Developments in colour display devices

Tim L Dawson

INTRODUCTION

For many years the most familiar type of visual display used in homes and offices has been the cathode ray tube (CRT), irrespective of whether the material being viewed was television, video or computer-based business data and graphics. In the vast majority of applications a multicolour display, as opposed to monochrome, has become a prerequisite while some users (e.g. specifiers, textile designers and colour printers) now require accurately calibrated and reproducible colour displays. Colour display devices were reviewed by Hawkyard [1] in 1991, but since that time there has been a multibillion dollar investment in Japan and the USA, and to a lesser extent in Europe, into the development of liquid crystal displays (LCDs). In addition the development of several potentially competing technologies is well under way and some of these seem to offer economic and technical benefits in the long term, or are particularly suited to specialised purposes such as large screen television, public information boards or military uses. The research and development into flat-panel displays (FPDs) has been driven by a rapidly escalating demand for portable equipment such as lap- and palm-top computers, mobile phones, digital cameras, camcorders and navigation devices, not to mention children's hand-held games. The present sales of FPDs are around £20 billion; the market is growing rapidly and is predicted to equal that of CRTs by 2005 [2]. This trend is already evident, with a major shift towards the replacement of CRT monitors by thin-film transistor, twisted nematic, liquid crystal displays (TFT TN-LCDs), particularly in offices and shops, as they offer considerable space-saving, despite their present higher cost.

The paragraph above illustrates the innumerable acronyms that this field has acquired and some of these are shown in Table 1, listing the main types of display now available, together with some pros and cons of their selection.

During the past decade a number of books on many of the above display systems have been published [3–5] but the field is developing so rapidly that they soon become out-of-date.

CATHODE RAY TUBE VISUAL DISPLAY UNITS

CRT monitors have been used since the introduction of personal computers (PCs). From the initial monochrome visual display units (VDUs) the past decades have seen continuous improvements in both definition and the number of colours which can be displayed. Since IBM's initial introduction of the CGA standard (320 × 200, 7-colour) display in 1981, improvements have continued and it is now standard practice to adopt the use of 24-bit RGB colour, corresponding to a theoretical 16.7 million possible colours, and as an absolute minimum the VGA or SVGA definition. The most common standards of definition are shown in Table 2 and it is these standards that any new display technologies must eventually meet.

Apart from trends towards higher definition in CRTs (SVGA or XGA definition for PCs and UXGA for many business uses), the average display size has increased both for desktop monitors and television (TV). The problem associated with large CRTs is their bulk and weight. Some business users, such as financial dealers and engineers using computer-aided design, require large displays, but weight is particularly a factor with CRTs for displaying high-definition TV (HDTV). For the best effect, HDTV requires a display of at least 1.00–1.25 m, at which size the glass enclosure of a CRT would weigh more than 100 kg [6]. The newer flat-panel and projection display systems are therefore of particular interest for such end-uses. However, CRTs still represent the cheapest full colour display system available and continue to warrant the development of improved features. Digital controls of display parameters are now almost universal and, like most electronic devices today, are 'plug and play'.

Two main technologies have existed for many years in which the individual R, G and B phosphors are struck by the beam from electron 'guns'. These are the aperture grill, a vertical array of fine wires in front of the CRT phosphor screen which itself carries a vertical array of phosphor stripes, and the shadow mask, a perforated Invar metal plate interposed between the electron beam and the screen, consisting of RGB 'triads' of phosphor dots. Because of its precision and stability the aperture grill type now predominates, providing the finest on-screen definition, with dot spacing down to 0.22 mm. Despite the use of low expansion Invar steel for the mask, its attachment to the glass envelope must be engineered so that as it heats up there is no tendency to distort [7]. The RGB phosphors may differ slightly from one manufacturer to another, but the most common set, known as the P22 Group, are Y_2O_5S:Eu (red), ZnS:Cu,Au,Al (green) and ZnS:Ag (blue). As an alternative to the triangular triad arrangement the phosphors may also be grouped in vertical or slanted stripes.

Touch-screen technology

Truly flat-faced CRT tubes with no loss of peripheral picture definition are now widely available. There is an

Table 1 Summary of the main colour display technologies available[a]

Display system	Acronym	Advantages	Disadvantages
Cathode ray tube	CRT	Cheap to manufacture Reliable/long life (20 000 h) Reproducible colour (once calibrated)	Bulky & heavy Flicker sometimes noticeable Too heavy & power-consuming for either portable or large displays
Light emitting diodes	LED	Easy & simple to manufacture Low power/high efficiency Very long life (10^6 h) Combined RGB diodes available	Large displays possible but limited colour range/definition For maximum brightness viewing angle is small (30°)
Laser diodes	LASER	Suitable for very large displays Focused image at any distance	Complex optics required Projection not possible across public access areas (hazardous)
Liquid crystal display (supertwist nematic)	STN-LCD	No flicker Flat & light Very long life (50 000 h)	Too slow response for video Requires backlighting Higher power consumption than TN-LCDs Limited viewing angle
Liquid crystal display (thin film transistor, twisted nematic)	TFT TN-LCD	Lower power, brighter (250 cd/m^2), better angle of view (120–150°) & faster response than STN-LCD	Requires backlighting Limited temperature range (e.g. 5–35 °C)
Ferroelectric LCD	FE-LCD	Long term display effect (memory) Much faster response than TN-LCD Wide viewing angle	Interest limited to projection TV, military use & possibly advertising
Polymer dispersed LCD	PDLC	Ideal for 'switchable' windows	Multicolour not available
Organic light-emitting diode (this group includes light-emitting polymers)	OLED	Self luminous (100 cd/m^2) Low power consumption	Manufacturing techniques for: larger screen sizes not yet perfected
Organic light-emitting polymer	LEP	Wide viewing angle (160°) Very thin & light (can be flexible)	Improvements in durability yet required
Plasma display panel	PDP	Very thin & lightweight for big (0.85–1.65 m) displays Very bright (500 cd/m^2). . . can be viewed in direct sunlight Excellent viewing angle (180°)	Resolution not as good as LCD Too expensive for mass market
Thin film electro-luminescent display	TFEL	Very low power, very high definition so miniaturisation possible – ideal for helmet displays for the military (suitable for night vision) Wide viewing angle (160°) Simple, solid state, non-laminated structure	Colour reproduction limited Luminance of blue phosphor needs improving High drive voltages required
Field emitter display	FED	Very wide temperature range (–40 to +70 °C) Wide viewing angle (vertical & horizontal)	Very high drive voltages required Scale-up of manufacture difficult

a Further basic summaries on the choice of a display can be found at http://www.meko.co.uk

Table 2 Present-day VDU display standards for computer monitors

Designation	Definition	Line frequency (kHz)
VGA	640 × 480	30
SVGA	800 × 600	40
XGA	1024 × 768	50
SXGA	1280 × 1024	65
SXGA+	1400 × 1050	75
UXGA	1600 × 1200	90

increasing use of touch-screen systems, formerly used mainly for industrial control purposes [8], but now increasingly for public use in libraries, information centres and museums [9], and recently for multipurpose public phones. The touch control facility may be incorporated during the manufacture of the tube or may be attached later to an existing installation and used with appropriate control software. Position-sensing technologies are resistive, capacitative, optical (infrared) and, more recently, acoustic [10]. One unusual device, the Seiko InkLink system, uses ultrasound sensors which can be fixed to a special clipboard and used as PC input for conventional writing or graphics using normal paper.

Resistive and capacitative touch-screens usually comprise a sandwich structure between two thin glass sheets. When even the lightest pressure is applied to the surface there is a local variation in the thickness of the sandwich, which affects the particular physical property that the system is sensing from the horizontal and vertical edges of the screen. Touch-screens are sometimes incorporated into tablet LCD PCs with a stylus to replace not only mouse control but also, using handwriting recognition software, even the keyboard.

