State of the art and new developments in optoelectronic displays

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Starting by classifying optoelectronic displays in three categories – commercially established, engineering models and under research and development; the present state of the art is reviewed and significant new developments are noted. In comparing the features of the various types of display, their information handling capabilities are discussed in detail and future perspectives for displays with high information handling potentials are pointed to.

Optoelectronic displays represent a highly dynamic branch of industry in which established techniques are being further refined while at the same time new principles are undergoing explorative study. The incentive for this line of work stems from the need for the growing torrent of information to be visually displayed by suitable devices. This is accomplished with the aid of displays which form an interface between the human operator and the machine.

Displays can be classified according to various aspects. One simple but extremely important consideration for the user, is availability, on the basis of which displays will be classified in three categories:

- commercially established
- engineering models
- under research and development (Table 1).

COMMERCIALLY ESTABLISHED DISPLAYS AND THEIR FURTHER REFINEMENT

Cathode ray tube

The cathode ray tube (crt) display is still predominant among display devices with a medium to high information handling capacity. Since all new displays are expected to come up to the same high standards as the crt display, exacting demands have to be met because the crt is a highly developed product. It has however the physical drawback of being bulky (Fig. 1) as well as possessing certain technical disadvantages such as poor edge definition.

CRT displays and new optoelectronic displays differ significantly in their drive circuitry. In a crt display the individual picture elements are bright following successive activation by the electron beam, while a Wehnelt cylinder controls the brightness. In flat display panels on the other hand the picture elements, arranged in the form of a matrix (Fig. 3), are activated in rows. The required drive circuitry is complicated and costly, but further progress in the development of integrated circuits will in due course open the way to more favourably priced solutions.

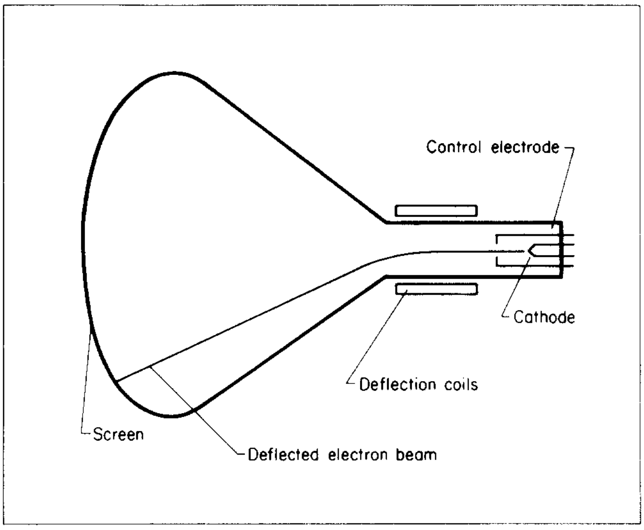

Fig. 1 Cathode ray tube

Table 1 State of the art of display technology (availability)

Commercially established	Engineering models	Under research and development
CRT displays	Electroluminescence	Utilization of large variety of physical effects
Vacuum fluorescent displays	Electrochromic	
Plasma displays		
Liquid crystal displays		
LEDs		

Vacuum fluorescent displays

Vacuum fluorescent displays[1] are flat crt displays in which a fluorescent material is activated by electrons. Their resemblance to a triode can be recognized from the schematic representation shown in Fig. 2. The cathode consists of a thin metallic filament coated with oxide, while the control grid is a finely meshed metal net. The conductive film deposited on the isolating substrate of the anode is coated with a film of fluorescent phosphorus that emits light in response to low electron energies. All the electrodes are enclosed in a vacuum sealed glass envelope.

In seven segment displays the anodes are arranged in the form of bars. Since the anodes can be given any desired

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shape it is also possible for alphanumerics or other symbols arranged in a matrix configuration to be displayed. Driving is accomplished through the application of voltages to the control grid and the anode segments. To activate a segment the control grid must be driven positive and voltage must be applied to the anode segment. Multiplexing displays of simple design can also be realized. Although the display is viewed through its control grid, the viewer will notice neither the control grid nor the filament. The required information appears with good contrast in agreeable bluish green light. The various segments are uniformly illuminated and allow a broad viewing angle.

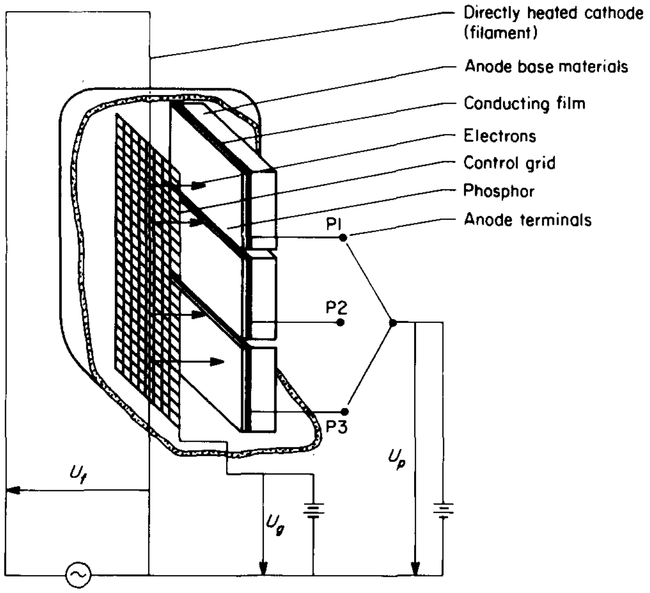


Fig. 2 Constructional design and mode of operation of a vacuum fluorescent display

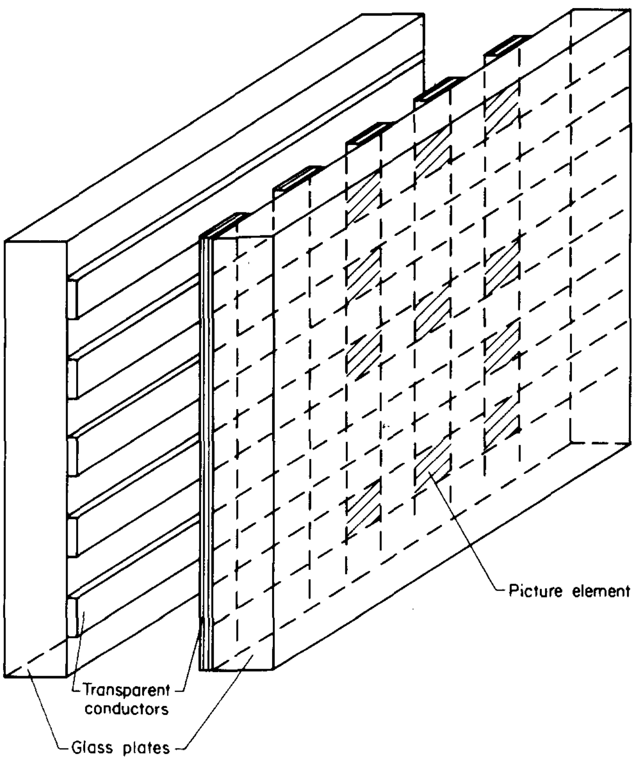


Fig. 3 Schematic representation of a gas discharge display

A large variety of vacuum fluorescent displays are available as seven segment displays. Recently introduced 14 segment and dot matrix displays are additionally available. The former restriction of the display colour to bluish green has been overcome by using a variety of special kinds of phosphorus that can be activated by low energy electrons. Vacuum fluorescent displays are all of Japanese provenance.

