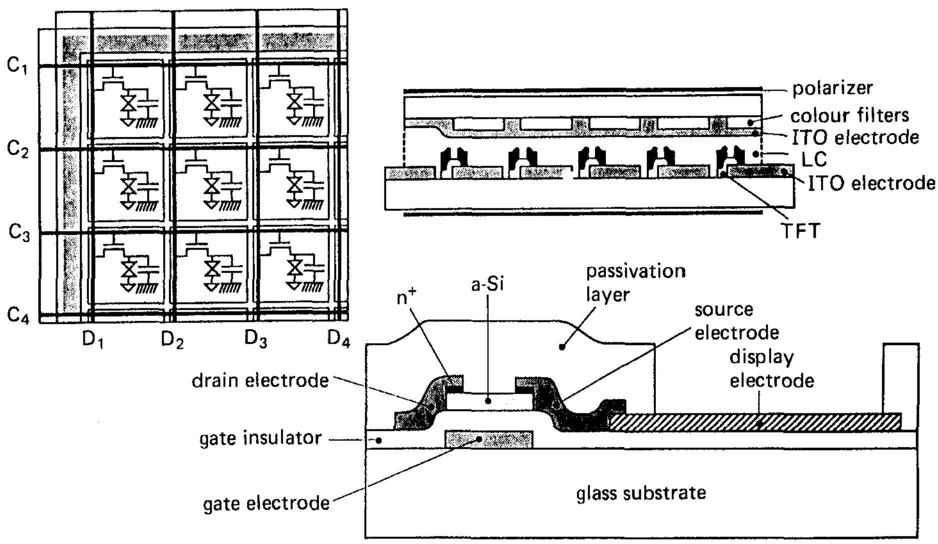
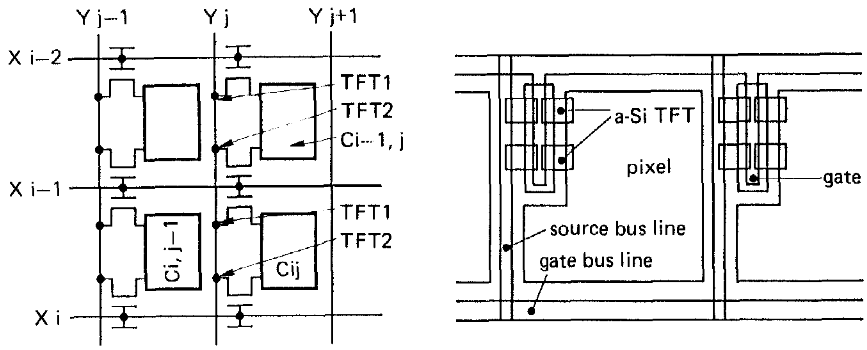


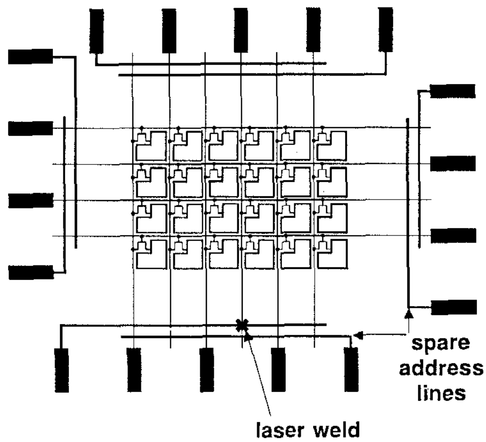
Figure 8. An active matrix with thin-film transistors TFT.

In the former case a switching element with a steep response curve is added to the LC pixel as a serial diode or a non-linear element (there are different types, including a-Si diodes, tantalum oxide or silicon nitride). The role of the extra diode is to add a steep response curve to each LC pixel. For the latter the advantage is a very good signal-to-noise ratio on the addressed pixel because the transistor fully isolates the pixel from the others in the matrix during the entire frame period. Amorphous silicon is the most widely used because the low-temperature process is compatible with ordinary glass.

