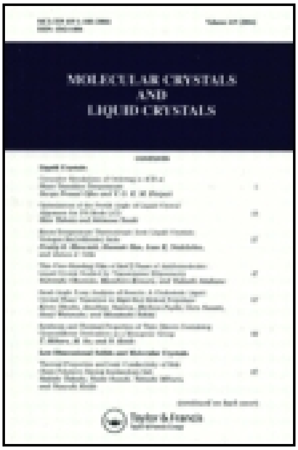


Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

A Brief Review of Histoty, Present Status, Developments and Market Overview of Liquid Crystal Displays

Birendra Bahadur [a]
[a] Data Images Inc., 1283 Algoma Road, Ottawa, Ontario, K1B 3W7, Canada
Version of record first published: 17 Oct 2011.

To cite this article: Birendra Bahadur (1983): A Brief Review of Histoty, Present Status, Developments and Market Overview of Liquid Crystal Displays, Molecular Crystals and Liquid Crystals, 99:1, 345-374

To link to this article: http://dx.doi.org/10.1080/00268948308072055

Mol. Cryst. Liq. Cryst., 1983, Vol. 99, pp. 345–374
0026-8941/83/9904–0345/$18.50/0

Printed in the United States of America

A Brief Review of History, Present Status, Developments and Market Overview of Liquid Crystal Displays†

BIRENDRA BAHADUR

Data Images Inc., 1283 Algoma Road, Ottawa, Ontario, Canada K1B 3W7

(Received May 20, 1983)

This paper reviews the present status, recent developments, future trend and market of liquid crystal displays. It also describes the historical developments very briefly. Today over 99% of LCDs are twisted nematic and their dominance is expected to continue in the near future. Recent developments in polarizers, glass plates, sealing, alignment, liquid crystal materials, etc., are described. Advances in multiplexing, thermally addressed S_A displays and dichroic displays are discussed. Dye phase change and TFTs may find considerable application in the future. Three major sectors of LCD market—calculator, watch and clock displays will remain almost static in terms of total dollar value though the number of units will be increasing. Trenendous growth rate of LCDs is expected in industrial and consumer items, office equipment, personal computers, business equipment, automobiles, avionics, military and telecommunications.

INTRODUCTION

The popularity of electro-optical displays over the mechanical displays has increased tremendously during the last few decades. Electro-optical displays allow direct indication and reading of symbols, letters and numbers and can display more information in less space compared to analogue meters and mechanical devices. The display devices, therefore, play an important role as a communication link with human elements. As data processing and other information-based industries develop and adopt visual

†Based on the papers entitled: (1) "History and Market Review of Liquid Crystal Displays," and (2) "Present Status and Developments in Liquid Crystal Displays." Both were presented at the Ninth International Conference on Liquid Crystals held at Bangalore, December 6–10 (1982).

methods, display devices will assume greater significance. During the last decade the growth of display industries has been nothing short of phenomenal. This industry has paralleled the growth of the semiconductor industry and the trend is expected to continue in the future. However, there is a significant difference between the semiconductor and display industry. The semiconductor industry is essentially based on a single technology, silicon, whereas the electronic display industry utilizes many different techniques, both emissive and passive.

Presently a large number of displays such as vacuum fluorescent, incadescent lamps, nixie tube, plasma, light emitting diodes, electroluminiscent, liquid crystal, etc., are available in the market.[1] Each of these displays has its own special characteristics and the proper choice of display, for a particular use, depends on a number of factors such as cost, size, brightness, life, power consumption, temperature range, operating voltage, drive circuits, etc. Of all these displays, liquid crystal displays have emerged as the most promising display during the last decade.

Starting from almost scratch in the seventies, liquid crystal displays captured 30% of the market of large area displays, excluding CRTs, in 1980 and are expected to have a tremendous growth rate in coming years. The extremely low power consumption, low voltage operation, readability even in glaring sunlight, low cost and flexibility of the size, are just some of the distinctive features which make LCDs preferable over other types of displays. Liquid crystal displays consume the least amount of power among all the displays and thus are the natural choice for portable and battery operated equipment. Another important factor contributing to this rapid growth is the capability of liquid crystal displays to interface directly with the integrated circuits which has revolutionized the elctronics industry and substantially cut the cost and size of consumer and professional equipment. LCDs are also having intrinsic multiplexibility and capability to exhibit gray scale to some extent.

Moreover, LCDs are very good guys. Unlike CRTs, they do not emit any harmful radiation. This will give LCDs some advantage in future applications, specially in educational aid instruments. LCDs are truly flat panel and so devices can be made very compact and thin using LCDs which is not possible with CRTs. The tremendous success of LCDs in watches and calculators has allured its use in various flat panel displays exhibiting more complex information and demanding stringent requirements. In fact everyday we are seeing more and more novel applications and new market sectors for LCDs. This article reviews briefly the history, present status, future developments and market of liquid crystal displays.

HISTORY OF LCD DEVELOPMENTS

Although the first liquid crystal, cholesteryl benzoate, was discovered in 1888 by an Austrian botanist, Reinitzer, its application in electro-optical devices could not be visualized for a very long period. In 1968, about a lapse of 80 years after its discovery, first of all, RCA scientists proposed its application in electro-optical devices. In the earlier period of the field, the novelty and dual nature of liquid crystals created much interest in it and a lot of basic work was done on various aspects of liquid crystals by the mid thirties. During this period Reinitzer, Lehmann, Friedel, Mauguin, Miesowicz, Oseen, Zocher, Vorlander, Kast, Ornstein, Foex, etc., contributed a lot to the synthesis and understanding of the interesting physical properties of liquid crystals.[2] In 1933 an international conference was organized by the Faraday Society. Except for some chemical synthesis and scattered physical measurements, the field was almost dead from the mid thirties to the mid fifties, and so-so up to the late sixties. During 1957–60, four major events happened: (i) a series of papers on the theory of nematic liquid crystals were written by W. Maier and A. Saupe; (ii) a detailed and systematic review of liquid crystals was given by G. H. Brown and W. G. Shaw in *Chemical Reviews,* (iii) an international conference on liquid crystals by the Faraday Society took place in which F. C. Frank presented his logical and simplified version of the continuum theory; and, (iv) the application of cholesteric liquid crystals in thermal mapping was proposed by James L. Fergason, which provoked the exploration of liquid crystals for other types of technological applications. In 1966, an international conference on liquid crystals was organized by Prof. G. H. Brown at Kent State University which played a major role in future developments of liquid crystals and paved the way for a series of international and regional conferences on liquid crystals. The potentiality of liquid crystals in electro-optical applications was first proposed in 1968 by G. H. Heilmeiter and group workers (RCA group) in the form of dynamic scattering mode displays. This not only boosted the applied research in liquid crystals but also attracted a lot of physists and chemists to understand the liquid crystals in a better way. These developments have changed almost all the old concepts of liquid crystals. Side-by-side research also started for developing better materials and packaging techniques. Dynamic scattering mode display was quickly followed by the advent of twisted nematic mode displays in 1971. Due to its superiorities, twisted nematic mode display has become the most common display and today over 99% of the LCDs are twisted nematic mode displays. However, it is disputed who discovered it first, Helfrich and Schadt at Hoffman La Roche (Switzerland) or James L. Fergason at U.S.A. Fergason's patent was valid in the United States while Helfrich and Schadt's patent was valid in Europe and other markets. Later on Fergason sold his patent to Hoffman La Roche and now both the patents are owned by Hoffman La Roche. In the late sixties, Heilmeir *et al.* also proposed guest-host mode displays in which dichroic dye is used as a guest in liquid crystal matrix. In this type of display, only one polarizer is needed. In 1974, White and Taylor proposed a major improvement in guest-host displays termed as dye phase change display where polarizers are not needed at all and one gets colorless or white digits on colored background. In the same period the tunable birefringence displays were also proposed, though the physical effect, Freedericksz transition, was already known in the thirties.