Television and high-definition television

The most noticeable recent trend in TV sets has been the change in screen dimensions, the 4:3 aspect ratio being extended to 16:9. This is logical because about 40% of UK broadcasts, and all advertisements, are in wide screen format and this proportion is increasing rapidly. Digital satellite and terrestrial TV in the UK is now becoming accepted, with some nine million people at present thought to have access. It is in fact proposed that analogue transmissions will be phased out between 2006 and 2010.

High-definition television (HDTV), when it does arrive, will also require digital transmission but again, despite much publicity over the past decade, progress towards its introduction has been painfully slow [11], the only universal agreement being on the aspect ratio of 16:9. However, limited systems have been available since 1988 in Japan (1125 lines at 60 Hz) and from 1994 in the USA (1250 lines at 60 Hz), where there are now some 120 h per week of HDTV broadcast. The present European 'standard' is 1250 lines at 50 Hz. HDTV transmission requires a theoretical broadcast bandwidth of 27 MHz. However, it has recently been demonstrated that, using special video-compression techniques (MPEG) and modulation methods, which would allow the simultaneous transmission of both vertically and horizontally polarised signals, the existing transmission system (625 lines at 8 MHz) might still be used.

Projection video

Small high-intensity CRTs have been available for many years and for a time back-projection displays were popular, for example for displaying broadcast sporting events in pubs. Similarly, three-tube projection displays have been used for in-flight films in aircraft but give a somewhat indifferent display due to poor brightness and inexact registration of the RGB images on the screen. However, a device for projecting very large pictures, the Eidophor system [12], has been available since the earliest days of TV.

Eidophor projectors were continuously refined and only recently became obsolete with the advent of TFT-LCD and laser projectors. The system was based on the displacement caused by a modulated electron beam scanning a small area of a very thin film of oil under vacuum. The size of the deformations produced on the oil surface were proportional to the intensity of the electron beam. A high-intensity light beam was projected on to the oil surface and the reflected image could be shown on a screen 12–15 m wide. Three separate beam scans (for the RGB signals) were made and the light beam passed through the optical system using a synchronised rotating RGB filter wheel. The latest Eidophor projectors used 5 kW xenon lamps and could project an image over 200 m, with an intensity some 80 times that of the best CRT projector system.

A much cheaper and more popular method of producing a large screen effect, typically for trade exhibitions, is the use of a so-called video-wall, comprising a stacked arrangement of VDUs combined with software which spreads the whole picture over the entire 'wall'. Despite the fact that VDUs now have very narrow surrounds, the dark areas bordering each picture element tends to spoil the effect and a back-projection system is usually preferred. However, 'seamless' tiling has been attempted, using a thin lens at the edges of each sub-screen display, and large displays have also been achieved by Screen Technology of Cambridge using stacks of LCD screens having a common backlighting and output screen system.

Many so-called 'light-valve' projection systems have been developed over the years [13], and these are discussed in the appropriate sections of this review. However, not all projection CRTs are aimed at extra large displays and extremely small devices have also been manufactured [14]. Such units have been used as the basis for versatile head-mounted displays for day and night use aboard military aircraft [15].

Flicker, jitter and interlacing

CRT displays, particularly those used for TV, depend on the persistence of human vision since at any one moment of time only one group of RGB phosphors is being addressed by the electron beam and the picture is refreshed at 50 Hz (i.e. every 20 ms). The whole screen appears to be continuously illuminated because the refresh rate for the screen image is too rapid for flicker to be noticeable. A TV refresh rate of 50 Hz would be on the borderline were it not for the fact that an interlaced display system is used, in which the image is scanned using, say, the even-numbered lines and then rescanned using the odd-numbered lines. However, interlacing introduces its own problems in that details in the display may appear to jitter or dither owing to slight variations in spacing between adjacent lines. When very high-resolution monitors were first introduced many used an interlaced display but nowadays most are non-interlaced and flicker-free. Movements as small as those subtending only 20 s of arc to an observer are noticeable but in colour displays the spatial arrangement of the RGB phosphors also plays a part [16,17].

LIGHT-EMITTING DIODES AND DIODE LASERS

Light-emitting diodes

These devices are based on a light-emitting effect resulting when a voltage is applied across certain inorganic monocrystalline materials based on elements in Groups II and V of the Periodic Table. Everyone is familiar with the small red, plastic encapsulated, light-emitting diodes (LEDs) used as power indicators and warning lights, and with the recent advent of high-brightness white LEDs they are becoming used in small lighting applications such as torches and bicycle lights.

Until comparatively recently, however, there were no bright blue diodes for use as a triad with red and green diodes for large colour displays. The first stable blue LED, based on silicon carbide, was made in 1990 but had very low luminance (5 mcd compared with 1000 mcd for modern 'ultra-bright' LEDs) [18]. These were replaced in 1996 by the gallium nitride diode as the first truly ultra-bright, blue LED. This could then be used with ultra-bright (3000–6000 mcd) versions of red and green diodes based on aluminium indium gallium phosphide (AlInGaP) and indium gallium nitride (InGaN), respectively. By incorporating trace dopants (usually Group III rare-earth metals) the wavelength of the emitted light can be changed so that, for example, the inclusion of erbium (yellow emitter) and europium (red emitter) into gallium nitride can result in an LED capable of emitting light of intermediate hue depending on the applied voltage [19].

White LEDs have also been produced either by incorporating chips of the above red, green and blue materials into the single die or by embedding a blue gallium nitride emitter in a matrix containing a phosphor (an yttrium aluminium garnet) which converts some of the blue/violet radiation into bluish-white light. As already mentioned these devices can be used as small light sources to replace incandescent bulbs, but also as backlights for LCDs. The BSI Environmental Design Award for 2002 was won by a student design for a solar-powered hand torch based on ultra-bright white LEDs sealed in a block of acrylic polymer.

With the combined RGB-type diode any colour temperature of white, and indeed any colour over a very wide gamut, can be produced by varying the voltage signals between each of the three anode connections and negative. The efficiency of modern high-brightness LEDs is very good (50–100 lm/W) compared to that of tungsten filament light bulbs. It has been estimated that if all the traffic lights in the USA were changed to multi-LED arrays there could be a 20 million MW h energy saving, with the additional benefit of much less frequent bulb replacement. In the UK, such changes are now beginning to be made. With the advent of ultra-bright LEDs, large public displays for passenger information in transport terminals are rapidly replacing the older electromechanical information boards. Multicolour LED displays are also used in sports stadia, where the relatively low definition and limited colour range of this system is unimportant. Large area decorative displays are also being constructed from standard multiple RGB array boards complete with on-board microprocessor circuits.

Laser diodes

There are several types of laser (an acronym for 'light amplification by stimulated emission of radiation'), namely gas, liquid and solid-state semiconductor lasers. It is the semiconductor diode laser which is of particular interest for medium-size displays [20].

A semiconductor laser consists of a junction between two pieces of semiconductive material similar to that used in an LED. Thus the familiar, low-power red laser pointing device is based on gallium arsenide and aluminium gallium arsenide. When a current is passed through the device, laser light emerges from the junction region. The emitted light beam is very coherent and can be used in a projection system over considerable distances without losing focus. As in the case of LEDs, there has been no suitable blue laser until recently, but the problem has been solved with the advent of gallium nitride [21]. Typical systems of this type consume less than 20 W [22].

The second type of solid-state laser used for display purposes is the so-called optically pumped device, in which more powerful laser beams can be generated by surrounding a rod of the semiconductor (such as neodymium yttrium vanadium oxide) with a pulsed gas discharge, for example a xenon lamp. Several pulsed RGB laser displays are commercially available [23,24]. The most powerful lasers used for display purposes may be gas, liquid or dye types [25], the display being scanned using very high speed rotating mirrors. Dye lasers, which have been extensively reviewed [26], are an important group since by choice of dye the wavelength of the emitted light can be readily controlled. Other micro-mirror reflecting systems are also available, such as Texas Instruments' digital mirror arrays [27] and the grating light valve, a microreflective ribbon array devised by Stanford University.