Unfortunately, the main disadvantage of active-matrix technologies is the need for switching elements of a few *micrometres* size, which means high-resolution lithography and generally the occurrence of point defects. So, at the moment, it appears



(a)



(b)

Figure 9. (*a*) Different redundant structures in TFT–LCDs with two-transistors per pixel. (*b*) Redundant TFT matrix with spare address line.

that the basic configuration of the a-Si transistor is becoming standard, with a technological redundancy in all the difficult process steps of its fabrication. The only innovations that have been introduced are more in the architecture of the TFT matrix itself. To avoid point defects, the matrix should be made defect-tolerant [18] or redundant (examples are given in figures 9 (*a*) and (*b*)) [19, 20].

Even with all these refinements, the active-matrix addressed LCDs are now facing difficult problems of yield. On the other hand, the multiplexed technologies have shown their potential for progress during the past year and, because of their inherently low manufacturing cost, they still have to be considered for all kinds of applications.

4. Comparison of LCD technologies

4.1. *Viewing performances*

Among the parameters that are of prime importance for the user, the visual quality is especially important (see table 3). The best contrast is obtained with an active-matrix addressed TN. The problem with OMI–STNs and FLCs comes from the rather low transmission in the white state. It should be noted that the contrast of FLCs and TFTs would be the same even for 1000 scanned lines. This is different

Table 3. Viewing performances for the different LCD technologies.

	STN	OMI	GH	D–STN	ECB	FLC	TN/A.M.
Contrast maximum	● Yellow or blue	○	●	●●	●	○† Not depending on duty	●●●
Viewing angle	○	●	○	○‡	●●	●●●	●●§
(Optical thickness) $\Delta n\, d$	(0·8–1 μm)	(0·6 μm)	(0·8–1 μm)	(0·8 μm C 0·9 μm)	(1 μm)	(0·25 μm)	(0·5 μm first minimum
Brightness	Coloured	○	○	●	●	○†	●●

† Possible improvement of contrast and brightness by increasing cone angle.
‡ Possible improvement of viewing angle by optimizing compensation.
§ If ECB mode is used then viewing angle is increased.

to multiplexed LCDs, *where the contrast depends on the duty ratio.* The viewing angle, is best for FLC LCDs. It can be seen that the viewing angle, to a first approximation, is given by the optical thickness of the LC birefringent medium. Because we are concerned with crystalline optics, the thinner the medium, the larger the viewing angle.

Two remarks should be made.

(1) For ECB the optical compensation plate has the effect of reducing the apparent optical thickness. So this is not an exception, as it would appear from this general rule.
(2) For a double-layer STN the optical compensation cell (letter C) has generally a lower optical thickness in order to optimize both contrast and viewing angle.

The maximum brightness is attained by TN, the minimum being FLC, but as we have already discussed, it will probably be increased if the liquid-crystal mixtures are optimized.

4.2. *Viewing uniformity*

Another important feature is the uniformity of the background of the LC cell (see table 4). There are two critical points: the first is the gap accuracy and the other is uniformity of alignment. If we classify the technologies according to the sensitivity to variations in the gap, then the best is the TN mode while the worst are D–STN and FLC. In addition, for all supertwist structures, the effect of the cholesteric additive is to affect the threshold voltage, which is more severe than changing only the optical parameters.

For FLCs there is no true threshold voltage but rather a critical product of voltage and time, which is sensitive to gap thickness.

Regarding director alignment, the most difficult is FLC, in order to avoid the nucleation of zig-zag defects, but ECB or the different supertwist will also require optimized alignment techniques in order to operate under their optimum conditions. A flicker-free operation of a TFT addressed TN requires a high *RC* value, that is a high liquid-crystal resistivity.

Table 4. The problem of visual uniformity for the different LCD technologies.