The use of smectic displays was first proposed by Kahn by laser addressing. The idea was picked up by some other groups. Thomson C.S.F. people developed a smectic A display where the heating is also done using a passage of pulsed voltage through rows, and field is applied on columns. Kylex people used the same idea but using pleochroic dyes embedded in smectic A matrix. The smectic A displays consume more power but multiplexing is no problem with them. They can also exhibit memory effect for a long period of time. Recently the use of ferroelectric liquid crystals has been proposed by the author and other workers which may have very fast switchings (μ s). In another approach for generating high level multiplexed displays, a nonlinear device (thin film transistor, variastor, metal insulator metal, etc.) is used in conjunction with each picture element of LCD. This enhances the multiplexing capability to a large extent. In S.I.D. Conference 1982, a lot of discussions were concentrated on the TFT approach. The operating principle is nice but the problem is now with the yield of the display. Once the problem related with the yield of TFTs is solved, it will become a major share in LCDs.

As regards the materials, most of the early research was concentrated on azoxy compounds, Schiff bases, alkoxy benzoic acid, etc. Eighty percent of the research up to 1970 was done only on a single compound, *p*-azoxyanisole (PAA), a liquid crystal exhibiting a nematic range from 118–134°C. The advent of dynamic scattering mode displays and, later on, twisted nematic displays, required much better materials and specifically the materials which can exhibit a liquid crystalline phase much below room temperature to high temperature (at least from 0° to 50°C). Organic chemists responded very well to the demand. In 1969, the first moderately stable room temperature liquid crystal *p*-methoxybenzylidene-*p*-*n*-butylaniline (MBBA), having a nematic range from 20 to 45°C, was synthesized. It soon became the second most widely studied liquid crystal. During this period a lot of material developments were done and liquid crystalline room temperature mixtures using Schiff bases, azoxy, azo and ester compounds were made. Mixtures having negative dielectric anisotropy were made for the dynamic scattering mode while those having positive dielectric anisotropy were made for twisted nematic and guest-host modes.

Initially developed mixtures, using Schiff bases, were not very stable. Later on, mixtures having sufficient shelf life were developed using esters and azoxy compounds. The major instability was caused due to breaking of the central linkage by moisture, UV and visible light, thermal cycling, etc. In the seventies a yellow filter was a common feature in Japanese calculators which, besides having a little more eye appeal, was also acting as UV barrier. In 1973, G. W. Gray and co-workers at Hull University developed cyanobiphenyls which were not having any unstable central linkage. These compounds and their mixtures (like E_7, E_8, E_{43}, E_{44}, E_{70}, E_{80}, E_{90}, E_{100}, E_{110}, E_{120}, E_{130}, etc.) are very highly stable and enhanced the life of the display to more than 50,000 operating hours. Very soon, due to high UV and chemical stability, they became very popular. Nowadays biphenyls are the most widely used materials in LCDs. In 1977, chemists at E. Merck reported phenylcyclohexanes, another group of extremely stable liquid crystals having no central linkage. Today, these have become the second most widely used materials in LCDs. Materials like pyrimidines, bycyclohexanes, and cyclooctanes, etc., have been also synthesized. Besides, biphenyls and phenylcyclohexanes. Schiff bases and esters are also in use due to easy synthesis, ease in homogeneous alignment, low cost and no protection from patents. Research is still going on to improve the material characteristics such as birefringence, viscosity, dielectric anisotropy, elastic constants, operating temperature range, etc.[3] A lot of the research is concerned toward the development of better materials for high level multiplexing. Improved smectics and stable cholesterics[4] (such as nonsteroids) are also being synthesized. The earlier dyes, used in guest-host mode displays were azo dyes which were pretty unstable to UV light and thermal cyclings. Recently, anthraquinone dyes have been synthesized which are pretty stable. A lot of improvements have been made also in packaging techniques and materials, such as homogeneous and homeotropic alignments, polarizers, glass plates, hermatic sealings, zebra and pin connectors, etc.

HISTORY OF LCD MARKET

In the early seventies there was an increasing demand for electronic mini calculators in the U.S. market where dynamic scattering mode displays started to find some market in readout applications along with LEDs and vacuum fluorescent displays. However, dynamic scattering mode displays could not make any major breakthrough in the U.S. market due to problems of quality, poor production technology, relatively higher power consumption and limited life. DSM, first introduced in the Japanese local market in 1973 in calculators, remained stabilized there from 1973 to 1976 while T. N. mode LCDs rapidly emerged as a promising substitute.[5] During the second half of the seventies, T. N. LCDs enjoyed a tremendous growth in demand, primarily for electronic calculators and watches. Gruen Watch, a U.S. company, which started making LCD watches in 1972, is said to be the first LCD watch manufacturer. The LCDs were supplied to them by LXD (United States). These developments were quickly picked up by some large manufacturers, some of which were already making LEDs for watches. There emerged a great demand for LCDs in watches during 1974 to 1978 in the U.S. market and companies like Beckmann Instruments, American Microsystem Inc., Optel Corporation, Integrated Displays Systems, Motorola, etc., which increased their production more than twofold every year, were unable to meet the demand.[6] This prompted the Japanese companies, which by that time, more or less perfected the large volume production of T.N. mode LCDs, to enter in the U.S. market. The fierce competition in large volume production resulted in cheaper prices of the modules and over-inventory of watch LCDs by mid 1980. A Swiss company in Europe started to manufacture LCD modules in LCD watches at about the same time as in Japan and the United States. Many small European companies also started production of LCDs in Germany, England, Romania, Hungary, Czechoslovakia, Austria, Belgium, etc. The USSR and China are also manufacturing LCDs. During this period some good research and development work was done by GPU, NPL and RRI scientists in India for developing the display technology. Some small firms in India also started production of LCDs based on NPL's know-how in the latter part of the seventies and early eighties. Very good research and development work on liquid crystal materials and displays is also being done in Europe by Royal Radar and Signals, B. D. H. Chemicals, Thomson CSF, Philips, Hoffman LaRoche, E. Merck, A. G. Telefunken, Balzers etc. Several universities, research institutes and LCD manufacturers are also doing very good research on LCDs in the United States, Japan, England, France, Switzerland, G. D. R., West Germany, India, Canada, etc. These researches are contributing very significantly in the development and improvement of LCD technology.