Laser display units available at present range from hand-held low-power monochrome projectors to sophisticated multicolour projection units. As the projected light beams are coherent and have no focus point they can be used to display high-definition images on either planar surfaces (such as a back projection unit) or on to a distant multi-curved surface. Even more complex devices are available by which holographic images can be traced out, for example three-dimensional images which change perspective as the viewer moves his position of view.

LIQUID CRYSTAL DISPLAYS

Numerous types of liquid crystals have been used as the basis for information display, but the two principal types of LCD over the last 20 years belong to the supertwist (STN) and twisted (TN) nematic classes. Nematic (thread-like) liquid crystal materials consist of special linear fluoro-alkenyl compounds which must have extremely high resistivity, typically 10^{13} Ohm/cm, and must remain free from all traces of contaminant during manufacture and use [28,29]. These materials are now bulk speciality chemicals and the major supplier is Merck. Reviews of both technologies, and some less important alternatives, have been published by a number of authors [30–33]. Both types of display were formerly used in reflective mode, and relied on ambient illumination as do present day monochrome displays for calculators, digital watches and TV controllers.

However, most larger LCDs operate in transmission mode, usually back lit with special flat, cold cathode fluorescent tubes [34], although the advent of ultra-bright, diffuse white LEDs offers an attractive alternative. The actual LCD panel is usually relatively thin (2–3 mm) and the backlighting system occupies most of the space in the familiar lid structure of a laptop computer. The principle

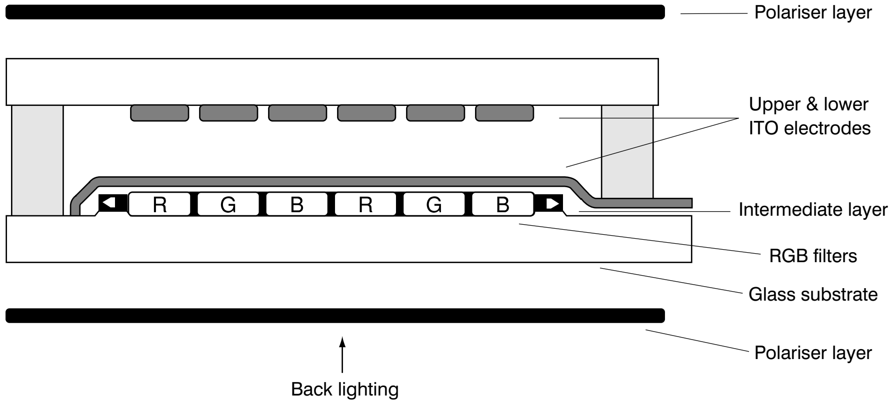

Figure 1 Basic structure of a passive STN-LCD

of the display is that when a voltage is applied across a thin layer of LCD material it causes a change in the degree of twist in the plane-polarised light beam from the backlight/polariser system. The backlight needs to have considerable luminosity as the attached polariser transmits less than 50% of the tube's output. After passing through the LCD layer, if the plane of polarisation of the transmitted beam is parallel to that of the top polariser the display will be white, and if it is 90° to the orientation of the top polariser the screen will appear black, with shades of grey between these extremes.

Supertwist nematic crystal displays

STN-LCD displays were introduced in the early 1990s. Like all flat-panel displays the construction comprised a complex, multilayer sandwich consisting (top and bottom) of polarisers, glass panels and conductive, transparent electrodes of indium tin oxide (ITO) corresponding in position to RGB colour filters forming each display pixel element.

Figure 1 shows the basic structure in which the ITO electrodes were laid down in narrow upper and lower strips lying at 90° to each other, so that each pixel element could be addressed by applying a suitable voltage between the crossover points of the electrode matrix. In this and subsequent representations showing multilayer structures one should disregard the relative thickness of each layer since in reality, apart from the glass panels, each is no more than a few microns thick.

Each pixel was approximately 100 × 150 μm in area and surrounded by a narrow border of black chromium oxide to prevent light-bleed between contiguous pixels. The electrical activation of the matrix of pixels was achieved by an external multiplexed address system [35]. However, the speed at which individual cells could be addressed was limited by the need to attain high contrast. Response times were therefore slow, typically 200–400 ms initially, although this was improved to below 100 ms in later devices employing a so-called active matrix addressing system [36]. The slow response was very noticeable in early laptop computer screens when moving the mouse cursor and such displays were totally unsuitable for video or TV use.

Other failings were the limited angle of view, small screen size (25 cm) of early models and limited contrast and colour (16–32 level) grey-scale display capabilities. The natural background colour of STN-LCDs is either yellow or blue, which arises from interference caused by their very high degree of twist. These background colours are quite acceptable for the monochrome STN displays now commonly used at retail sales points, but for white background monochrome or colour displays the natural colour is removed by the use of a double supertwist layer or by incorporating a birefringent polymer layer or retardation film (not shown in Figure 1). This simplifies manufacture and has therefore become the preferred approach [33].

Despite their technical disadvantages STN VDUs are still widely used as they are considerably cheaper to make than the more versatile TFT TN-LCDs. Thus for many business uses where full colour is not required, for example retail cash desks, the familiar black and white display on a blue background will often be selected in preference to a full colour TFT display.

Thin-film transistor twisted nematic displays

Many of the problems with early LCDs mentioned above have been overcome by the development of TFT TN-LCDs, but at the price of greater complexity and, at least initially, in much higher cost due partly to high reject rates in production. The particular advantage with this system is that each individual pixel is actively controlled by a tiny switching transistor which occupies about 10% of the total pixel area (see Figure 2).

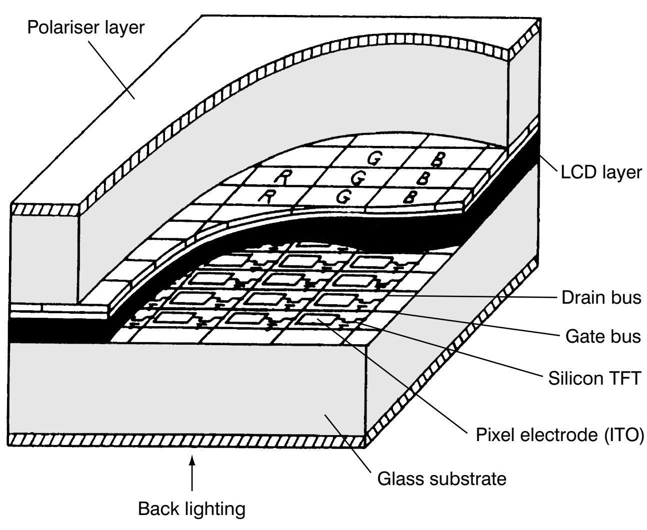

Figure 2 General structure of an active matrix TFT-LCD (Courtesy of GEC)

Present day TFT displays have full colour capability (256 grey level) and are commonly available up to about 60 cm size and at very high (UXGA) definition. This is the result of enormous investment devoted to perfecting fabrication techniques, particularly in Japan [37]. Initially, temperatures above 500 °C were employed at various stages, particularly when the deposited layers of amorphous silicon had to be annealed to convert them to a polycrystalline form, on to which the various elements of the transistor were subsequently laid down. To accommodate these it was necessary to use costly high-temperature glasses based on quartz or a special boroaluminosilicate. Processing temperatures have gradually been reduced, in particular by the use of pulsed laser beams to effect this conversion while heating the glass layer to no more than 250 °C for less than 100 ns [38]. This development has been so successful that it is now possible to mount TFT-LCDs on polyester film, thus producing flexible displays. Similarly, a low-temperature process also allows the use of cheaper soda-lime glass, which can be made by the Pilkington float-glass process.