Gas discharge displays

Gas discharge displays use numerous short gas discharge paths between two glass plates for the display of alphanumerics (Fig. 3). A typical feature is the red-orange light produced by the neon gas discharges. The discharges are always triggered at the intersection of two selected conductors. As the gas discharge is either on or off, half selection is readily possible and a dot matrix can be addressed row by row in the multiplex mode.

Numeric displays

The display shown in Fig. 4 is intended for applications where only a relatively small information handling capability is required. The segmented cathodes are deposited, for instance, in thick film technology on a substrate^2. The transparent anodes (for one numeric each) are on the front panel. The two substrates are glass sealed using a common spacer frame.

Besides dc numeric displays there are also ac versions. Matrix displays, which have a far greater information handling capability than numeric displays, are likewise available in dc and ac versions.

DC plasma matrix displays

Figure 5 shows a schematic representation of a dc plasma matrix display. Transparent conductors running along two glass plates cross at right angles. Between the two parallel glass plates, gas discharges can be triggered at the crosspoint of any two selected metal lines. An apertured plate sandwiched between the two glass plates isolates the various gas discharges from each other. The glass plates are hermetically sealed.

The matrix configuration of picture elements requires appropriate drive circuitry to which a large number of lines (as many as there are rows and columns) are bonded and assigned drivers. Greatly simplified drive circuitry is realized by using a shift technique. A corresponding display (Fig. 6) consists of a display section between the cathodes and the front anodes, and a priming section between the cathodes and the back anodes. In the priming section the gas discharge is continuously shifted from one cathode to the next and is always drawn into that portion of the display which has to be activated. One essential feature of this concept is that the cathodes are arranged in groups and brought out, for instance, as three lines. The shifting of the gas discharge is triggered by clock pulses applied to these lines. In order to trigger the shifting of the gas discharge from, for example, the first cathode (topmost cathode in Fig. 6) to the second, a pulse must be applied to the second cathode line. The gas discharge will then shift to the second cathode but not the fifth, eighth, etc, because only in the vicinity of the first cathode – below

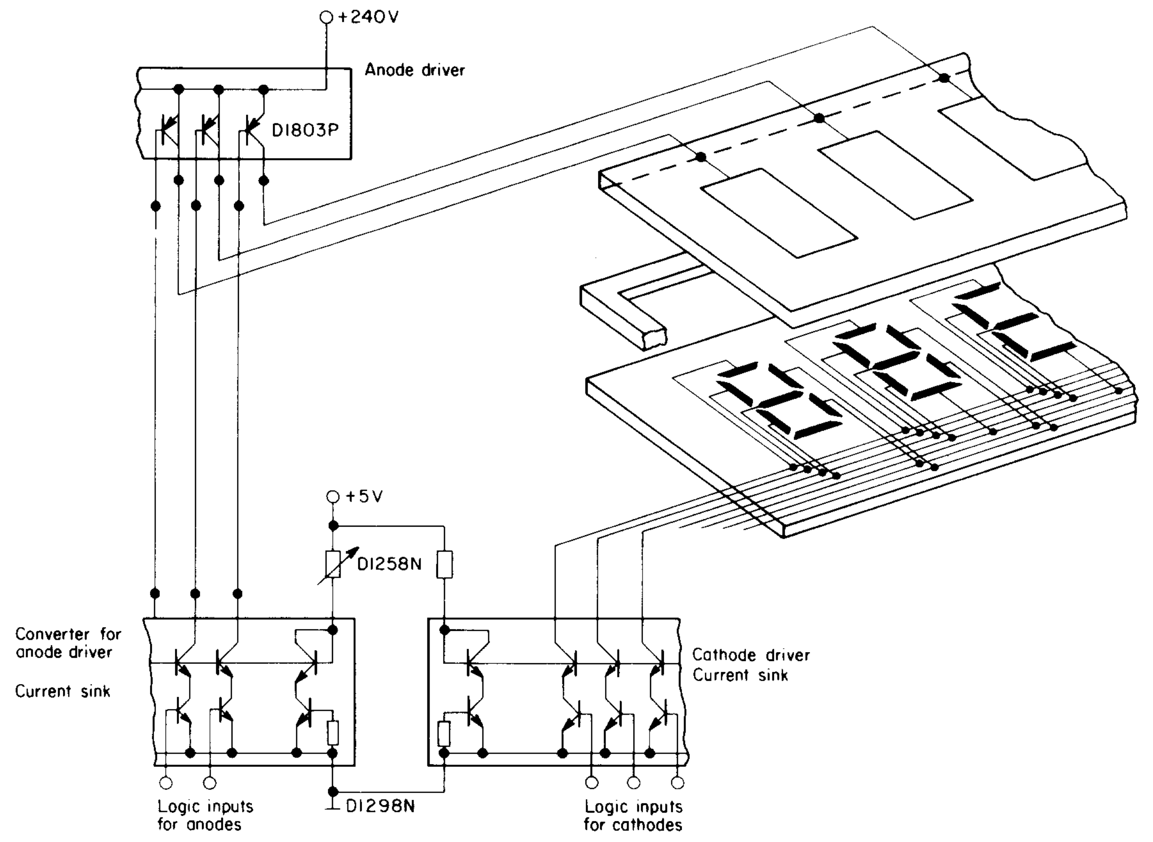


Fig. 4 Seven segment dc multiplexing plasma display

which the gas discharge initially glows – is the priming sufficient to trigger a discharge. Since this mode of operation requires only a few cathode lines instead of about a hundred be brought out, the drive circuitry, which is otherwise rather considerable in the case of a matrix addressed display, is greatly reduced.

The bar graph, a quasi-analogue display using one or more bars in an array of segments (cathodes), is like the mercury column in a thermometer. The length of the bar of light emitting segments represents the information wanted. To avoid having to bond a contact to each of the many (eg 200) cathode segments it is possible to drive the display by means of a shift technique (Fig. 7) in which, as shown in Fig. 6, the gas discharge is shifted by priming in the vicinity of a glow discharge.

AC plasma matrix display

The conductors of an ac plasma display^{5,6} are coated with an isolating film, as shown in Fig. 8. Since these isolating films store capacitive charge, the display also stores whatever information is written in, thereby obviating the need for an external memory. Although the full matrix circuitry is generally required, the expense of an external memory is saved.

Other commercial plasma displays are of similar construction to that shown in Fig. 8a. Since they do not use the charge storage effect of the isolating films, the tolerances which have to be observed in fabrication are less tight. They have the advantage over dc displays that no sputtering problems are encountered. Any sputtered cathode material will deposit on other parts of the display and induce undesired changes in the operating parameters. In dc displays the sputtering effect is usually greatly reduced by adding a small amount of mercury to the discharge gas.