In the latter part of the seventies, American and European LCD manufacturers started finding very tough competition on the prices of consumer and standard LCDs (mainly calculator and watches) from Japan and most of these LCD manufacturers have now either stopped the production of LCDs or shifted from consumer displays to custom and specialized displays.

The technical expertise in mass scale production, continuous modernization of plants, heavy investment and moderate labor cost have given the Japanese the edge over other LCD manufacturers in prices and quality. It has vitrually left no room for smaller LCD manufacturers with limited capital and resources to remain competitive in prices on standard LCDs. However, automation of plants and high capital investment make the Japanese reluctant for manufacturing small to medium volume, custom and specialized displays and here the small companies can exist safely. Most of the Japanese LCD manufacturers are also in semiconductor and IC business and this vertical integration gives them an advantage in producing better modules at cheaper prices.

The sudden drop in prices and over-inventory in 3.5 digit watch displays, one of the largest sectors of LCD market, during 1980 to 1981 resulted in a number of departures from business by some of the big manufacturers in the United States and Europe. This trend has continued for the last five years. Some of the major companies which closed the watch LCD business during this period are Fairchild Camera and Instrument Corp., Beckman Instruments, Brown Boveri, Ebausches S. A., Siemens, Hughes Aircraft, National Semiconductors, Texas Instruments, Motorola, Commodore, Optronics, Electrovac, Saunders Roe and Rank. Some of them have ceased to manufacture not only watch LCDs but also all sorts of LCDs.

The elimination of some of these big manufacturers from LCD business has created a vacuum. Small companies in North America and Europe, still struggling to exist in the LCD business, may benefit considerably due to the departure of big companies. However, these small companies should deal with small to medium orders on standard displays and try to influence some LCD market sectors by specialized and custom displays. They should put more emphasis on research and development for specialized items rather than making big volume standard products. While most of the European and U.S. manufacturers are going out of the LCD business, new manufacturers are emerging in the Far East, especially in Korea, Taiwan, Singapore, Hong Kong, etc., besides Japan. Some of these have now become high volume manufacturers of not only LCD watch displays but also calculators and instrument displays as well. Some of the U.S. and European LCD manufacturers have also shifted their production facilities to the Far East to remain competitive in prices. There is a vertical growth rate of new LCD

TABLE I

List of LCD manufacturers

(A) North America	
Canada	
Data Images, Inc.	Ottawa, Ontario
USA	
Commodore International	Dallas, Texas
Crystal Vision	Santa Clara, California
Crystaloid Electronics	Cleveland, Ohio
Electronics Display Systems	Hatfield, Pennsylvania
Fairchild Camera and Inst. Corp.	Santa Clara, California
General Electric–LXD Div.	Cleveland, Ohio
General Electric–Aircraft Div.	Wilmington, Massachusetts
Hamlin	Lake Mills, Wisconsin
Ladcor	Sunnyvale, California
Panel Vision	Pittsburg, Pennsylvania
Timex	Cupertino, California
UCE	Norwalk, Connecticut
(B) Far East	
Japan	
Alps Electric Co.	
Casio Computer Co.	
Citizen Watch Co.	
Daini Seiko	
Epson	
Fujitsu Electronics	
Hitachi Ltd.	
Matsushita Electronics	
Nippon Nontronics	
Nippon Seiki Co.	
Optrex (Mitsubishi and Ashai)	
Sanyo	
Seiko Clock Co.	
Sharp Corporation	
Sony Corporation	
Stanley Electric Co.	
Suwa Seiko	
Toshiba Electric Co.	
Other Far East Countries	
Conic Semiconductor Ltd.	Hong Kong
Display Technology Ltd.	Hong Kong
Epson	Hong Kong (Japanese firm)
RCL Semiconductor Ltd.	Hong Kong
Sturat Ltd. (Hamlin)	Hong Kong (U. S. firm)
Varitronics Ltd.	Hong Kong
Videlec (BBC and Philips)	Hong Kong (Swiss firm)
Hantronics	Korea
STC Corporation	Korea
Lattek	Phillipines
Timex	Phillipines (U. S. firm)
Printed Circuit Integration	Singapore (U. S. firm)

TABLE I (*Continued*)

Other Far East Countries	
Certified Electronics Ltd.	Taiwan (U. S. firm)
Intek	Taiwan
Megahertz Displays (SSI)	Taiwan
Mesostate Technology	Taiwan
Weston Pacific Electronics	Taiwan
Krystonics Ltd.	India
Punjab Display Devices Ltd.	India
Central Electronics Ltd.	India
Bharat Electronics Ltd.	India
(C) Europe	
NORSK LCD	Norway
Lucid Displays (English Electric)	England
Racal	England
ITT Components	England
Thomson CSF	France
AEG Telefunken	Germany
VDO Schwalbach	Germany
Normal Time	Germany
Christop	Germany

manufacturers in the Far East and now about 40 LCD manufacturers are there. A list of the Liquid Crystal display manufacturing companies is given in Table I.

Most of the liquid crystal materials were initially developed by the Europeans and Americans. European companies were having the lead from the very beginning. As the materials, especially the biphenyls and phenylchyclohexanes, are being guarded with very strong patents, the situation is reversed here compared to displays. Three European companies, B.D.H. (England), E. Merck (Germany), and Hoffman La Roche (Switzerland) are the major suppliers of liquid crystal mixtures throughout the world. These companies are continuously improving their LCD mixtures through research and development efforts and are coming up with novel and improved versions. As other display-related materials like indium tin oxide coated glass plates, polarizers, connecting pins, zebra connectors, thermoplastic and glass frit sealing materials, PVA, polyamide, silicon monoxide, etc., are concerned, they are evenly divided in Japanese vs American and European markets.