In the unpowered state, when the polarised light passes through the LCD layer the plane of polarisation is twisted through 90°. When fully powered by the TFT, however, there is no rotation and light is transmitted through the upper polariser. Intermediate states allow for a range of greys. The number of grey levels, and hence the maximum number of colours that can be displayed, is controlled by the voltage applied to each pixel electrode by the complex drive circuitry [39], and the incorporation of additional drive chips at the edge of the display matrix can greatly simplify circuit design. A very simplified view of the several layers which comprise a TFT-LCD is shown in Figure 2, in which the RGB filters are arranged in vertical stripes. Figure 3 shows individual RGB pixels with the drive transistors at the edge of each cell and in this case they are arranged in a 'brick-wall' triad.

Initially the colour filters were produced by a series of photoetching and deposition processes to yield small, gelatine-filled cells which were dyed to produce the RGB filters. The pixel arrangements were similar to those of the phosphor dots in CRTs, as trichromatic strips or as triads in various arrangements [40]. These and other methods of forming the colour filters have been reviewed by Tsuda [41] who states that the lightfastness of the dyed filters is not very good but that this can be improved by spin-coating or the electrodeposition of extremely fine pigment dispersions (< 0.5 µm) in an acrylic/epoxy binder. The possibility of applying the filter cells by printing has also been evaluated.

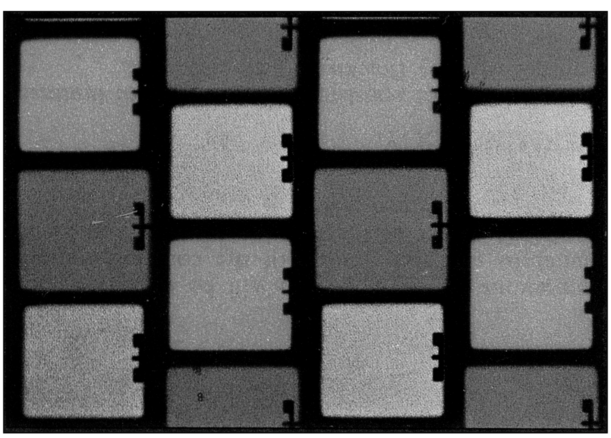

Figure 3 Microphotograph of the RGB pixels and drive transistors of a TFT-LCD

The complex nature of the structure of a TFT-LCD is an indication of the lengthy series of individual stages in its manufacture. These are mostly carried out under 'clean-room' conditions and may involve more than 50 steps, so the total fabrication process can take up to three weeks. By contrast the fabrication of a CRT is accomplished in 24 h. An additional problem with LCDs lies in the fact that faults at the individual pixel level, which can in turn affect a whole row of pixels, are not easily detected until the end of the production cycle.

In the early days of manufacture it was accepted that reject rates could be as high as 50%, often because of interconnect short circuits, which could account for 60% of all faults, adventitious dust being a major cause of defects [8]. Rejection rates can now be improved either by 'spot' laser treatment, since the loss of an isolated pixel can be tolerated, or by allowing for pixel redundancy in the design. Recently TFT-LCD computer monitors have become available with a guarantee of no 'dead' pixel faults, thus complying with ISO 13406-2 Class 1.

Ferroelectric LCDs

Bi-stable ferroelectric liquid crystal devices were first devised in 1980 [42]. Because of certain unique properties they are equally suitable for very large high-definition displays, and for miniature displays, for example for military applications. Their unique combination of properties is as follows:

- the display has a memory effect and remains fixed when the power is switched off;
- the response time is very fast (micro- rather than milli-seconds);
- the contrast is very high and does not change with viewing angle; and
- they do not require complex TFT technology to drive them.

However, the manufacture of ferroelectric liquid crystal devices requires just as high a degree of precision as other types of LCD, as the cell thickness of the ferroelectric chemical is 1.5–2.0 (± 0.05) µm across the whole of the display, which is about a quarter of the cell gap in an STN-LCD [43].

Colour displays can be based either on an RGB colour filter array or, because their response time is so fast, by a rapid sequential RGB scanning system. This type of LCD is the most recent to be fully commercialised, products ranging from flat-panel monitors (Canon) to a micro-display panel for projection TV (the Displaytech Lightcaster unit is used in a new Samsung HDTV unit). Because of their memory effect, possible uses for monochrome displays include destination boards on public transport vehicles and perhaps even shelf labels in supermarkets.

Polymer-dispersed LCDs

Several types of polymer-dispersed LCDs (PDLCs) have been devised, some of which were originally developed as ‘intelligent windows’ whose light transmission properties could be switched between a transmissive and an opaque light-scattering state. Automotive uses include sunroof and security/privacy side windows. PDLCs consist of a flexible film of polymer containing droplets of liquid. The on and off states of the dispersion, which forms a thin (20 μm) layer between two conductive ITO-coated glass or polyester sheets, is accomplished by applying an alternating current at about 50 V across the cell. Switching of individual pixel electrodes can be achieved using a normal TFT array, except that the driver electronics have to handle a higher voltage TFT-LCD.

There are several ways of producing PDLC films [44], of which the polymerisation-induced phase separation method is the most popular. In this a prepolymer and the liquid crystal material are coated on to the substrate and then polymerised by heat or ultraviolet (UV) radiation. The film so-produced consists typically of 50–60% of the liquid crystal material. Unlike other types of LCD, PDLCs do not require polarisers. For maximum contrast it is usual to incorporate a black dye into the cell, the back of which carries a brightly coloured fluorescent reflector. When viewed by reflected light this is seen as a high-contrast coloured display on a black background. Display contrast increases with film thickness and dye concentration, but this leads to a reduction in brightness [45].

LCD-based projection displays

During the past ten years LCD projectors have become the standard method for showing data and images for business and conference presentations, for which the old 35 mm slide projector has all but disappeared. This is quite understandable when it is now possible to assemble a professional presentation using software such as Microsoft Powerpoint in a much shorter time than producing the required graphics and then making colour slides.

These units are based on small TFT-LCD films fitted into special projection optics using dichroic mirrors and a metal halide or xenon light source. In contrast to direct view displays the projection system uses three separate LC panels, one each for the RGB signals. Since LCD light-valve projectors are single lens devices with very accurately produced image plane geometry, they are not plagued by the convergence problems of the older triple lens CRT projectors.

Although widely used for business, LCD projectors are not yet cheap enough for general home use but no doubt this situation will soon change. One interesting compromise which might bridge this gap is a laptop PC in which the backlight panel can be hinged away and the exposed LCD panel placed on a conventional overhead projector. Active matrix TN-LCDs used in projectors still require polarisers, which reduce light output considerably, and some work has been done to develop PDLCs, which do not. However, for good contrast PDLC projectors require a small lens aperture, which again reduces screen brightness [46].

LCD projectors are commonly used for video-conferencing, but the level of lighting in the conference room needs to be bright enough for the video cameras but low enough for maximum screen brightness and contrast. One solution is to polarise the RGB images horizontally and project on to a special polariser screen, while the overhead room lights have multilayer polaroid filters so arranged that the ambient light reaching the screen is vertically polarised [47].

Digital light-processing projectors

The problem of limited brightness in projecting digital images has largely been solved by an entirely different technology. This uses the digital light-processing projector (DLP), a semiconductor-based microelectromechanical system developed by Texas Instruments in the late 1980s [48–50]. This on-chip device consists of a packed array of aluminium micro-mirrors which can be matrix addressed at up to 5 kHz, so that any applied voltage pulse from the underlying memory cell tilts the mirror by 10°, deflecting a beam of light from a xenon or metal halide lamp. The cells, which are fabricated by plasma etching, are about 15 μm square and packed extremely closely on the surface of the chip, giving a tighter array than is possible using TFT-LCDs. This produces a highly magnified image which exhibits less obvious ‘pixellation’ than a TFT-LCD display.