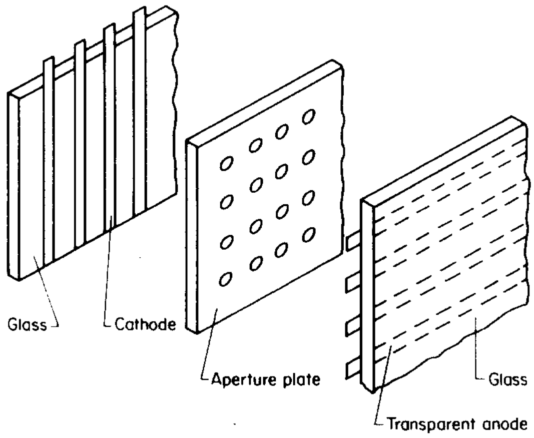


Fig. 5 Basic elements of a dc plasma matrix display

AC plasma displays for shift operation[7] combine the advantage of storage with that of reduced drive circuitry. The production yields so far obtained are however rather modest because even a single defect in the display will result in a breakdown. DC and ac plasma panels (Fig. 9) are used among other things in bank terminals. They offer a number of technical and ergonomic advantages such as well defined graphics and complete freedom from flicker but they are still too expensive – due mainly to their rather complicated discrete drive circuitry. One major development objective is therefore to develop drive circuitry in integrated technology.

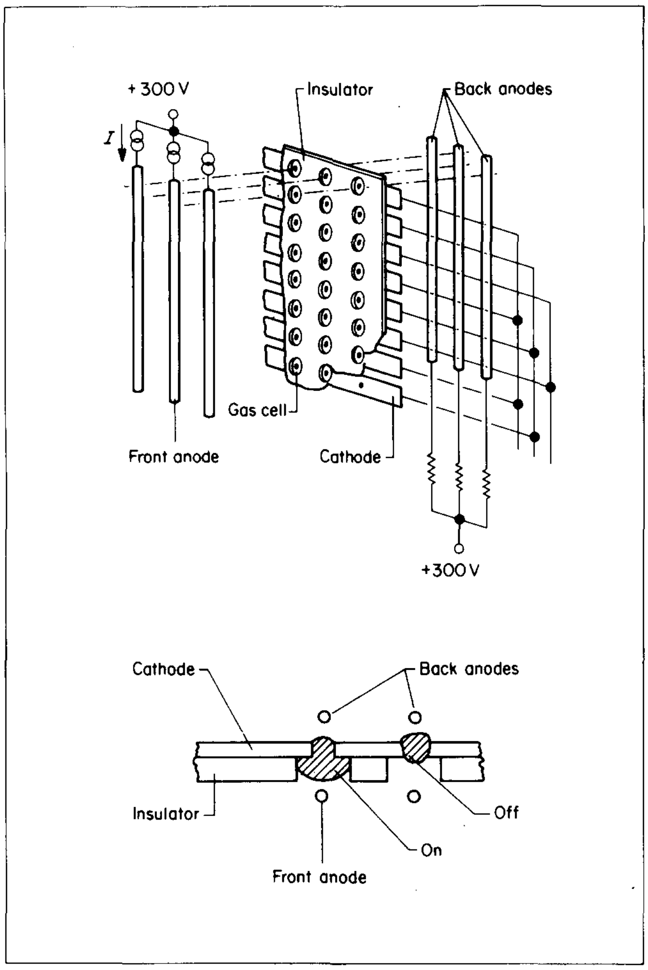


Fig. 6 Basic elements of a dc plasma display with a shift feature

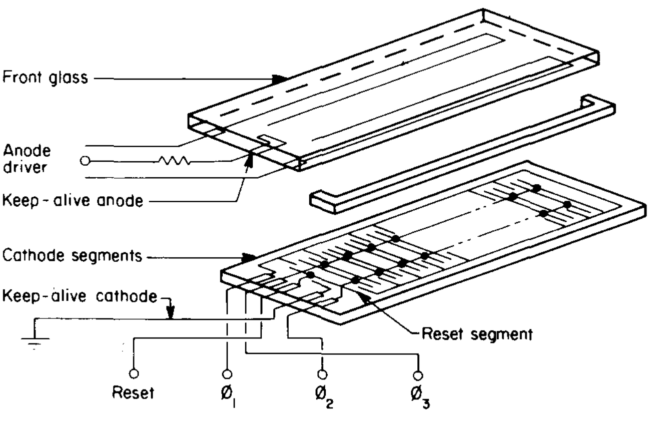


Fig. 7 Bar graph plasma display

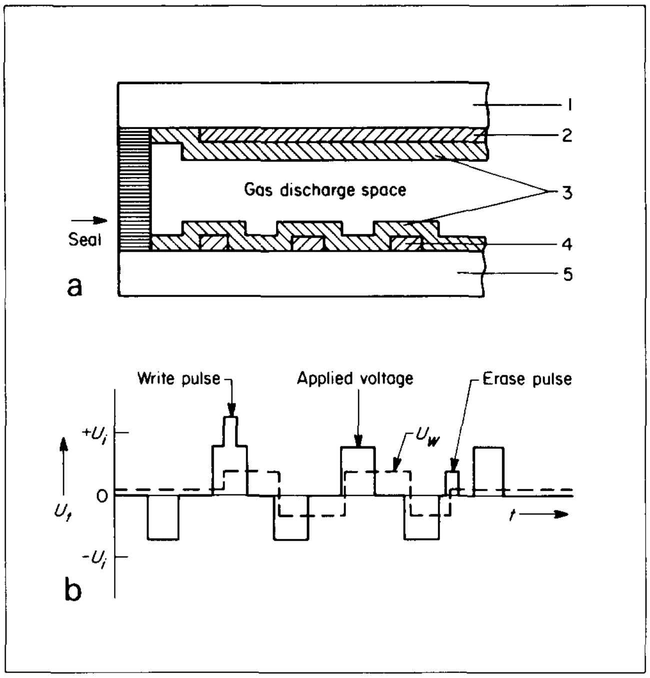
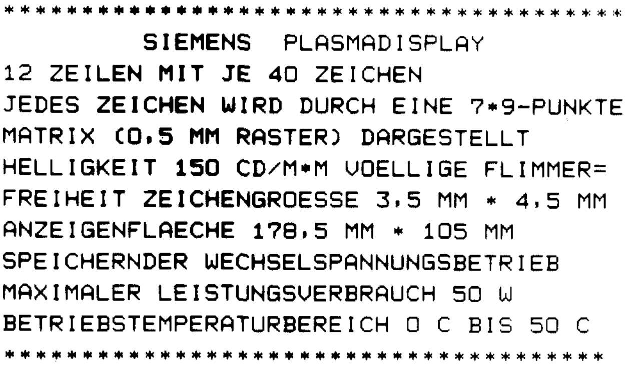


Fig. 8 General configuration of an ac plasma display; a – Cross section; b – Driving principle; U_w inner surface voltage, U_t trigger voltage, 1 glass plate, 2 x conductor, 3 dielectric, 4 y conductor, 5 glass plate



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JEDES ZEICHEN WIRD DURCH EINE 7*9-PUNKTE
MATRIX (0,5 MM RASTER) DARGESTELLT
HELLIGKEIT 150 CD/M*M VOELLIGE FLIMMER=
FREIHEIT ZEICHENGROESSE 3,5 MM * 4,5 MM
ANZEIGENFLAECHE 178,5 MM * 105 MM
SPEICHERNDER WECHSELSPANNUNGSBETRIEB
MAXIMALER LEISTUNGSVERBRAUCH 50 W
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Fig. 9 AC plasma panel

Development of video panels

Video panels are being developed worldwide in the form of gas discharge, electroluminescent and liquid crystal display units. Only gas discharge panels have so far been demonstrated as engineering models with a capability of displaying moving scenes in colour[8]. The video panel not only has to meet stringent requirements with respect to the number of picture elements and the contrast range, but major problems still need to be solved with respect to the required brightness and the efficiency of conversion of electrical into optical power.