PRESENT STATUS

1. Starting from almost scratch in the early seventies, LCDs have made tremendous growth. They have pushed aside the LEDs, vacuum fluorescent, gas discharge, nixie tube, incandescent lamps, electroluminiscent,

etc., displays to secure the second position (in terms of dollar value). Now they are second only to CRTs.

2. The growth rate of LCDs is highest among all the displays. Only the growth rate of plasma displays is comparable to it.

3. *Total Worldwide LCD market (in terms of constant $ in 1982).* 1981, $427.6 Million; 1982, $433.2 Million; 1985, $497.8 Million; 1990, $660.1 Million.

4. *Geographical distribution of LCDs.* Japan and Far East (Hong Kong, Taiwan, Korea, Singapore, etc.), 80%; European Market, 12%; U.S. Market, 6%; Rest, 2%.

5. *Applications.* Established Market: watch–calculator–clock; Expanding Market and Application: industrial and consumer electronics, measuring equipment, analytical instrumentation, process control equipment, on line process analyzers, domestic appliances, petrol pumps, agriculture, marine, automobile, military, telecommunications, avionics, medical equipments; Future Application: computer terminal–T. V.–large flat screens.

6. *Dynamic Scattering mode.* (the first version of LCDs) almost eliminated from the LCD Market. Tunable birefringence, smectic, cholesteric and dichroic displays are very limited in use.

7. *T.N. Mode Displays.* T.N. mode displays are the most widely used displays and today over 99% of the LCDs are T.N. mode. T.N. mode displays are going through continuous improvements and their dominence in the LCD market will remain practically unchallenged in the near future. The most important research being done in T.N. mode displays[3] are:

(i) To develop high level multiplexed displays (dot matrix or alphanumeric) with high resolution especially for use in telecommunication, educational aid equipment, medical equipment, computer terminal, T.V., etc.

(ii) To improve the performance of the displays like brightness, contrast, viewing angle, switching time, etc. Efforts are also being made to develop displays having an operating range from −50° to 100°C. Another area is improvement in thermoplastic sealing and polarizers for their performance in high humidity and high temperature environments.

(iii) To produce colored LCD based on field effect twisted nematic by coupling T.N. LCDs with colored filters, birefringent sheets or colored polarizers.

8. *Dichroic Displays.* Though discovered just three years after the discovery of T. N. mode displays and projected as much more superior than

twisted nematic, dye phase change effect displays could not make any major breakthrough in the LCD market.[3] In fact, simple dichroic displays, the guest-host effect, were discovered in the late sixties, much earlier than the T.N. mode. There were four chief reasons:

(i) A lot of research was already made during these three years for improving the packaging, materials, and polarizers for T.N. displays and by the time dye phase change displays were discovered, T.N. mode technology was almost matured. During a latter period also researches were more concentrated toward T.N. mode displays rather than dye phase change displays. Still today the situation is the same.

(ii) Dye phase change effect displays have lower intrinsic multiplexibility compared to T.N. mode displays. However, once the problems with the yield of TFTs are solved, dye phase change effect displays will be preferred over T.N. mode displays as counterpart with TFTs due to its wider viewing angle and eye appeal.

(iii) These displays operate at relatively high voltage (approximately 15–20 V).

(iv) At the time of its discovery, dye phase change and guest-host mode displays were badly suffering from dye related limitations such as life and hue of the dye, its order parameter and solubility in liquid crystal mixtures. Most of these problems have been solved during these years and now dye phase change effect display is being considered as the serious contender for T.N. mode displays in the coming years.

9. Recently there started a great demand for colored LCDs (dichroic as well as colored TN mode) in industrial, automobile and avionics industries. Market leaders for this sector like Stanley, EDS and Data Images forsee a huge growing market and potentials for colored LCDs in coming years.

10. The other areas which are expected to capture considerable market are smectic A display, ferroelectric liquid crystal displays and liquid crystal displays with active matrix.

RECENT DEVELOPMENTS

Continued research is making LCDs more and more versatile and suitable for novel applications. During the last decade tremendous improvements have been made in glass, ITO coating, thermoplastic sealing, alignment, liquid crystal material, polarizers, zebra and pin connectors, etc., which improved the overall performance and reliability of LCDs. Research is being made continuously to improve the instrinsic multiplexing capability of TN mode displays. About five to six years ago it was hard to believe that LCDs could be multiplexed over four levels. Now 16-level multiplexed LCDs are commonly available in the market.

Recent research in dichroic displays have made it more acceptable. However, still a lot of material research has to be made to make it able to snatch any significant market from TN mode displays.

Emphasis is being made on development of LCDs coupled with two terminal (Variastor, metal insulator metal, etc.) and three terminal (TFT, etc.) nonlinear devices to increase the limit of multiplexing. These developments will generate future LCD TV screen and computer terminals.

1. *Glass*. Commonly used glass is sodalime glass or sodalime glass with a SiO_2 barrier coating. Sodalime glasses contain a lot of sodium ions whose migration causes the problems (i) blooming or fattening of digits, (ii) loss in alignment, and (iii) increase in power consumption. These problems increase tremendously at high temperature, high humidity operations. The problem can be overcome to a great extent by using sodalime glasses with SiO_2 barrier coating but the ultimate solution is glass containing the least amount of sodium and other alkali ions. SiO_2 undercoated glasses are recommended for vacuum filling procedures. In drop filling procedures generally these are found to create unwanted problems like air bubbles in the cell. Moreover, the glass should be flat. Recently some companies like Corning have started manufacturing such glasses for LCDs (Corning 7059, 7740).[7] The use of plastic sheets in place of glass have been proposed recently.[8]

2. *Transparent Electrically Conducting Coating*. Commonly used coating is ITO (indium tin oxide). It is easy to etch. SnO_2 coating is also being used but its use in the LCD industry is declining. Better ITO coating with less pinholes are now commercially available from several companies.

3. *Thermoplastic Sealing Material*. In most of the liquid crystal cells, thermoplastic sealing acts as a sealant as well as the spacer. To maintain the thickness uniformity the use of glass fiber or glass bead (of standard diameter dispersed throughout the cell) is increasing. Sealing material composition is restricted by possible chemical reactions with liquid crystals as well as the need for fairly hermatic, strong and moisture tight sealing. Nowadays better thermoplastic materials are being used. The doping of proper silane in thermoplastic materials increases the bonding strength with glass as well as the moisture tight sealing. The surface treatment of the glass with proper silanes also enhances the strength and moisture tightening of the thermoplastic sealing. The use of glass frit sealing approach is declining due to problems occurring at high temperature sealing, no possibility of rework and availability of much better thermoplastic sealing materials.