Colour displays can be achieved in a number of ways, using one to three chips in the projection system. The simplest lightweight single-chip projector combines both the latest and the oldest technology in colour projection by using a rotating RGB filter in conjunction with sequential scanning of each picture frame. This approach is also used for the brighter, two-chip system.

Three-chip projectors are configured in a similar manner to those based on TFT-LCDs but with a very compact but complex prism/lens optical system (Figure 4). Gradations of grey are achieved by pulse width modulation and 24-bit colour (256 grey levels) is readily achieved. The mechanical response time of the mirrors is incredibly fast (15 μs), making these units particularly suitable for projecting high-speed video or HDTV, for which a resolution of 1920 × 1080 (2 million pixels) can be achieved using a chip with a diagonal size of only 3.8 cm [51].

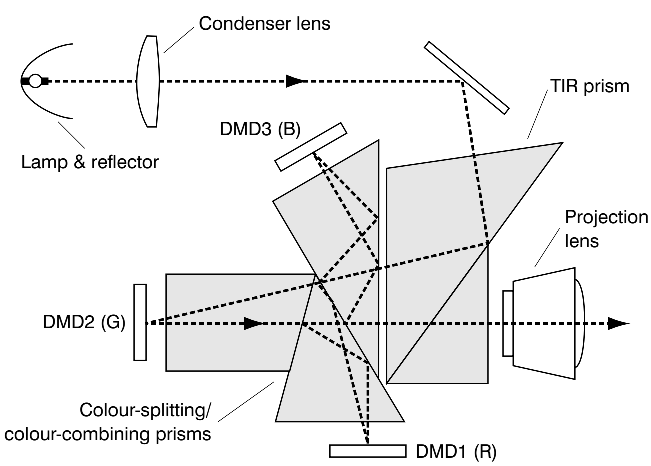

Figure 4 Optical system for a three-chip DLP (Courtesy of Texas Instruments)

ORGANIC LIGHT-EMITTING DIODES

During the past 20 years or so there has been increasing interest in the electrical properties of certain organic materials. Independent work in this field on both sides of the Atlantic has led to discoveries heralding a new and potentially cheaper display technology, the organic light-emitting diode (OLED). This type of display has been under very active development since the late 1980s [52].

Two principal types of OLED have emerged, the development of which began in the USA and the UK and for which large international business groups have formed partnerships, one result of which appears to be very long authorship lists in technical publications. Despite the major investment in this field, the only OLED colour displays at present commercially available are very small (about 5 × 5 cm). A similar situation once existed with TFT-LCDs, however, and in this case 38–45 cm displays have now become standard and models up to 76 cm are available.

The light-generating part of an OLED consists of a multilayer sandwich, usually built up on a light glass substrate carrying a very thin transparent conductive coating of ITO. Equally thin layers (< 1 μm) of the two organic components are then successively spin-coated over the ITO. Finally a calcium/aluminium cathodic layer is added. This basic structure can be enhanced using a range of organic compounds to produce different wavelengths of light, including white light. In association with RGB colour filters and TFT 'switches' this produces a full colour display in an analogous manner to active matrix LCD devices. Unlike LCDs, however, OLEDs are self-luminous and no power is therefore required for a backlight. A simplified diagram of the multilayer structure of an OLED is shown in Figure 5.

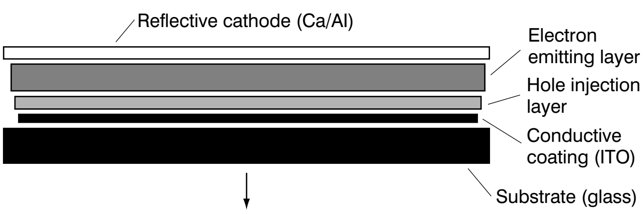

Figure 5 Basic layer structure of an OLED device

The very thin layers, a few hundred nm thick, of the organic materials on the glass substrate of an OLED can be applied by thermal evaporation *in vacuo* (for 'small molecule' devices) or by a simpler spin-coating process from solvent (for polymer displays). Thermal evaporation can in turn be replaced by low-pressure organic vapour phase deposition, which is cheaper [53]. ITO electrodes for individual pixel elements have usually been produced by a conventional mask-resist process, but for very high resolution displays (pixel size < 100 μm) laser ablation of an overall ITO coating has been used. This is unsuitable for mass production, however, and a photolithographed pixel patterning system has been demonstrated [54].

Small molecule devices

The principle of the 'small molecule' OLED was first demonstrated by Ching Tang at Eastman Kodak in 1987 [55]. Using glass coated with a transparent ITO cathode, which in turn was coated with a substituted triphenylamine (the hole transporter or p-type junction) and an electron-emitter layer (the n-junction) composed of the aluminium complex of 8-hydroxyquinoline attached to a silver/magnesium anode, it was shown that the application of a low voltage (5–10 V) produced light at the p/n junction. Further investigation showed that certain substituted perylenes and quinacridones were more efficient emitters.

Similar devices have been developed by Universal Display Corporation, Sony and Samsung, based on work carried out at Princeton University. They have patented stacked multilayer structures from which the combined light output from RGB filter layers is used to produce each pixel [56,57]. Their OLED materials were polycyclics such as substituted dinaphthylanthracenes with specific dye dopants for the RGB primaries. The R and G dopant/polymer combinations show good durabilty (40 000 h) but the blue dopant degraded more rapidly (10 000 h). In some cases special dyes are used as dopants, these products being already available for use with dye laser devices [26]. The useful lifetime of these displays can be dramatically increased if the driving current is limited, so that the screen brightness is restricted to a maximum of about 100 cd/m^2. Much brighter displays are however possible.

As with the older types of LCD, OLEDs can be given an active matrix construction based on a similar polysilicon TFT structure [58]. Colour displays can be achieved in various ways. Stripes of the RGB emitters can be deposited using the normal mask/resist process but this is viable only for the larger displays. A second method is to add special dopants to the emitter in order to produce white light [59], and then to use passive colour filters as in LCDs.

Light-emitting polymer displays

The second type of OLED, the light-emitting polymer display (LEP), was developed in 1989 by Burroughes, a PhD student working under Professor Friend at Cambridge University [60,61]. He discovered that certain conjugated polymers such as polyphenylene vinylene, which gave a yellow-green light, could also be used to construct light-emitting diodes. This led to the formation of Cambridge Display Technologies (CDT) and acquired an international slant once DuPont/Uniax and Dow in the USA, Philips in Holland and Seiko Epson in Japan became involved.

Other semiconducting polymers were soon discovered including polyanilines, polythiophenes, polypyridines, polyfluorenes and certain polyphenyl oligomers [62–65]. As with the small molecular size OLEDs there have been problems in producing a high stability blue-emitting doped polymer, but certain polyfluorene-based polymers yield a more stable display, especially if a narrow band of molecular weight of the polymer is used [66,67]. Extremely high light outputs are possible (> 100 000 cd/m^2) but again the high drive current required reduces the lifetime of the device and also tends to negate the power consumption advantage compared with LCDs. It has recently been reported that pulsed laser deposition of an electron injecting layer of diamond-like particles between the ITO electrodes and a polyoctylthiophene polymer produces a device with a much decreased power consumption [68]. Present-day OLEDs are in fact similar to, or somewhat better than, CRT displays in their luminous efficiency, of the order 5–10 lm/W.

A novel fabrication method for LEPs using a precision ink-jet printer to deposit the various polymer layers has been proposed, and to further this development CDT are cooperating with Litrex Corporation in the USA. This application technology is said to be capable of placing the polymer spots to an accuracy of ± 10 μm [69].

A further interesting possibility shown to be feasible with OLEDS is to fabricate them on flexible substrates [70,71]. Although in time usage of OLEDS may extend to large displays, immediate interest lies in small high-definition colour displays for the new generation of mobile phones and in general for highly portable/wearable micro-displays [72]. According to Covion (Avecia), in 2002 the market for OLEDs was £65 million, but this is expected to grow to around £5 billion by 2007.