The objective behind the use of the positive column[8,9] is to realize the same brightness and conversion efficiency in display cells as positive columns have in conventional fluorescent lamps. The inherent problem is however that display cells intended as video panels need to have dimensions of about 0.5 mm, which is far smaller than those of fluorescent lamps, and that their brightness and efficiency are greatly influenced by their dimensions. Although the required peak brightness can be realized through storage operation, the efficiency problem still remains to be solved.

Liquid crystal displays

The displays described above are active displays, ie they themselves generate light. This is always an advantage when a signalling effect is desired. If however there is a desire for a display with the appearance of a printed page, which is one of the objectives of text processing, a passive display will offer a more favourable solution.

The passive display has the advantage that its contrast does not decrease with increasing illumination and, as it is non-bleaching, the information remains clearly legible under sharply changing lighting conditions, eg even in direct sunshine. Since a passive display does not generate light but only modulates the ambient light, it uses very little power, which is an important factor with all battery operated devices. The principal passive displays at present are lcd's.

Physics and technology

Liquid crystal molecules have either a strong constant electric dipole moment or a high polarizing capability that causes a strong dipole moment to build up when an electric field is applied. With the aid of this applied electric field it is possible to influence the orientation of the liquid crystal molecules through its interaction with the dipoles, thereby initiating a change from one definite orientation to another. As a result of the refractive index anisotropy, this leads to various optical states which can be used to represent information[10].

Dynamic scattering cells, which rely for their operation on a very small current flow that induces a turbulent flow in the liquid crystal, have already been largely superseded by field-effect cells. The principal representative of these is the twisted nematic cell (tnc) whose mode of operation is shown in Fig. 10[11]. The liquid crystal molecules are arranged parallel to the substrates, their orientation twisting by 90° from substrate to substrate. When the cell lies between two crossed polarizers, the display turns light because the cell rotates the polarization plane of the light by 90°. An applied electric field will orient the molecules parallel to the electric field, so that no rotation of the polarization plane occurs and the display will absorb light. With this mode of operation dark alphanumerics appear on a light background. If the polarizers are arranged in parallel, the alphanumerics show up on a dark background. Since the physical mechanism consists solely of a rotation of the liquid crystal molecules under the influence of an externally applied electric field, the power needed to operate a twisted nematic cell is minimal. Thus a display for a wristwatch, for instance, uses only about one microwatt.

The constructional design of liquid crystal cells for displays is shown in Fig. 11. The liquid crystal is sandwiched as a thin film with a thickness of typically 10 μm between two parallel glass plates whose inner surfaces are coated with a transparent electrode film of, for example, indium tin oxide (ito), into which the geometrical structures required for the display are etched. The liquid crystal is activated by applying a voltage between the front and back electrodes. The uniform orientation of the liquid crystal molecules by means of appropriate preparation or by coating the inner surfaces of the cells is a very important process step.

LCDs are always driven with ac voltage because in the case of dc operation irreversible electrochemical mechanisms would be liable to set in. Conventionally the phase shift method is used. A symmetrical squarewave voltage of, for example, 1.5 V is here applied to the back electrode of the display. The back electrode voltage is applied to the non-driven segments of the front electrode – the difference voltage is 0 V; a voltage of the same amplitude and frequency but offset in phase by 180° is applied to the driven segments – the difference voltage is 3 V.

Millions of mass-produced liquid crystal displays are already in use, having found wide acceptance as displays in wrist watches and pocket calculators. Medium-sized

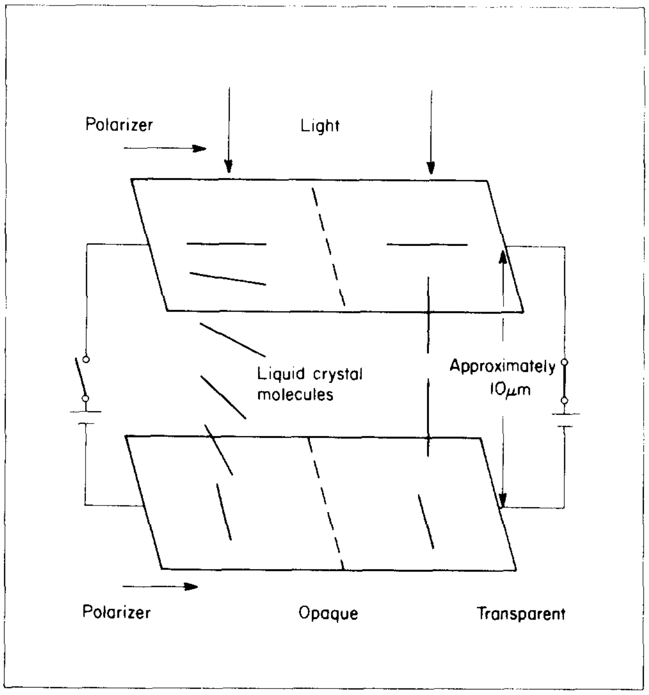

Fig. 10 Underlying principle of twisted nematic cell

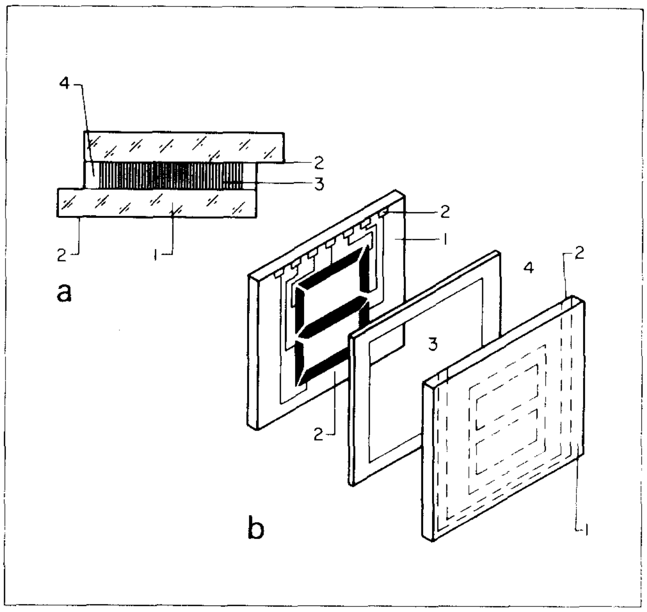

Fig. 11 Constructional design of a liquid crystal cell: a – Cross section; b – Constructional design; 1 glass plate, 2 electrode film, 3 liquid crystal film, 4 seal and spacer frame

displays, which are considerably larger than wristwatch displays, are opening a variety of new areas of application for liquid crystals. Besides being used in table clocks and measuring instruments they will also find application in control systems, system instrumentation, entertainment and recreational electronics such as cassette recorders and film cameras, electronic games, washers, cooking ranges and other electronic household appliances, as well as in telephone equipment. Further areas of application are automobile dashboards and filling station displays. The operating temperature range of lcds is being steadily expanded and there are already versions capable of operation between -15°C and +80°C.