Sensitivity to gap-thickness variations (↓)		Gap accuracy		LC alignment
	TN/active matrix	$4\text{–}6 \pm 0{\cdot}3\text{–}0{\cdot}5\,\mu m$	$\Delta n\, d$ affected	Planar (high resistivity of LC)
	ECB	$4\text{–}6 \pm 0{\cdot}1\text{–}0{\cdot}2\,\mu m$		Hometropic (pretilt needed)
	OMI	$4\text{–}6 \pm 0{\cdot}1\text{–}0{\cdot}2\,\mu m$	V_{th} affected	Planar (high tilt desirable)
	STN, GH	$4\text{–}6 \pm 0{\cdot}1\,\mu m$		
	D–STN	$4\text{–}6 \pm 0{\cdot}05\,\mu m$		
	FLC	$1{\cdot}5\text{–}2 \pm 0{\cdot}05\,\mu m$		Weak planar (avoid zig-zag defects)

4.3. *Electrical crosstalk* (*see table 5*)

Another kind of non-uniformity can be observed when the panel is operated with a given picture. This generally looks like vertical trails across the LCD screen (see figure 10). For multiplexed LCDs the crosstalk is caused by the *RC* signal attenuation, which is proportional to the square of the number of scanned lines. The effect is particularly significant for high-frequency components, the most difficult being high duty and more than eight grey scales.

Table 5. Electrical crosstalk in the different LCD technologies.

	Multiplex (STN, ECB, FLC)	Active-matrix (TFT, diodes, MIM)
Main causes of crosstalk	*RC* attenuation ($\sim N^2$) High-frequency components Grey scales High duty	Internal capacitance of switching elements (compared with pixel capacitance)
Potential solutions	Low-resistance electrodes Addressing schemes	Fine patterning of switching elements
Limitations	Difficulties for large-size panels ($\geqslant$ 14 in.) (especially for FLC panels)	Difficulties for high-resolution panels (pixel pitch $\leqslant 50\,\mu$m)

Let us analyse in greater detail what happens in a multiplexed dot matrix LCD (figure 10). The data signal waveforms used to display, for example, the letter 'E' are shown on the left of figure 10. We can see that the frequency components differ strongly, depending on the content of the displayed information along each column. Unfortunately, because of the equivalent electrical circuit of each pixel in the matrix, some voltage attenuation takes place, especially on the high-frequency side, as shown on the curve on the right-hand side of figure 10. The net result is an attenuation of the voltage effectively applied to the pixel on the columns addressed with high frequency components. The visual result will be vertical trails with reduced contrast, as shown in the figure. A potential solution is to reduce the resistance of the ITO

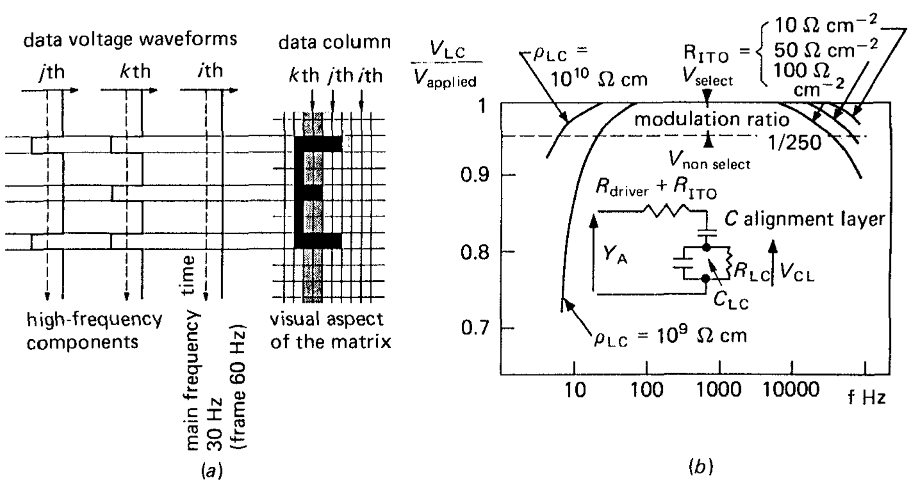


Figure 10. Electrical non-uniformities/crosstalk. (*a*) Visual perturbation in an LCD matrix (*RC* attenuation). (*b*) Voltage attenuation versus frequency.

electrodes or to limit the frequency spectrum by using special addressing schemes. A limitation will occur for large-size panels and especially for FLCs because of the value of the capacitance due to the small LC thickness.