FLAT-PANEL DISPLAY SYSTEMS USING PHOSPHORS

The colour display from the familiar CRT is produced by the impact on the RGB phosphors of electrons emitted from the three heater/cathodes of the RGB 'guns' at the base of the tube. In this application very precise alignment of the guns, focus and deflection coils, the shadow mask and the screen is essential to produce a uniform sharp display to the edge of the screen. It follows that there should be advantages in constructing a flat-panel display in which each pixel cell can act as a self-contained micro-CRT with a very short flight path to the 'screen'. Indeed, several other display devices have been developed in which each element of the display is a cell with its own electron source and phosphor-coated target. Electroluminescent and field emission displays fall into this category. Similarly, suitably selected phosphors can also be activated by short-wave UV radiation and this is the basis for the plasma display panels commercially available for several years.

Field emission displays

An extensive and up-to-date review of this field was published by Burden [73] who concluded that development has presented designers with a myriad of problems concerning the choice of materials and the stability of the various layers used in field emission displays (FEDs).

Many variations on the basic structure have been evolved, the earliest involving the formation of micro-cells, within each of which a pointed discharge tip is formed (the cold cathode). This is necessary to create the field intensity necessary for field emission [74]. Surrounding the cold cathode is an insulator layer carrying the gating anode electrode on its surface (Figure 6). The electron discharge from the tips is accelerated across a narrow high vacuum gap (100–200 μm, typically 10–6 torr) on to the phosphor- and ITO-coated glass anode. The drive voltage for these devices is high (typically 1–7 kV), but this is much lower than that of CRTs (10–35 kV) and therefore requires different phosphor materials. Typical low-voltage phosphors are YAG:Eu (red), YAG:Tb (green) and Y_2SiO_5:Ce (blue), where YAG is yttrium aluminium garnet [75], also used to make white LEDs.

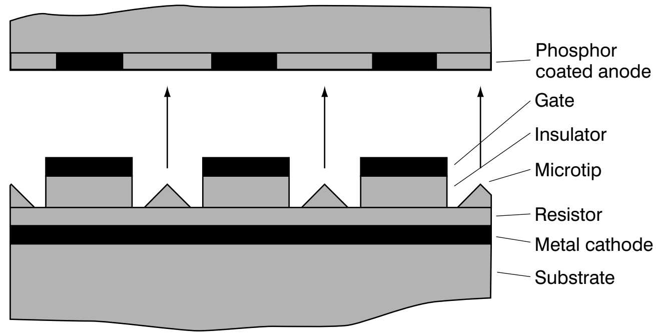

Figure 6 Construction of a microtip-type field effect display

A number of manufacturers have marketed small colour displays based on a microtip structure. However, owing to the manner in which they are formed, using typical semiconductor fabrication processes, it is not possible to make displays larger in size than 20 cm. Accordingly many variations on the basic design have been evaluated, for example using rod-shaped cathodes with emitter surfaces composed of various types of carbon, ranging from amorphous diamond-like forms [76], graphite and, more recently, films containing dispersed carbon nanotubes [77].

For large area displays it is necessary to look for alternative fabrication techniques and the most promising is that of printable field emitters using composites of very small (*ca*. 5 μm) conductive particles in an insulating medium. These are being commercialised by a UK firm, Printable Field Emitters [78], in a structure for which the various layers of cathode, emitter, insulator and gate tracks can be applied by printing, greatly reducing production costs. By this means it is hoped it will be possible to manufacture large (50–100 cm) field emitter displays at about 60% of the cost of plasma displays by 2010.

Thin-film electroluminescent displays

Thin-film electroluminescent displays (TFELs) differ from all other multilayer devices in that at no stage in manufacture is it necessary to align and assemble the two halves of the structure, since the entire solid-state composite is built up on one substrate, the completed result being very thin (1–2 mm). The most commonly used system is of the AC type (driven typically at 80–160 V at 1–10 kHz). Because of the high voltages involved, the base electrodes and associated transistor drives are produced using silicon-on-insulator technology, while the upper electrodes consist of thin, transparent films of ITO applied to the upper glass substrate (Figure 7). Between these are the RGB phosphor pixels, composed of polycrystalline compounds based on Group II and VI elements (Figure 6). As is the case with other displays using phosphors there have been problems in finding a blue with sufficient luminosity and durability. At present the red phosphor is produced using ZnS:Mn (luminosity 70 cd/m^2) in conjunction with a filter, the green with ZnS:Tb (600 cd/m^2) and the blue with Sr or $CaGa_2S_4$:Ce (only 10 cd/m^2). To obtain reasonable colour balance it is therefore necessary to make the blue pixel about double the size of the red and green pixels, although this tends to lower the overall display brightness.

As an alternative to using individual RGB phosphors a

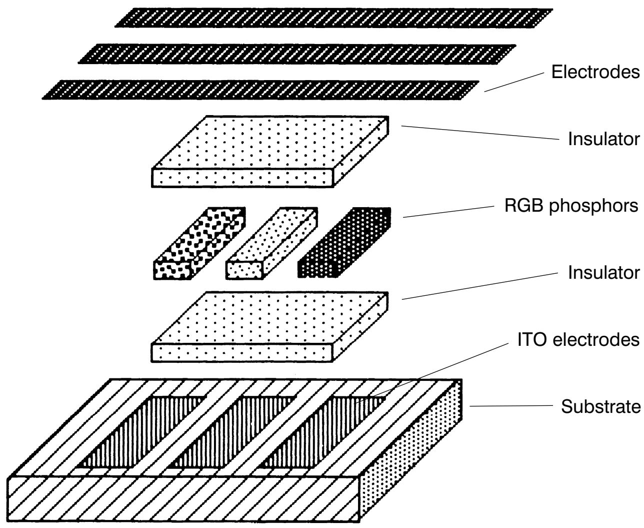

Figure 7 Structure of an active matrix EL device

composite phosphor (SrS:Ce,K,Eu), which emits white light, can be used in conjunction with RGB filters. Even when filtered, the luminosity of the blue component from such a system can be considerably better than that from the blue-emitting phosphor [79]. Despite the need for additional colour filters this concept of 'colour by white' is very attractive as a means of simplifying the manufacture of full-colour TFELs, particularly for HDTV displays [80]. Such displays have high brightness (typically 150 cd/m^2) and are very durable (only 10% loss after 50 000 h) [81].

For very small displays, such as helmet-mounted military units, the structure is built up on a silicon chip, but for larger systems the substrate is usually glass. As with LCDs, solid-state active matrix controls can be incorporated using conventional silicon chip fabrication techniques. Electroluminescent displays (ELDs) are equally suitable for very large display purposes and may well rival plasma technology for this outlet [82].

Being an AC device the control of an ELD differs from other systems in which the various grey levels of the display are usually controlled by the drive voltage. In the case of ELDs the levels of the grey response are prescribed by the 'on-time' during which each pixel cell is accessed, determined by the number of pulses transmitted in a fixed period, say 15 ms. The net result in the viewer's eye is that these high frequency pulses are integrated as a grey-level response [83]. A similar drive sequence can be used with displays incorporating LEDs, although in this case DC pulses are used. With either system the grey level, the luminance of the device, is linearly proportional to the cycle 'on-time', the so-called duty cycle.

Plasma displays

In plasma display panels (PDPs) the pulses of light for each pixel element are created by a plasma discharge, which is produced by applying an AC voltage (100–200 V) to a 10:90 mixture of xenon and neon filling each micro-cell of the display matrix. There are various methods of forming the cells, typically 50 × 150 × 100 μm for a high-resolution panel, and these dimensions affect not only the resolution of the display but also its luminosity and luminous efficiency [84,85]. The walls of the cells are coated with RGB phosphors. If a white pigment is also applied to the side walls, the display benefits from an improved viewing angle (160°) and less change in the chroma of colour displays viewed from the side, occurring due to an increased effect of the orange xenon/neon discharge glow.