Multiplexing liquid crystal displays

Wristwatch displays are rather simple displays with relatively few numerics that are directly driven, ie each segment of a seven segment display has a separate lead and driver. There is a growing demand for complex displays with a larger information handling capability, but economic considerations here disallow the direct driving of segments because of the more elaborate drive circuitry that would then be required. A solution is offered by a matrix drive designed for multiplexing lcds[12]. Figure 12 shows the mode of operation of a multiplexing liquid crystal display, while Fig. 13 presents a photograph of an lcd module. The drive circuitry is implemented in cmos-ic technology.

Future liquid crystal displays

There are various approaches to the development of liquid crystal displays with a medium to high information handling capability that are also suitable to a certain extent for black and white television applications:

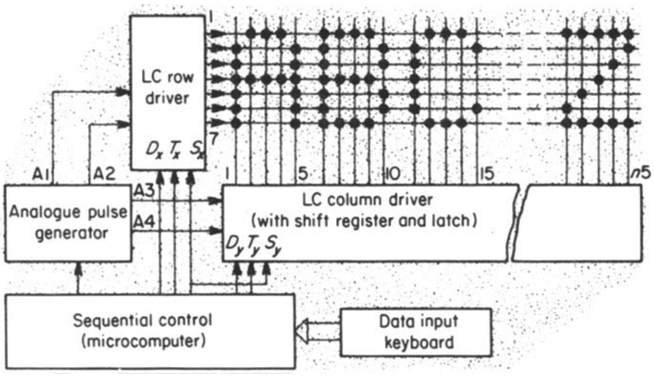

Fig. 12 Configuration of a multiplexing liquid crystal dot matrix display

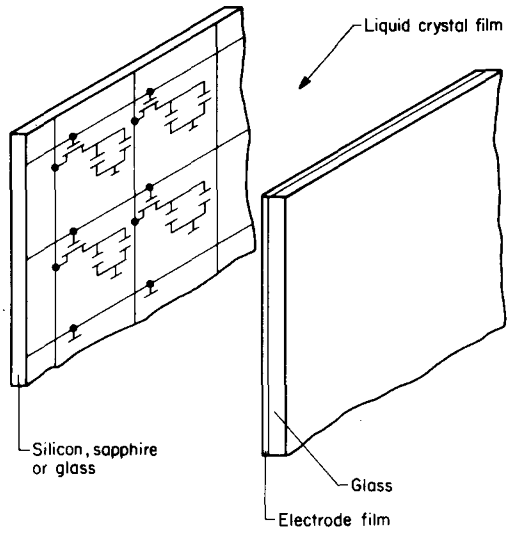

Fig. 14 Configuration for directly driving the picture elements of a liquid crystal film via an active matrix

1. By increasing the number of multiplex steps of twisted nematic crystal displays, eg by choosing appropriate illumination (Hitachi)[13,14].
2. By use of the phase shift effect, eg with limited storage capability (Siemens)[15].
3. By directly driving the lc cells with transistors deposited on silicon or sapphire (Hughes, Matsushita)[16,17] as shown in Fig. 14.
4. By directly driving the lc cells with thin film transistors (Westinghouse, University of Dortmund)[18] as shown in Fig. 14.

Directly driving the lc cells as provided for in approaches 3 and 4 will overcome the rather limited multiplexing capability of lcds; also the otherwise disturbingly long switching delays of the liquid crystal are here relatively unimportant. On the other hand the use of silicon transistors limits the size of the display and the thin film transistors have not yet been developed to the point where fabrication can begin. Which of these approaches will prove the more successful will depend on the solution of the prevailing problems.

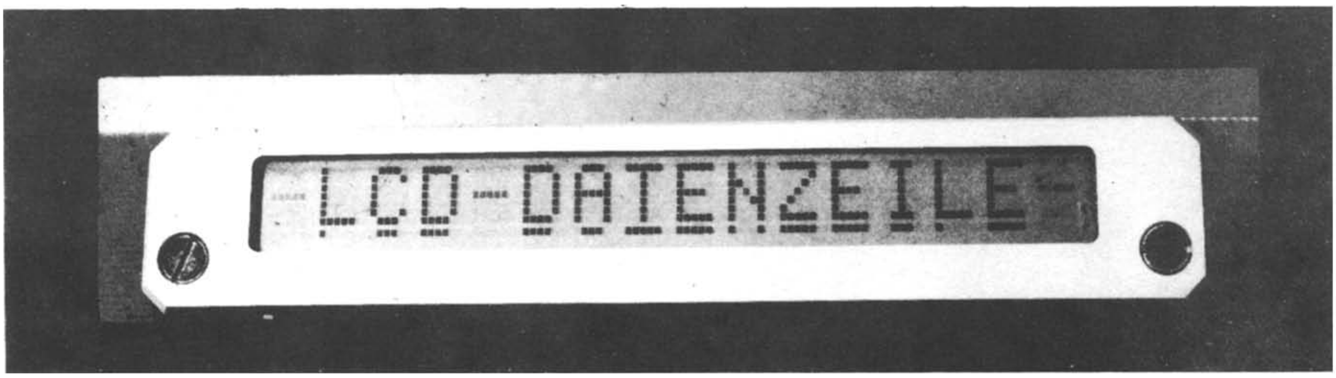

Fig. 13 Liquid crystal dot matrix display

Although already entirely acceptable, the optical appearance of liquid crystal displays is being continuously improved. In this connection fluorescence activated displays (flads) and dichronic dyes deserve mention. In flads[19] a plastic light collector plate is used in combination with a liquid crystal display (Fig. 15). The collected light generates fluorescent light which is simply coupled out at the segments of the display to produce light alphanumerics on a dark background. Dichroic dyes (Fig. 16)[20] are special dyes that are added to the liquid crystal. The application of an electric field causes the liquid crystal to change, for instance, from the focal-conic to the nematic state, together with the dye molecules, so changing the hue. Displays of this type will, once the problem of lifetime has been solved, be of special interest because they do not rely on polarizers, which absorb much light and become sensitive to humidity at higher temperatures.

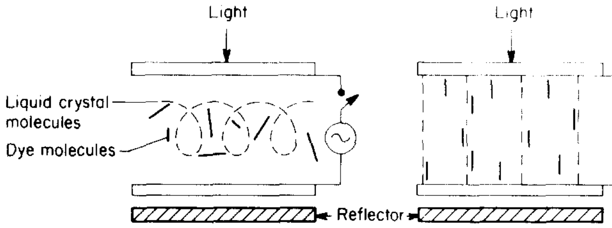

Fig. 16 Liquid crystal cell with dyes

LED displays

Physics and technology

LED displays are widely used wherever power consumption is not a key factor. They are semiconductor devices which emit light in response to an applied voltage[21,22]. This light emission is induced by the recombination of electrons and holes in the pn junction of a semiconductor chip (Fig. 17).