The phenomenon of crosstalk in active matrices originates in the capacitance of the switching element itself, compared with the capacitance of the LC pixel. This capacitive coupling effect can be reduced by reducing the physical dimensions of the active element, but the problem of yield will be even more difficult to solve, especially for high-resolution matrices.

4.4. *Response time* (*see table 6*)

We have seen that even the computer market will require LCD panels with video-rate capability. The current situation is that FLC and TN active matrices already have short response times, while ECB and supertwisted LCDs have to progress. In fact, these technologies will demonstrate soon that short response times are quite feasible. The practical improvement will be to lower the gap thickness to about 4 μm. Flicker could appear for TFTs at high temperatures owing to the drop in resistivity of the liquid crystal. Another point is the longer response times between grey scales because of the slow director rotation between non-saturated states. For supertwist structures the cell must be operated far from the hysteresis regime in order to obtain short response times.

Table 6. Dynamical characteristics and response times for different LCD technologies.

Technology	Response time: Current status	Response time: Future	Comments
FLC	60 μs/line	a few μs/line	Depends on η/P.E.
TN/active matrix	20 ms	—	Problem of flicker (high temperature) Higher response time for non saturated levels
ECB	100 ms	50 ms†	
STN	200 ms	50 ms†	Hysteresis must be avoided
GH–STN	300 ms	?	Higher response time for high duty

† Low-viscosity LC (η = 13–18 cSt); gap = 4 μm.

FLCs have a strong potential to achieve very short response times because of the dependence of the polarization and the electric field of both T_{on} and T_{off}.

4.5. *Grey scales*

The possibility of grey scales (see table 7) has been considered to be impossible for a long time with STNs and FLC. What we can say is that it is difficult, but now different experiments have shown that it is possible by using different techniques. There are different techniques to obtain intermediate levels in a dot-matrix LCD. The first is spatial modulation by using sub-pixels; the second and third are pulse or amplitude modulation of the data signal during one scanning time; and the final technique is modulation by using two or more successive frames to display intermediate

Table 7. Grey-scale capabilities for the different LCD technologies.

	STN OMI/D-STN/GH	ECB	TN/active matrix	FLC
Current status	Difficult	Easy	Easy	Difficult
Number of scales demonstrated	$\leqslant 8$	8	8	5
Main problem	Hysteresis			Bistability
Technique	Frame/frame (but flicker) Pulse modulation	Pulse modulation	Amplitude modulation Pulse modulation (MIM)	Dithering Frame/frame

Techniques to achieve grey scales	
1. Spatial modulation (dithering)	3. Amplitude modulation
2. Pulse modulation	4. Frame/frame modulation

levels. This last solution needs a short response time to avoid flicker. At present, only FLCs are compatible with this technique.

The current status is that the TN mode addressed by TFTs is able to show analogue grey scales. This has been demonstrated on pocket TVs, but for larger-size screens and under different observation angles probably no more than 8–16 grey levels will be distinguishable. For all other kinds of dot-matrix LCDs, and especially with multiplexed displays, the grey scales are digitized. Generally the data pulse is subdivided according to the number of grey scales to be displayed.

4.6. *RGB colour filters*

Generally, a mosaic of RGB colour filters is added to the pixel electrodes inside the liquid-crystal cell (see figure 11 and table 8). The liquid crystal acts as an optical shutter, the colour being produced by the array of RGB filters. Because the transmission factor of a LCD colour cell is low (about 5 per cent), a back-lighting source is needed. This back light generally consists of a white fluorescent tube. Two possible solutions could be imagined. In the first (upper scheme in figure 11 (*a*)) the colour filters are deposited on top of the transparent electrodes, while for the second (lower scheme in figure 11 (*a*)) the transparent electrodes are deposited on top of the colour filters. In practice, the trend is now to use this solution. Indeed, for multiplexed displays the voltage drop across the colour filters (as shown on the curve in

Table 8.