5. *Polarizers*. Earlier the polarizers were the weakest link in LCDs. They were unable to stand in high humidity, high temperature operation for a long time. Problems were drastic decreases in polarization efficiency, delamination of polarizer, air bubbles, etc. Recent developments have resulted in extremely stable polarizers. High performance polarizers from Nitto, Hoechst, Sanritsu, etc., have increased the life of T. N. cells drastically.[9] The efficiency of the polarizer decreases with increase of transmission. An ideal efficient (100%) polarizer cannot transmit more than 50% of the ambient light. For good LCD, i.e. with high contrast and brightness, polarization efficiency and transmission both should be high. Recent improvements from manufacturers have yielded good results in this direction.

5. *Material (Liquid Crystal Mixture)*. Material is the heart of liquid crystal displays. General material requirements are: (i) Long life, UV and chemical stability; (ii) Wide temperature range—it is achieved by making eutectic mixture; (iii) Low viscosity for fast switching; (iv) High birefringence for T. N. mode and low birefringence for dye phase change effect displays; (v) Proper dielectric anisotropy, for T. N. mode it is generally $\sim +5$ to $+15$. Low dielectric anisotropy is required for higher operating voltage ($\sim$15–20 V) and high dielectric anisotropy is required for low operating voltage; (vi) Sharp threshold characteristic for multiplexed displays; (vii) Low temperature coefficient i.e. d/dt(Vth) and d/dt(V90) should be low; (viii) d. $\Delta n \geqslant 2\lambda$ to avoid the coloration where d is the thickness of the cell, λ is the wavelength visible light and Δn is the birefringence; (ix) Proper Vth and Vop according to available chips. A lot of research has been made and now better materials are available commercially from Hoffman La Roche, BDH and E. Merk. Some of the companies like Data Images are modifying the basic mixtures purchased from these companies to suit the best requirements of the displays.[10]

6. *Direct Driven Displays*. The major improvements in direct driven displays have been made in their reliability and longer life. Using thinner spacing compared to earlier versions, switching times have been reduced drastically. L. C. materials having large nematic range has lead to displays operating in a very wide temperature range. Recently Data Images has released the fastest LCDs to date operating from −55°C to +80°C and having total on + off time within a second at −40°C and half second at −30°C.

7. *Multiplexed Displays*. Here we will discuss only intrinsic multiplexing. Active matrix addressed LCDs and smectic A LCDs are discussed in later sections. The performance of a multiplexed twisted nematic mode liquid crystal display is greatly dependent on three factors: (1) packaging,

(2) materials, and (3) driving of the display with a compatible chip. The most important parameter is the sharpness of threshold characteristic.

Packaging. Requirements are (i) Maintenance of thickness uniformity. It is being done by using glass fiber or glass beads. (ii) $d \cdot \Delta n \geqslant 2\lambda$ to avoid coloration, (iii) Thin cell (for sharper threshold), (iv) Low tilt alignment, and (v) Proper viewing quadrant.

Materials. Besides the general requirements listed in material section, multiplexed displays require a very sharp threshold characteristic. The special requirements are: (i) Low K_{33}/K_{11} (for sharper threshold characteristic), (ii) Low $\Delta\varepsilon/\varepsilon_{\perp}$, (iii) Low viscosity to avoid the sluggish response at the lower end of the operating temperature, (iv) Selection of proper material (proper Δn, η, Vth and Vop), (v) Preferably low dVth$/dt$ and dVop$/dt$, (vi) Linear temperature variation of Vth and Vop in the operating temperature region.

Driving. Requirements for driving multiplexed LCD s are (i) Low d.c. content, (ii) Voltage selection scheme or biasing according to $s = 1 + \sqrt{N}$, where N is the level of multiplexing, (iii) Proper output voltage, and voltage variation compatible with l.c. material, (iv) Preferably

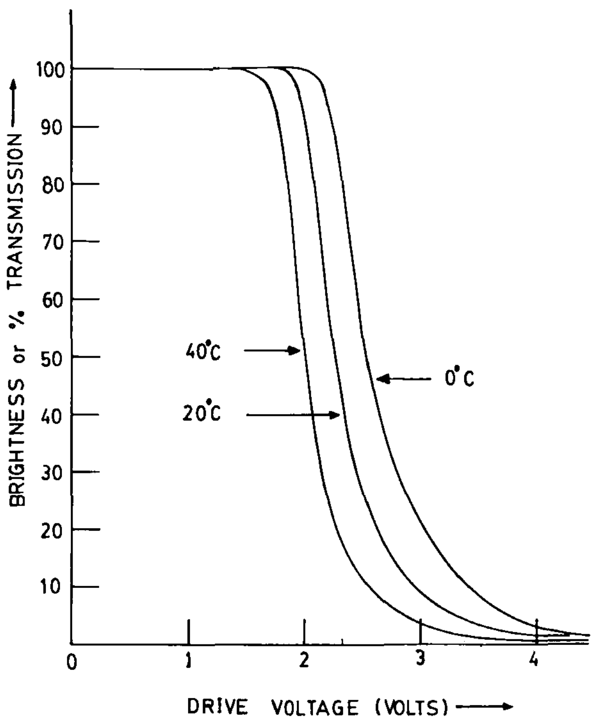


FIGURE 1 Temperature variation of the threshold characteristic of a twisted nematic cell.

higher voltage operation for high level of multiplexing to give more margin in (Von − Voff), (v) Temperature compensated circuits for high level of multiplexing, (vi) Low cost, (vii) Reliability, (viii) Functions.

Some of the important parameters for multiplexing are given below. The number of maximum multiplexible lines Nmax is

$$N\text{max} = \left[\frac{(1 + p)^2 + 1}{(1 + p)^2 - 1}\right]^2$$

$$p = \frac{\text{Vop} - \text{Vth}}{\text{Vth}}$$

Vop being the voltage able to produce acceptable contrast and Vth is the threshold voltage.