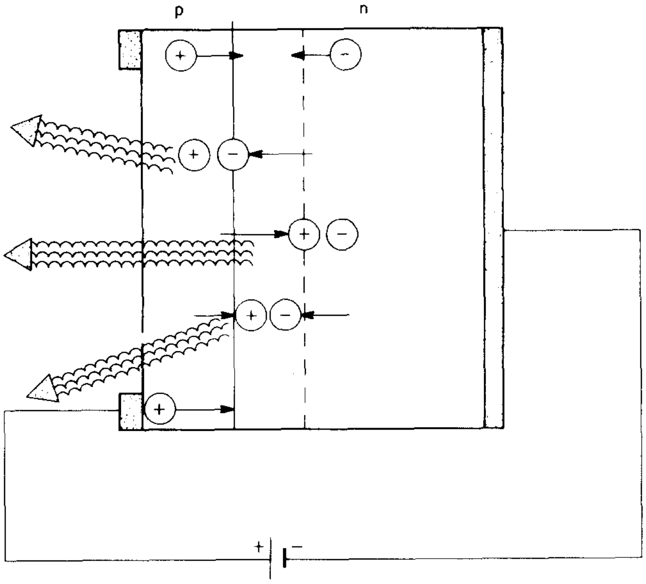

Fig. 17 Mode of operation of a led chip

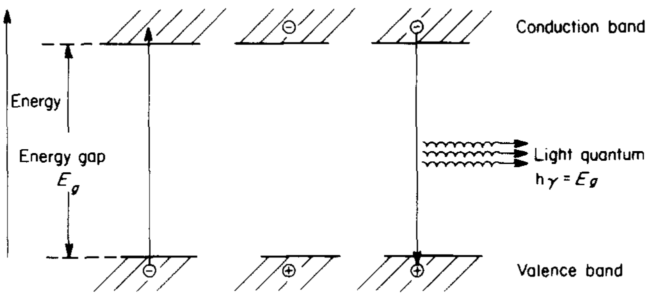

Fig. 18 Energy bands of a led

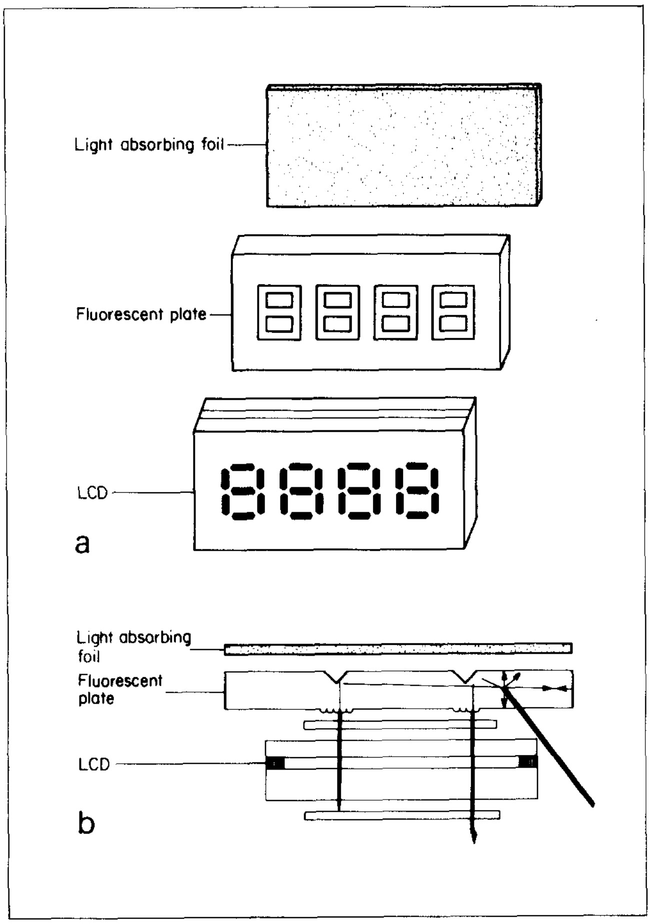

Fig. 15 Underlying principle of the flad; a – Configuration, b – Cross section

Figure 18 is a schematic representation of the energy bands, the electron excitation mechanism, recombination and the resulting emission of a light quantum. The energy of the light quantum is given by the energy gap E_g between the valence and conduction bands. For the emission of visible light the energy gap E_g has to be larger than 1.8 eV because the visible spectral range extends from 1.8 eV to 3.10 eV, representing an optical wavelength range of 700 nm to 400 nm. Silicon and germanium, with respective energy gaps of 1.1 eV and 0.7 eV, are threefore unsuitable for this application. Larger energy gaps are found in semiconductor compounds such as GaAs (1.43 eV), GaP (2.26 eV) and GaN (3.5 eV). With $GaAs_{1-x}P_x$ it is possible to realize any colour between red ($x = 0.3$) and green ($x = 1$) by appropriately controlling the concentration of phosphorus.

Since the electron hole recombinations need not be associated with the emission of light but can also take place non-radiatively with the development of heat, it was an important initial objective in led technology to optimize the efficiency for light emission by increasing the probability

Table 2 Physical performance data of various light emitting diodes

Photoactive material	Colour (wavelength, max, emission in nm)	External quantum efficiency*, %	Light source efficiency, lm W^{-1}
GaP:N	Green (565)	0.05 to 0.7	0.36 to 2.16
$GaAs_{0,15}P_{0.85}$:N	Yellow (585)	0.05 to 0.1	0.26 to 0.52
$GaAs_{0.35}P_{0.65}$:N	Red (640)	0.3 to 0.5	0.57 to 0.95
$GaAs_{0.6}P_{0.4}$	Red (660)	0.2 to 0.3	0.15 to 0.23
GaP:Zn, O	Red (698)	2.0 to 12.6	0.4 to 2.52

*From commercial to highest laboratory performance.

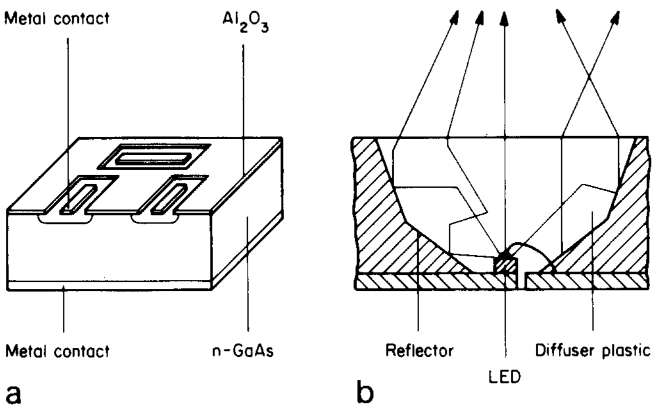

Fig. 19 Cross sectional view of; a – a monolithic and; b – a discrete led display

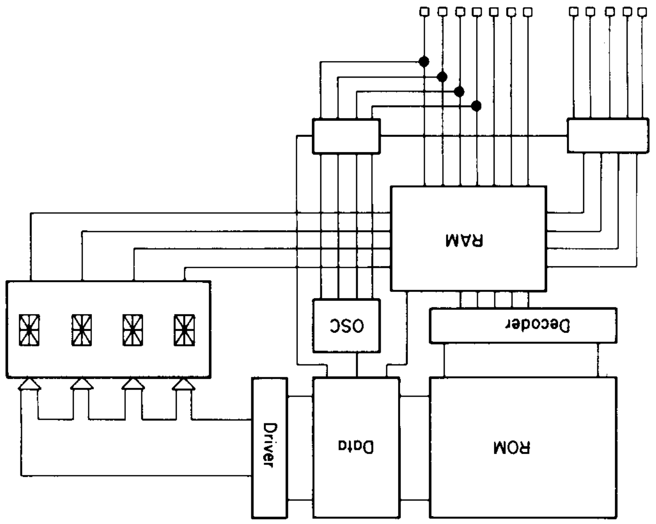

Fig. 20 Intelligent display

of radiative recombination and reducing the probability of non-radiative transitions. Non-radiative transitions occur at lattice defects such as impurity centres and lattice dislocations. The avoidance of such dislocations proved to be a difficult technological problem.