The disadvantage of a reflective coating is poor performance in bright daylight, although monochrome PDPs have, for example, been used for rail transport information boards. The plasma discharge passes from the anode and expands towards the cathode extremely rapidly (20 ns) [86], but once initiated can be maintained by a lower holding voltage. For this reason some plasma cell designs incorporate a second 'sustaining cathode' (Figure 8). As with ELDs plasma displays can equally be constructed using only a white phosphor in association with RGB filters. Their luminous efficiency is rather poor (about 1 lm/W) because only a third of the input goes into energising the electrons and in turn only a third of the electrons produce the UV light impinging on the phosphors. The best performance has been obtained with low capacitance plasma cells driven by a high AC voltage [87]. At present PDPs are available from 80–165 cm but are still relatively expensive. In addition, their resolution is not as good as the present alternatives, so they have been used mainly for public information and video display systems.

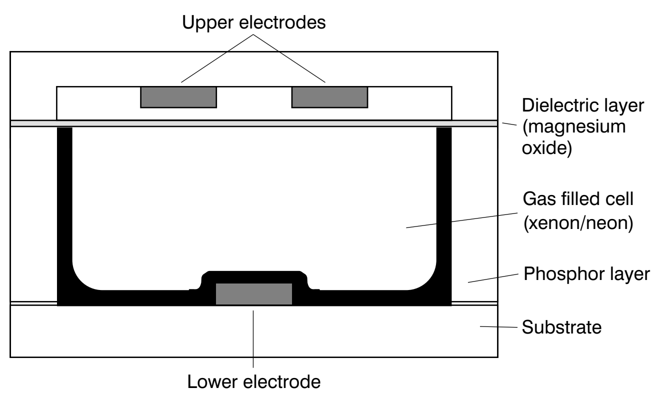

Figure 8 Basic structure of a plasma discharge cell

COLOUR MEASUREMENT AND CALIBRATION OF DISPLAYS

Standardisation of CRT colour displays

For many end-uses close control of the colour display is unnecessary. This is particularly true of TV screens, for which it seems the accuracy of colour rendering can be far from reality without the viewer being conscious of the mismatch. In this respect human colour vision is very uncritical and sees a colour display, for example of a natural outdoor scene, almost how it wishes to, irrespective of the colour fidelity of the display unit. However, with the widespread adoption of computer monitors and digital methods of colour communication the need has arisen for some means of ensuring shade reproducibility from one VDU to another [88].

The need for colour management systems (CMS), which ensure colour consistency between input devices, monitor displays and the final printed output, has long been recognised in the reprographics industry and there are many commercially available software packages which allow standardisation of the equipment used to acquire, display and print coloured images [89]. These use a widely accepted standard form of 'ICC Color Profile', as defined by the International Color Consortium (ICC) [90], to ensure that colour consistency can be achieved and communicated between devices and between users. Although there is an accepted and open standard for displayed colours, the colour management systems used for electronic communication of colour data are at present mostly proprietary. However, the possibility of setting 'open' standards for colour communication is being addressed by subcommittees of both the AATCC and the SDC [91].

The requirement for the design computer monitor to display the desired colours exactly and consistently varies from one user to another. Some firms employ colour communication software which ensures that their customers can specify shades purely from on-screen appearance using systems such as ColourTalk [92], ImageMaster [93] and the ColorVision system [94]. Generic ICC profiles are usually available for the type of monitor being used but the only really satisfactory standardisation method involves the use of a screen spectrophotometer in association with software which can perform the necessary colour coordinate matrix transformations [95]. Examples are the Minolta CA100 colour analyser, GretagMacbeth's Spectrolino and the ColorVision Spyder monitor calibrator, in all of which colorimetric data is acquired to adjust the 'white point' (D_{50} for graphics and D_{65} for textiles) and measure a range of displayed control shades [88].

Initially opinions seem to have differed as to whether TFT-LCD monitors could be satisfactorily standardised using spectrophotometric methods. This was because the displayed colours changed with angle of view and towards the screen periphery, particularly with the more standard type of LCD monitor, and some LCDs were insufficiently stable for accurate colour control. Recent advances in manufacture have, however, produced very high resolution LCDs which have a wide viewing angle and give consistent colour across the full width of the screen. Clearly one cannot uitlise a spectrophotometer using a suction cup on the screen of an LCD, as the application of surface pressure distorts the LCD layer. The recently introduced GretagMacbeth Eye-beamer can however be used remotely from the colour surface being measured and is therefore suitable for calibration of both LCDs and digital projectors.

Several workers have also shown that the gamma-correction model, a simple power function, which is satisfactory for the colorimetric characterisation of CRT displays, is not adequate to describe the response of LCDs as these follow an S-shaped function curve. The colour reproduction characteristics of LCDs also differ from those of CRTs in that the white-point colour temperature increases as luminance decreases, an effect known as 'grey tracking'. This can be corrected by modifying the video look-up table of the display device driver [96]. There are also problems in that chromaticity in the LC cell display changes with applied voltage, which affects grey level, and there may be 'cross-talk' effects between the R, G and B channels in LCDs. These factors were discussed at the 10th Color Imaging Conference (2002) [97,98] and it appears that, by choosing a suitable characterisation model, good colour management of LCDs can in fact be achieved.

When comparing coloured patterns with a screen display it is preferable to house the display monitor in a viewing cabinet with a relatively low level of illumination [88]. The system is standardised using a CMS package that allows for differences in type of illumination and viewing conditions. This requires a reliable chromatic adaptation transform [99] and colour appearance modelling system such as the improved CIECAM97s model [100], which can be incorporated into the CMS software. The effect of different surround colours when comparing an LCD projected image (dark surround) with an LCD monitor (dimly lit surround) has been examined but the effect of changing the background was found to be relatively small [101].

Similarly, various colour difference formulae have been evaluated for different viewing conditions (so-called parametric effects) and the latest proposal, CIEDE2000, shown to perform best [102]. As an alternative to a VDU-based colour display, the proposed Coloron unit is based on a screen illuminated by multiple LEDs, used to simulate or match coloured samples, though the claim that it is more precise and gives better reproducibility than a standardised CRT seems unlikely [103].

Colour gamuts

Standard CRT VDUs can display a very wide gamut of shades, particularly in tubes incorporating the green phosphor of the NTSC TV colour system, which is very similar to that proposed for HDTV (SMPTE-240M). CRT colour gamuts depend on screen luminance; as this diminishes so does the size of the gamut. Conversely, as the external illumination increases the gamut size decreases. An even wider gamut could be produced using the latest ultra-bright RGB LEDs or lasers (Figure 9). However, a two-dimensional CIE (x,y) display can be misleading compared to three-dimensional (x,y,Y) visualisations [104,105].

Quite apart from the size of any colour gamut it is important the finest gradations of shade can be adequately displayed, and this is determined by (a) the number of grey level gradations that the system can display (e.g. 16–256 grey levels each for the RGB values corresponds in theory to 4900 to 16.7 million displayable colours); and (b) the viewer's assessment of the smallest detectable colour difference that can be perceived on-screen under the expected ambient illumination.

In general, 24-bit colour (i.e. 256 grey levels each for the RGB values) gives adequate sensitivity for critical applications [89]. For non-critical use such as video or TV viewing, however, it is possible that only about 800 colours would be adequate [106], say 3 bits each for R, G and B. Better TFT-LCDs are also capable of displaying the 24-bit colour range (so-called TruColor) with a 38–45 cm screen, giving a definition of XGA or higher. Indeed LCDs with up to 80 cm screens are currently available. This highlights the considerable improvements in specification since 1990, at which time these devices would at best have had a 25–30 cm screen with a 16 grey level capability (maximum 4913 colours).