The voltage applied from the circuitry on the selected (Von) and non-selected (Voff) segments are

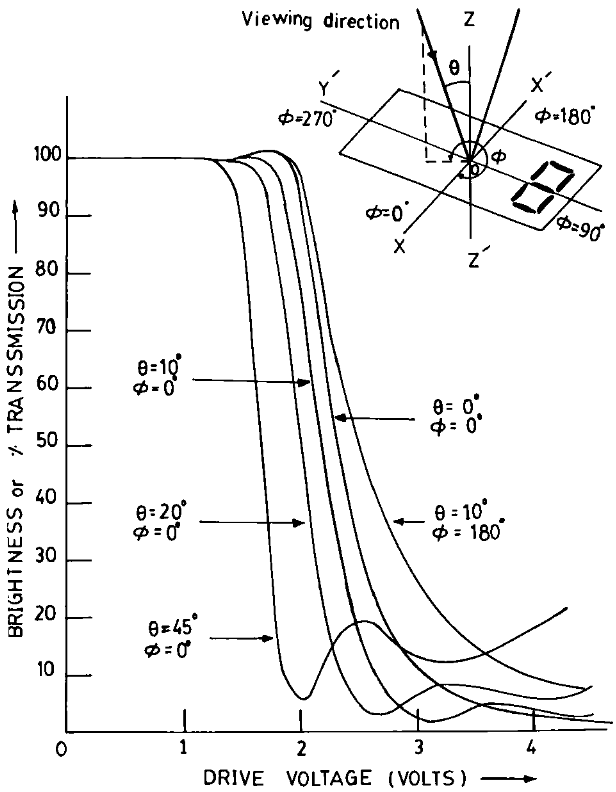


FIGURE 2 Viewing angle dependence of the threshold characteristic of a T. N. mode cell.

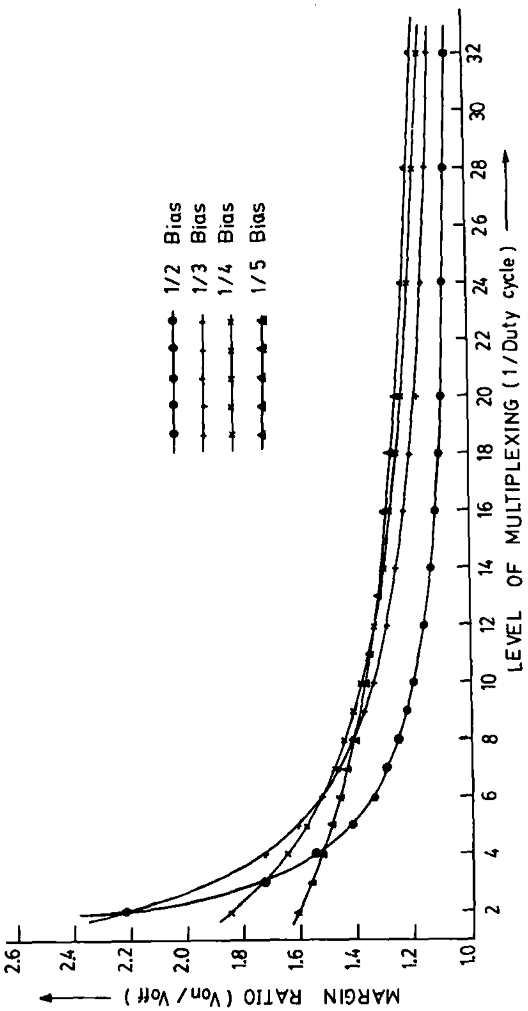


FIGURE 3 Voltage margin Von/Voff for a multiplexed T.N. mode cell.

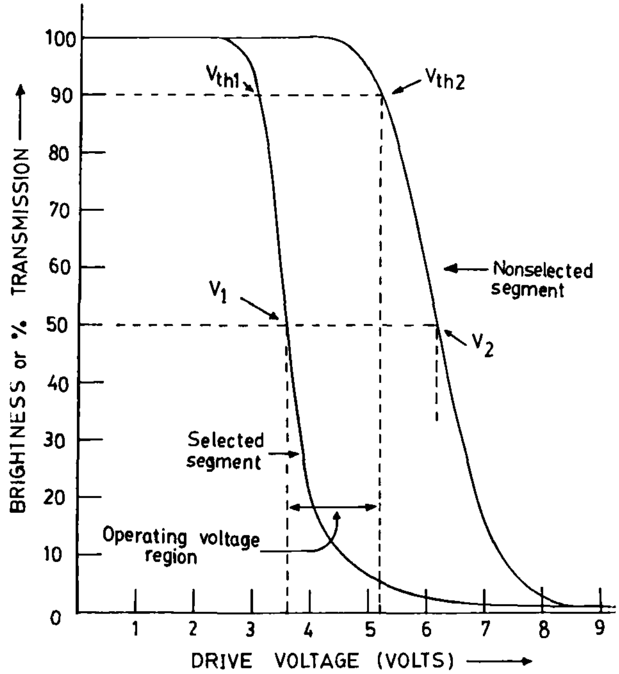


FIGURE 4 Threshold characteristic of select and nonselect segment vs voltage applied on select segment in a multiplexed T. N. cell.

$$\mathrm{Von} \approx \frac{V_b}{s}\sqrt{\frac{(N-1)+S^2}{N}}$$

$$\mathrm{Voff} = \frac{V_b}{s}\sqrt{\frac{(N-1)+(S-2)^2}{N}}$$

where V_b is the battery voltage and s is the biasing or voltage selection scheme.

$$s = 1 + \sqrt{N}$$

For maximum Von/Voff

$$\frac{\mathrm{Von}}{\mathrm{Voff}} = \left(\frac{\sqrt{N}+1}{\sqrt{N}-1}\right)^{1/2}$$

Threshold characteristic of material is temperature and viewing angle both dependent, (Figures 1 and 2) limiting the multiplexing in wide temperature and viewing operation. For low-level multiplexing (2–4) l.c. materials are used without using temperature compensation circuit. However, for higher level of multiplexing, temperature compensated circuit is recommended very strongly. The ratio Von/Voff for various biasing is shown in Figure 3.