STN	ECB	FLC	TN/TFT
Planarization required	—	Planarization required	Multigap for RGB adaptation
To avoid voltage drop and keep multiplexability $\rightarrow$ low $R_{\square}$ ITO/colour filters (c.f.)			High-$R_{\square}$ ITO/c.f. tolerable
—	—	LC alignment more difficult	—

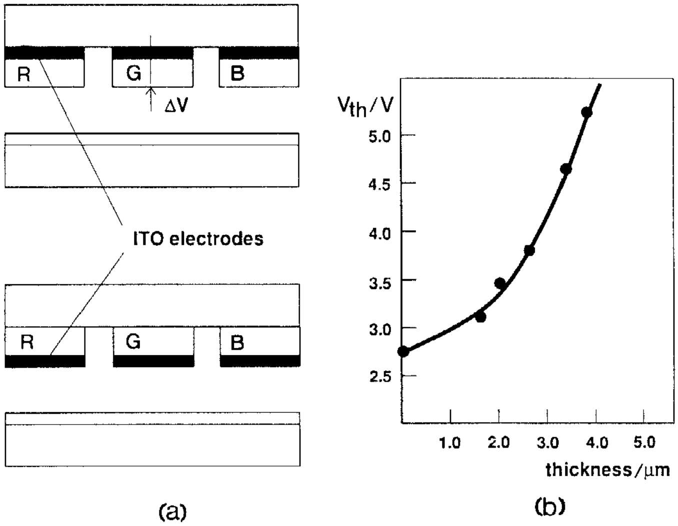


Figure 11. Specific requirements due to the presence of colour filters. (*a*) Filter location on the transparent electrodes. (*b*) Threshold-voltage variation with colour-filter thickness.

figure 11 (*b*)), and its possible variation from place to place, make it necessary to deposit the ITO electrode on top of the colour filter. However, to keep a low *RC* value, low resistance ITO is needed. The thickness variations of the colour filters make it necessary to employ some planarization layer in order to maintain the accuracy of the LC thickness. Finally, the surface roughness of the colour filters could be a problem regarding the alignment of the liquid crystal, especially with printed colour filters.

Three techniques are of current use in manufacturing colour filters (see table 9). The first is dyeing, which needs at least three lithographic steps; the second is electrodeposition which needs ITO electrodes; and the last is printing. Printing and electrodeposition have become widely used because of their low cost. The only problem with printing is the lack of accuracy, which could be a problem for high-resolution screens.

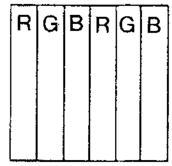
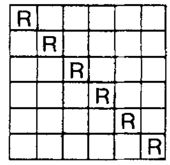
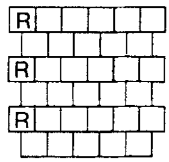
The most classical geometrics for the RGB mosaic are described in table 10. Depending on the applications, striped, diagonal or triangular colour filters can be patterned. In special cases (mostly to save luminance) a combination of two green dots, one red and one blue dot per pixel have been used.

Table 9. Colour-filter technologies for LCDs.

	Dyeing	Electrodeposition†	Printing‡
Cost	○	●●●	●●●
Accuracy	●●●	●●●	○
Chromatic fidelity	●●●	●●	●●
Heat resistance, Light resistance	●	●●	●●
Thinner layer	●●●	●●	●
Long-term reliability	●●	●●●	●●

† Electrodeposition needs striped ITO pattern.
‡ Surface roughness makes LC alignment more difficult.

Table 10. Colour-filter arrangements for LCDs.