Usable efficiencies are realized with epitaxial films deposited on semiconductor substrates. The principal substrate was for a long time GaAs, on which GaAsP was deposited by epitaxy. More recently GaP has also found widespread acceptance as a substrate. Besides the good efficiency of deposited epitaxial GaAsP films, there is the additional advantage that GaP is transparent. As a result, backward light emission can be turned around by a reflector and utilized. This GaP substrate technology is commonly referred to as tsn technology, tsn being an acronym for transparent substrate, nitrogen-doped.

Alphanumeric displays are of either discrete or monolithic design (Fig. 19). Discrete displays as used, for instance, in measuring instruments have a separate led for each segment of a numeric. A reflector or a diffuse scattering plastic element directs the light such that a light bar appears. Small displays, commonly used in pocket calculators, are monolithic and consist of semiconductor chips with seven integrated segments (one alphanumeric) each that can be separately driven. The front of the display is covered with a plastic lens for better readability. There are also monolithic displays with 16 segment alphanumerics or 5 x 7 matrices for the display of alphanumerics.

LED displays have found such widespread application because they operate with low voltages, possess ic compatibility, readily allow multiplexing and are both reliable and rugged. Since orange, yellow and green leds are available in addition to the conventional red, multicolour displays are readily implemented with leds. Although blue leds have been realized at the laboratory using GaN, SiC and II-VI compounds[23,24], their efficiency is still too low for practical purposes. Table 2 lists the principal physical data of various leds.

Intelligent modules

Intelligent displays are a recent development trend that is not confined solely to led displays. These displays are combined with lsi semiconductor devices into a unit in which the lsi circuitry contains not only decoders, multiplexers and drivers but also memories[25]. Used on conjunction with a microprocessor, such modules are able to display a running text. A relatively large amount of information can in this way be displayed sequentially, using only a limited number of leds. A typical example is the Type HA 4041 four digit led display with 16 segment alphanumerics, the internal circuit configuration of which is shown in Fig. 20.

ENGINEERING MODEL DISPLAYS

Electroluminescent displays

Electroluminescent (el) displays rely for their operation on a physical mechanism similar to that of leds. Whereas the semiconductor material used for leds is of the single crystal type, that used for el displays is in polycrystalline form. Light emission is induced by the application of an electric field. Typical materials used for el displays are II-VI compounds such as ZnS doped with manganese. It is a general drawback of el displays that they operate on a relatively high voltage. Their principal advantage is that they are pure solid-state devices. EL displays are conventionally classified according to their technology – powder or thin film; and drive voltage – dc or ac.

Attempts to use the effect discovered by Destriau in 1936 for illumination purposes in the 1950s and for display purposes in the 1960s proved relatively unsuccessful due to inadequate brightness and lifetime.

Thin film electroluminescence

A breakthrough was achieved with ac thin film electroluminescence in 1974[26]. Figure 21 shows the basic design of an ac electroluminescent display. The evaporation deposited active film (eg manganese-doped ZnS) is sandwiched between two similarly deposited insulating films (eg Y_2O_3 or Si_3O_4) used primarily to protect it from moisture. The sandwich is stacked on a glass substrate with transparent conductors (SnO_2 or In_2O_3). The back electrode is metallic, being made of, say, deposited aluminium.

The electrodes can be conventionally arranged in a seven segment or matrix configuration so that alphanumerics will be seen by looking at the display through its glass substrate. As the deposited ZnS:Mn and insulating films are transparent, a contrast enhancing dark background may be added. The brightness versus applied voltage reaches saturation at about 300 V (5 kHz). There is a voltage threshold at which light emission begins and, since the voltage characteristic is relatively steep, multiplexing is possible.

In a recently commercialized ac electroluminescent matrix display with twelve rows for 40 alphanumerics each, the striking feature is the yellow hue of the light emitted by the ZnS:Mn. Although other hues can be realized by choosing other materials, the brightness and efficiency would be inferior. A development breakthrough is here needed.

Experiments with electroluminescent television panels are nevertheless still being conducted at the laboratory level. A panel with a 15.25 cm diagonal, 180 rows and 240 columns (0.5 mm raster) already allows the display of reasonably good video images in black and yellow. An image or data can be statically held through the use of a storage effect[27]. Light pens allow the direct electrical readout of stored optical information. Although experiments have shown that thin dc electroluminescent films can be driven with only 40 V[28], the development of a final product is still far off.

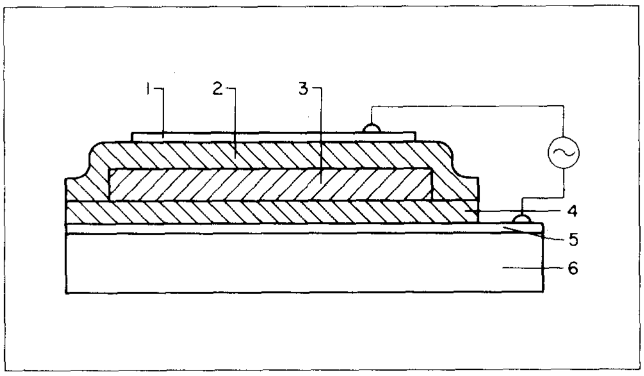

Fig. 21 Underlying principle of an ac electroluminescent display 1 metal film (eg Al), 2 isolating film (eg Y_2O_3), 3 active film (eg ZnS:Mn), 4 isolating film (eg Y_2O_3), 5 transparent electrode (eg SnO_2), 6 transparent substrate (eg glass)

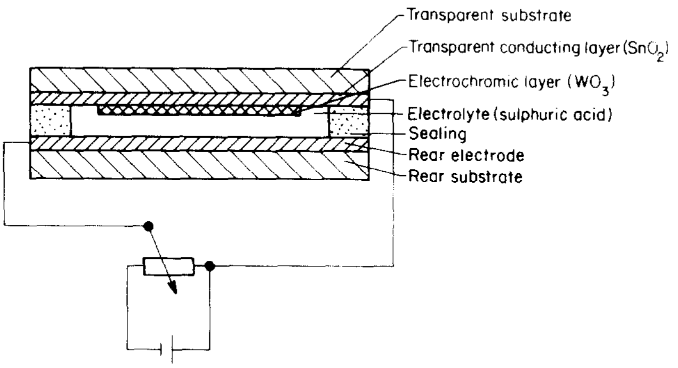

Fig. 22 Underlying principle of electrochromic display.

Electroluminescent powder

Development work is also still in progress on more conventional displays built around an active layer of material in the form of a powder. In connection with dc powder electroluminescence an 8 x 32 panel has already been commercialized and a discovery in the materials' sector has been made: alkaline earth sulphides have been shown to be capable of covering the entire visible spectrum[29].

AC electroluminescent powder display panels are generally driven by thin film transistors (tfts)[30,31] arranged in a matrix configuration in which each tft directly drives a separate picture element. Work is still in the research and development phase.