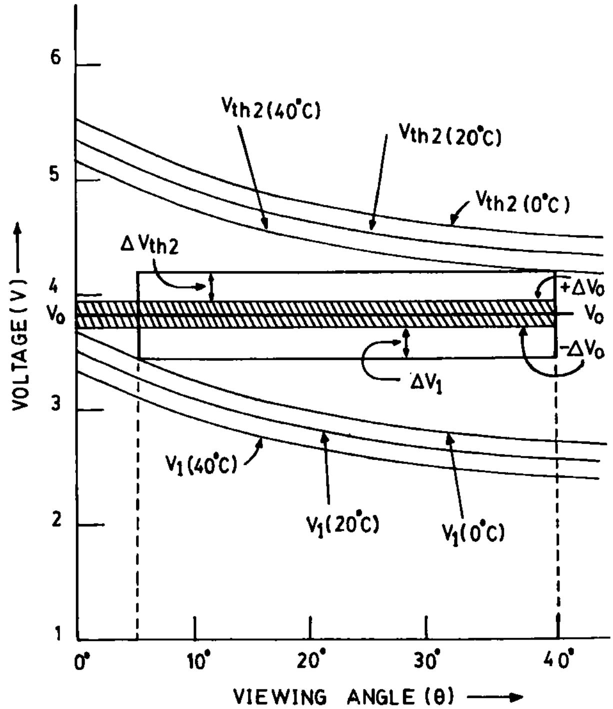


FIGURE 5 Voltage margin on a T. N. mode cell for wide temperature and viewing angle operation.

The contrast ratio of a T. N. mode cell (especially in multiplexed operation where operating voltage cannot be kept very high to avoid the cross talk) is strongly viewing angle dependent, thereby restricting its legibility from all the directions and generating a preferred viewing quadrant. However, with proper alignment technique, the preferred or best viewing quadrant can be centered in most desired direction of viewing for the display.

Figure of merit of a multiplexed cell (M) with a temperature compensated circuit and viewing angle 0 to θ (as shown in Figures 4 and 5)

$$M = \frac{\mathrm{Vth2}(\theta) - V_1(0)}{\mathrm{Vth2}(\theta) + V_1(0)}$$

The polar plot of typical multiplexed display is shown in Figure 6. Other promising areas for higher level information contents are dual frequency addressing and multiple cell approach.

8. *Dichroic Displays*. Requirements:
- Photochemical stability of dye
- High Dichroism

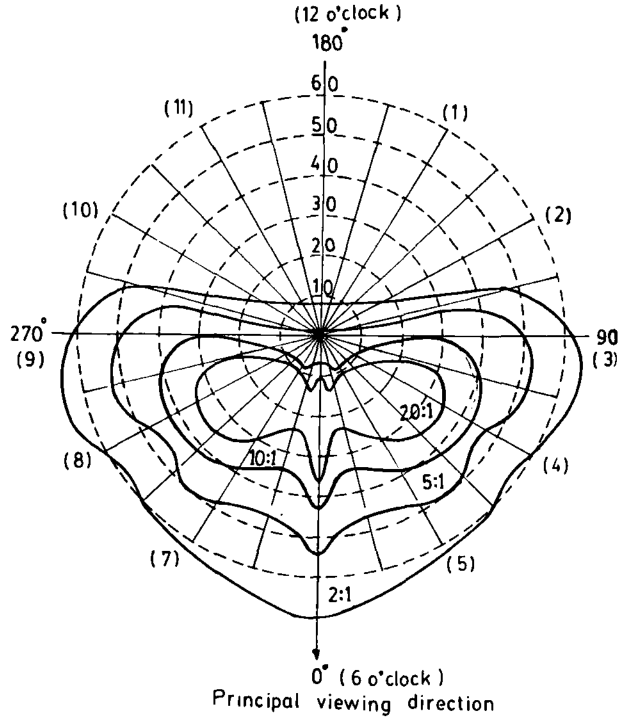


FIGURE 6 Polar plot for contrast and viewing angle of a multiplexed T. N. cell.

- High stability and solubility in l.c. matrix
- High order parameter
- Pleasant hue and color
- Liquid crystal material with high order parameter, wide temperature range, low Δn and high $\Delta\varepsilon$, l.c. should not shift absorption peak of the dye significantly.

Anthraquinone dyes are meeting most of these requirements. For a practical display without polarizer and compatible to or better than T. N., Order parameter of dye in l.c. mixture should be more than 0.8 (preferably 0.9) and $\Delta n = 0.05$.[12]

Phase change type of dichroic seems to be the most promising. They have excellent viewing angle and brightness but only 1:2 or 1:3 multiplexibility.

9. *Smectic Displays*.[13] The most promising smectic display is smectic A display, without polarizer and compatible to or better than T. N., Order parameter of dye in l.c. mixture should be more than 0.8 (preferably 0.9) nonscattering homeotropic alignment. When it is cooled in the absence of field, it adopts a strongly scattering texture. The field has no effect when

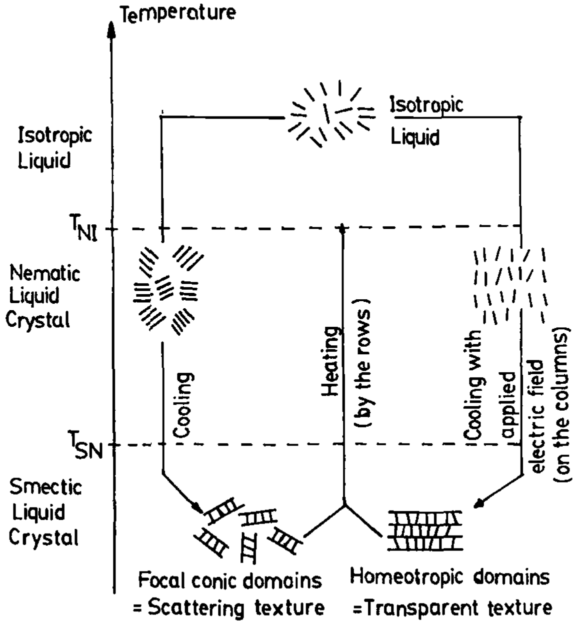


FIGURE 7 Operational principle of a thermally addressed S_A display.

it is in the smectic state. These physical principles were beautifully exploited to develop smectic A displays. The following three types are common S_A displays.

Thermally addressed S_A displays

Thermally addressed S_A displays using dichroic dyes

Laser addressed S_A displays

Smectic displays have a very long memory so they need not be refreshed frequently. Multiplexing is no problem with smectic displays. Memory can last up to a few months. Contrast is very good. However, the power consumption is very large which restricts its use. The physical principle is shown in Figure 7.

10. *Active Matrix Addressed LCDs.*[1,14] The problem of multiplexibility arising due to lack of proper sharpness of the threshold characteristic of LCDs can be obviated if a control device is added at each picture element. These types of cells are often called as active matrix addressed LCDs. Control device can be two terminal nonlinear devices (such as variastor, metal insulator metal) or three terminal switches (such as FET MOS, thin film transistor). They are placed in a series with the liquid crystal cell which acts as a capacitative load.