Stripe	Best for alphagraphics	
Diagonal	Usage for alphagraphics and image	
Triangular	Best for image	

5. Future trends

It turns out that the probable short-term evolution of dot-matrix LCDs will be a competition between TFT addressed LCDs (mainly TN mode), and multiplexed LCDs (compensated STN and ECB). The two major applications will be television and computers.

For *computers* the main goal is the full-page multicolour screen (size 14 in. diagonal, pixel count $640 \times 3 \times 500$). It is probable that multiplexed LCDs will take this market segment primarily because of their lower manufacturing cost. In order to lower the cost to the minimum level, the number of connections and IC drivers will be reduced, making it necessary to use duty ratios of 1/500. Both compensated STN and ECB are now under development, and if the performances of both technologies become similar then the manufacturing cost will be the key factor in selecting one of them. In the longer term and if the fabrication yields are improved then TFTs could also be introduced in computer applications, but it will take some time to go from the current 4–5 diagonal to the 14 in. diagonal. In addition, a colour monitor used for *alphagraphics applications* must have *no point defects*, and this will make the penetration of TFTs in this application area even more difficult. Special mention must be made for FLC LCDs because they have great potentials for high-information-content terminals. They could be used for large (A4) screens with more than 1000 scanned lines. For such high-resolution monitors the first step could be black and white and then multicolour screens with a few intermediate grey levels.

As far as *television* is concerned, the present estimation is that TFTs and diode matrix addressing have the best potential performances but they are still restricted to small sizes (3–5 in. diagonal). TFTs can be considered as a potential solution for projection devices for HDTV [21]. In that case, because of the poor transmission of light by colour filters, it will be more efficient to use three monochromatic cells and three separated RBG light beams.

6. Future LC–HDTV: a new challenge

The challenge is now to try to imagine what could be the ultimate approach (see figure 12) using three monochromatic LC cells. Because the cost of the projection

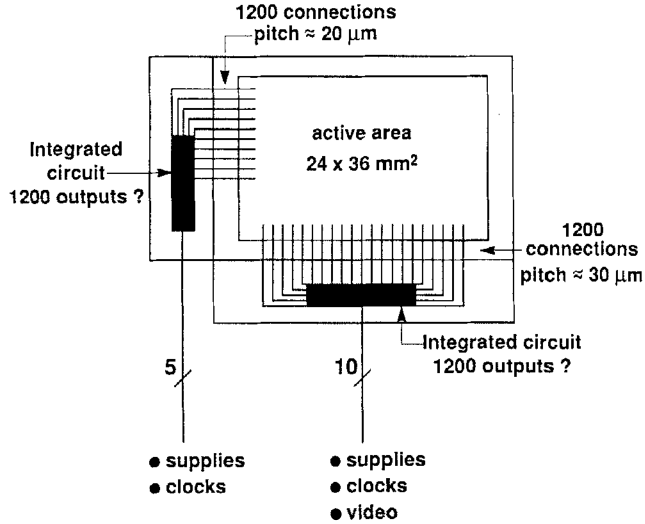


Figure 12. A projection-type LCD for HDTV. Interconnections and driving circuits.

optics must be kept as low as possible, the lens diameter must be small. This could lead to the size of a slide. In this example, there are two important consequences.

(1) The resolution must be very high, the pitch being around 20–30 μm. With current lithographic limitations, the aperture ratio, i.e. the ratio of useful pixel area over total area, would be only 25 per cent for a TFT matrix, while it could be more than 60 per cent with a multiplexed LCD using a ferroelectric liquid crystal.

(2) Another consequence is the need for 2400 connections at the same low pitch, which would require direct chip-on-glass mounting—possibly a specially shaped IC with as many as 1200 outputs.

As we can see, there are still many technical challenges between the metre-size direct-view LC–HDTV and the small-size LC-projected HDTV!

In any event, even if a major development effort has to be made in the different LCD technologies, it is certain that LCDs will have the dominant position in all the new flat-panel applications.

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