Table 3 Displays under research and development

Display	Principle
Electroluminescence	Light emission, eg of ZnS:Mn induced by application of an electric field
Electrochromic	Redox reaction, eg induced in WO_3 film by passage of current
Electrolytic	Electrolytic Ag deposition
Electrophoretic	Motion of charged particles in electric field
Colloidal suspension, gyricon	Orientation of electric dipoles in electric field
Magnetic particles	Orientation of magnetic dipoles in magnetic field
Bubble	Bubbles made visible by Faraday effect
Ferroelectric	Electrooptical effects in piezoelectric ceramic material
Piezoelectric	Piezoelectric deformation of metallized plastic foils
Electret	Motion of an electret in electric field

Table 4a Performance data of displays

Property	LED	Vacuum fluorescence	Plasma	LCD
Operating voltage (V)	2	24	approx 250 approx 50	3
Power (mW per numeric approx 12 mm in height)	140	100	50	0.005
Operating temperature range (°C)	-55 to +85	-10 to +55	0 to +60	-15 to +60
Switching delay (s)	100 ns	$< 50\ \mu s$	10 – 20 μs	100 ms
Multiplex performance	very good	very good	very good	possible
Contrast		dependent on illumination		$\geqslant 10$
Information handling capability	small	small to medium	small to large	small to medium
Surface area	small to medium	small to medium	small to large	small to large

Table 4b Performance data of new displays

Property	Electro-luminescence	Electrochromic
Operating voltage (V)	200	2
Power (mW per numeric approx 12 mm in height)	75	5
Operating temperature range (°C)	0 to +45	
Switching delay (s)	1 μs	200 ms
Multiplex performance	very good	under development
Contrast	depending on illumination	$\geqslant 10$
Information handling capability	medium	small
Surface area	medium	small to large

Electrochromic displays

Electrochromic displays (Fig. 22) are passive devices which display information by use of the transition from the transparent to a deep blue state occurring when an electric current is passed through a material such as deposited tungsten oxide[32]. The blue still persists after the current has been removed, which means that the display is capable of storing information. The transparent state is restored by reversing the polarity of the current.

The thin WO_3 film must be in physical contact with an electrolyte. The light absorption is changed due to the formation of hydrobronze according to the reaction

$$nH^+ + WO_3 + e^- \rightarrow H_nWO_3$$

where H^+ derives from the electrolyte and e^- from the transparent electrode[33]. Attempts to replace the fluid electrolyte by a solid in order to realize a passive electrochromic display in pure solid-state technology[34], which would offer numerous advantages, have not as yet yielded satisfactory results.

Development activities have been focused on numerous perspectives in the search for new materials having more favourable properties than WO_3. In particular attention is being devoted to fluid organic materials (IBM, TI)[35] and to a substance which can be switched to various hues according to the level of the applied voltage (Rockwell)[36]. The interest aroused by electrochromic displays is great because they provide a high contrast image, allow a broad viewing angle range, require a supply voltage of only about 2 V and possess information storage capability. The lifetime problem has however not yet been satisfactorily solved and a multiplexing solution is also still needed.

DISPLAYS UNDER RESEARCH AND DEVELOPMENT

Table 3 lists the many different display approaches using a variety of physical effects which are currently under research and development. Which of these approaches will finally be adopted depends on the solution of the remaining problems.

Comparison of features

Table 4 lists various significant features of the above optoelectronic displays so that comparisons can be made and their respective advantages and drawbacks for specific applications weighted against each other. It is obvious that led and vacuum fluorescent displays are suitable for displays of moderate size that have to handle relatively little information. Vacuum fluorescent displays are also capable of handling a medium amount of information. Alternatively plasma displays can be used for handling a large amount of information at computer terminals. The outstanding properties of liquid crystal displays are their extremely low power consumption, the far reaching independence of their contrast on the ambient light conditions, and the ready integrability of their display panel.

Electroluminescent (el) and electrochromic (ec) displays are currently being introduced to the market. EL displays have a medium and ec displays a small information handling capability. The requirements which have to be met by displays are so diverse that there can be no ideal all purpose display. The question of what is the best display for a particular application can only be decided *ad hoc.*

Consider for example just one feature of a display: its information handling capability (Table 5). It is obvious that the new optoelectronic displays will mainly be chosen for applications requiring only a small information handling capability for which the use of a crt display would not be meaningful. Nevertheless there is a marked trend towards displays with a medium information handling capability and sooner or later displays with a large information handling capability are bound to emerge.

Flat panels with large information handling capability

Among the new optoelectronic displays only plasma displays have so far found acceptance for applications in which a large information handling capability is required (Table 5). In the laboratory however a variety of approaches are being explored for the development of data and video panels with a large information handling capability. A survey is shown in Table 6.

Why is success so difficult in this sector? It has already been noted that the new optoelectronic displays are judged according to the standards of crt displays. Table 7 compares

Table 5 Information handling capability of displays

Information handling capability	CRT displays	Vacuum fluorescent displays	LED displays	Plasma displays	LCD*	EL displays	EC displays
Small (up to approx 10 000 pixels)		X	X	X	X		X
Medium (from approx 10 000 to approx 100 000 pixels)	X	X		X	X	X	
Large (from approx 100 000 to approx 1 000 000 pixels)	X			X			

*Also a large information handling capability in projection mode

Table 6 Flat panels under development

Flat crts	Gas discharge displays	Electroluminescent displays	Liquid crystal displays
Area hot cathode (Texas Instruments)	DC matrix displays* (Burroughs, Okaya)	AC thin film el** (Sharp)	TN multiplex (Hitachi)
Area SEV cathode (RCA)	AC matrix displays* (Owens-Illinois, IBM, Thomson, Fujitsu, NEC)	AC el powder Westinghouse, Brody, Fischer)	Phase change Siemens, Xerox, NEC)
Field emission cathode (Battelle)	Activation of phosphor by uv from negative discharge (NHK)	DC el powder** (Phosphor Products, Vecht)	Combination with ferro-electric capacitor or varistor (Siemens, Rockwell, GE)
Electron gun parallel to screen (Sinclair)	Activation of phosphor by uv from positive column (Philips, Zenich, GTE,NHK)		Direct driving by silicon transistors (Hughes, Matsushita)
	Activation of phosphor by uv from positive column with storage effect (Hitachi)		Direct driving by thin film resistors (Westinghouse, Brody)
	Activation of phosphor by electrons (Matsushita, Zenith)		

*Already commercialized.

**Engineering model.

Table 7 Performance data of flat television panels in comparison to crt displays

	CRT	Flat crt display	Plasma uv neg discharge	Plasma uv pos column storage effect	EL ac thin film	LCD tn-mux	LCD dsm direct driving
		(TI)	(NHK)	(Hitachi)	(Sharp)	(Hitachi)	(Matsushita)
Luminance in ft L	100	100	7	85	30		
Light source efficiency lm W^{-1}	3	3	0.05	0.07	1		
Contrast ratio	256:1	128:1	36:1	19:1	16:1	16:1	
Raster in mm	0.4	0.4	1	2	0.5	0.75	0.18
Uniformity	good	inadequate	good		defects		
Colours	all	all	all	all	yellow	black/white	black/white
Driving	dot sequential	line sequential					
Size in cm (diagonal)	67	25	40	20	15	16	6
Lifetime in hours	10 000	?	?	?	?	?	?
Price in Deutschmark	300	?	?	?	?	?	?

the properties of flat television panels (laboratory models) with crt displays. In developing displays with a large information handling capability it is obviously difficult to meet the standards of crt displays in all cases, quite apart from economic comparisons. Does this imply resignation? Not at all. The day is bound to come when flat colour television panels become available, but before this is possible a number of physical, technological and economic problems must necessarily be solved.

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