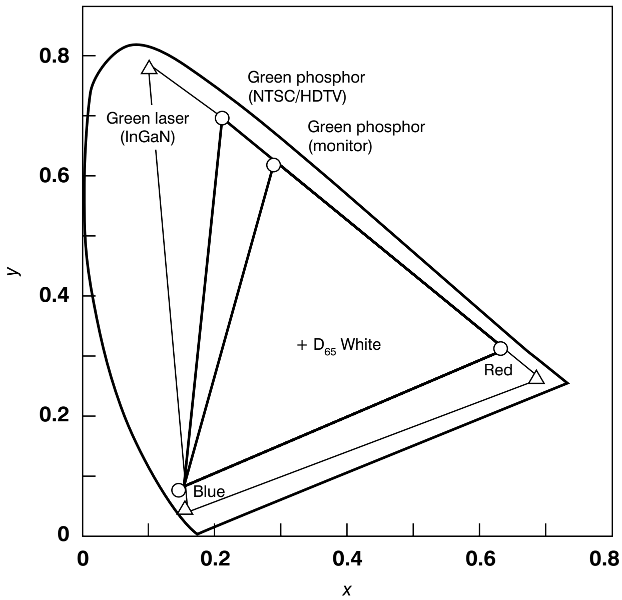

Figure 9 Colour gamuts of screen phosphors and LED/lasers

Non-CRT display gamuts

TFT-LCDs offer the closest colour performance to that of CRT displays. It is important to choose the backlights and the RGB filters in such a way that when the filters are equally illuminated the resultant white point is as close as possible to the required standard (e.g. D_{65} for PAL TV or a VDU; illuminant C for NTSC TV; and D_{50} for a reprographics workstation). Jenkins has reported a micro-spectrophotometer which enables measurement of individual filter elements in a TFT-LCD array [107].

The widest gamut in a backlit display is attained when the backlight, for example a Philips Colour 84 lamp, has a spectral power distribution with narrow band emission closest to that of the peak wavelengths of the RGB filters (about 650, 550 and 450 nm).

Apart from modern TFT-LCDs, there are some limitations to the colour gamut available with the newer colour display technologies. This is particularly true of systems where the light output depends on the use of RGB phosphors (e.g. plasma and electroluminescent displays) which at present give a smaller gamut than that of the standard CRT phosphors, particularly with respect to blue. However, this is of minor importance as such displays are at present unlikely to be used for high fidelity colour display purposes; a similar situation applies to OLED devices. A second restriction is in the number of achievable shades within that gamut, due to limitations in the number of grey levels that can be displayed.

FUTURE DISPLAY TECHNOLOGIES

In trying to predict which display technologies will predominate in the next 10 years it seems likely that there will be no outright winner, as each system offers benefits for specific end uses. There is no doubt, however, about the size of the display market, estimated to be worth almost $30 billion by 2005 [108].

At the moment the PC monitor (38–45 cm) market is about 85% CRT, but decreasing manufacturing costs for TFT-LCDs will surely see them continue to gain market share due to space-saving and portability. The market position for CRT use is even more entrenched for TV displays, where UK annual sales are about five million units, and only the wider adoption of large screen (100–130 cm) HDTV is likely to affect this position. For TV displays it is forecast the following changes will occur between 2000 and 2005: CRTs will decrease from 90 to 75% of the market share; LCDs will increase from 2 to 6%; and PDPs will be much increased, from 9 to 20% [109]. One forecast is that by 2010 personal TV head-up displays will be available, with 3D images that appear to hover in front of the viewer, and holographic displays for playing computer games [108].

In the immediate future it is difficult to see LCDs losing their present dominance in the laptop PC market. Despite a number of advances in battery technology there is, however, a need for less power-hungry devices and the 30–38 cm laptop display sector must certainly be an immediate target for OLED displays, which offer a 30% cost advantage over LCDs. At the moment, however, production experience is being gained with OLED colour devices by marketing them for the smaller screen displays in WAP (wireless application protocol) mobile camera- and video-phones, palm-top computers and viewfinders for digital cameras and camcorders.

LCDs are unlikely to be used for large displays (100–130 cm), which will probably be of the plasma discharge or electroluminescent type, both technologies being predicted to equal the unit cost of OLED devices by 2010, i.e. 30% lower than TFT-LCDs. Nevertheless, the total world market for VDUs for PCs alone is incredibly vast. It was announced in September 2002 that there are now over one billion PCs in use, which equates to one for every six persons in the world. One wonders how this figure was computed, given the rate at which PCs are now discarded for newer models.

Despite the apparent maturity of the LCD market and the variety of new display systems, it has been suggested that the potential use of LC types other than STN and TN should not be forgotten [110]. Recent developments with grating-aligned LCDs by ZBD Technologies is one such example [111].

The use of suspended particle devices (SPDs), a system which acts rather like the polymer-dispersed LCDs already described, was first investigated by Edwin Land (of Polaroid filter and instant photography fame) for use as a light valve, for example as an electronic light control for windows. SPDs offer a number of advantages over existing LCD technology, as they have very wide viewing angles, are brighter and have better contrast, but there remain technical problems with their stability [112].

Another development in novel LCD technology is so-called ‘liquid crystal painting’ [113]. Research at Philips has recently shown that LC materials can be incorporated into a prepolymer mixture and applied to a substrate by surface coating. The LC material (a cyanopolyphenyl type) dissolves in the isobornylmethacrylate-based monomer, but when this is polymerised by exposure to UV light the LC forms a separate phase which becomes trapped between the surface polymer film and the glass substrate. To form individual pixel cells, a two-stage polymerisation process has been devised so that by using a cross-hatched mask and exposing to UV light in two stages, polymerised 'walls' are first formed, followed by the second phase-separation stage. If this process could be carried out on the surface of a conventional TFT backplane it would represent a potentially cheaper manufacturing route [114].

Fabrication techniques involving printing are an obvious target for cost improvement, as has already been seen in potential new manufacturing methods for large display LCDs [115], OLEDs [69], FEDs [116] and PDLs [117]. At present most stages of fabrication of FPDs are batch processes and if some stages could be made continuous this could lead to cost savings. In particular, fabrication on to a flexible polymer substrate could be operated using a roll-to-roll system.

The use of plastic substrates such as polyester has been examined for STN-LCDs [118], active matrix LCDs [119] and OLEDs [120]. One such example is the deposition of the ITO electrode layer on polyester film using a pulsed laser beam to replace vacuum sputtering [121].

Philips are active in many new display technologies and in partnership with the E Ink Corporation of Cambridge, USA, are developing active matrix displays. These have high brightness and contrast and exhibit a memory effect, so that an image can be retained after turning off the power. They are ultra-low power devices which can be read, just like a printed document, from any angle without loss of contrast. When constructed as an active matrix composite they are thinner (< 1 mm) and lighter than LCDs, because polarisers and a relatively thick top glass sheet are not required. The principal component of an 'elecronic ink' display is a dispersion of encapsulated black and white pigment particles which respectively carry negative and positive charges, the capsule dispersion being contained between a glass sheet, carrying the usual array of ITO electrodes, and a plastic seal. When viewed from above, if the upper electrodes carry a positive charge the black particles migrate to the upper side of each capsule and the screen appears black, and *vice versa* [122].

In a similar vein Xerox/Gyricon are developing displays which use charged beads, one hemisphere being white and the other black, each carrying an opposite charge. At present only monochrome displays are available and are being used, for example, for in-store sales placards. However, colour versions of this novel technology are forecast before long and are likely to be available on plastic laminates.

Finally, for up-to-date statistics and market predictions, there are a number of internet sources [123–125].

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The author was employed by the former ICI Dyestuffs Division in the technical marketing, research and development of textile dyes for 30 years, and thereafter as a research associate working at UMIST on the development of ink-jet printing machinery, publishing many scientific papers on textile coloration and electronic devices throughout his career.