Two terminal devices are generally restricted to fully on or fully off display elements due to the fact that any variability in their conduction voltage results in a corresponding variation in liquid crystal voltage. Three terminal devices ideally act as a switch with a very low voltage drop across them and hence they are preferred in applications where gray scale is required. For three terminal device

$$R_{on}C_{lc} \lesssim T/N$$

$$R_{off}C_{lc} \gg T$$

where R_{on} and R_{off} are on and off resistances respectively. This enhances the multiplexing limit tremendously high. The major problem is the yield. The operational principle is shown in Figure 8.

MARKET REVIEW OF THE LCD

Table II shows the LCD market and its growth rate in comparison to other types of displays. The table also indicates that while the high power emissive area is shared by so many types of displays, the low power or non-emissive area is unchallengingly occupied by LCDs. During the last ten years LCDs, starting almost from scratch, have made tremendous growth. They have pushed away LEDs, plasma, nixie tube, electroluminescent, etc., to firmly secure the second place just after CRTs.

Besides its unchallenged and established dominance in the watch and calculator markets, LCDs are gaining a major business in industrial and consumer electronics. The principal market in these areas are test and measuring equipment, analytical instrumentation, process control equipment, on line process analyzer, clocks, petrol pumps, domestic appliances (like thermostat, washing machine, microwave ovens, etc.), cameras, electronic games, telecommunication, marine equipment, office systems etc. LCDs are expected to make a major breakthrough in automobiles, military, avionics, electronic data processing, telecommunications and industrial appliances.

In the future we are expected to see some other novel applications of LCDs. The realization that a low cost, truly flat panel, low power display with good visibility and all the flexibility for shape and size is now available, has prompted many manufacturers of electronic devices and systems to incorporate LCDs in their equipment. In many cases they are also pushing aside the more power consuming LEDs, vacuum fluorescent and electroluminiscent displays.

Table III gives the worldwide market for different types of LCD displays in terms of constant (1982) U.S. dollars. In 1985 or 1990 dollars the

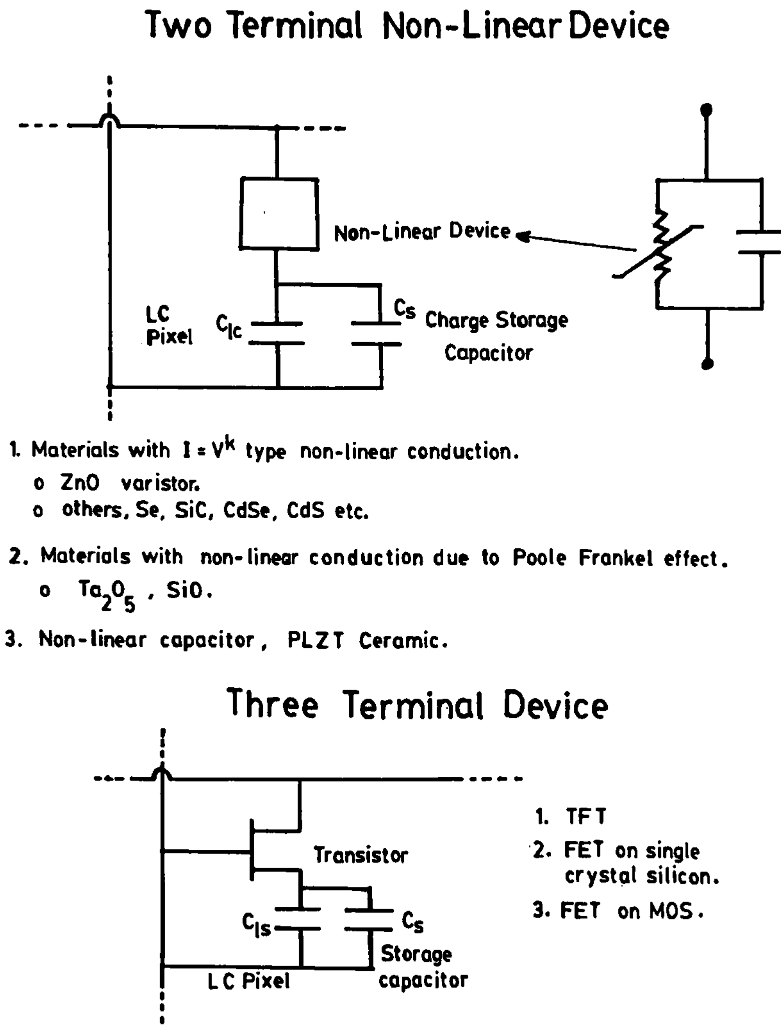
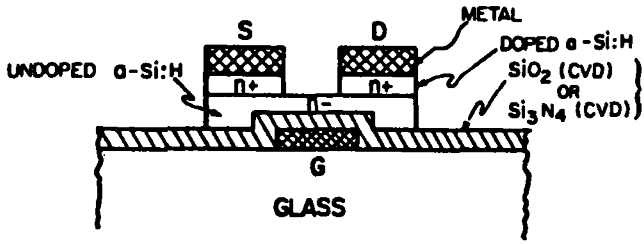
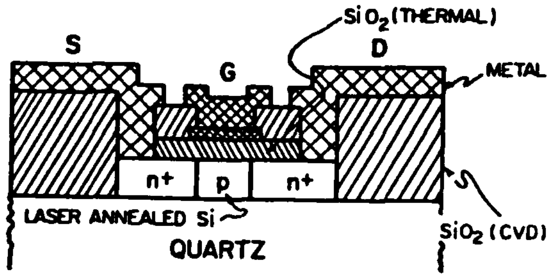


FIGURE 8 Active matrix addressed LCD.

shipment would be much larger, the magnitude will be determined of course by the inflation. If the inflation is assumed to continue more or less with the present rate, the growth rate of LCDs would be 15–20% in terms of the dollar value of the year. Table III has been made for the worldwide market for different sectors of LCDs. Our values lie somewhere in between as estimated by Hoffman La Roche and Stanford Resources.[15]



Cross section of amorphous Si TFT



Cross section of laser annealed crystalline Si TFT

FIGURE 8 (*Continued*)

LCD market and applications are expected to grow steadily in spite of worldwide recession. The traditional LCD market, calculator and watches, will remain almost the same, but anomalous growth is expected in the nontraditional market especially in industrial applications, telecommunications, data processing automobiles, defence and domestic applications.[15] The number of units of watches and calculators will be increasing but as the price of these displays is continuously decreasing, the total market for these sectors in terms of dollar value will remain almost constant. Moreover, the manufacturers will be also forced to put more functions and novelty in these displays. Very recently a Japanese manufacturer has combined a portable T. V. with the wrist watch displays. These attempts may give a little bit more market than expected to the LCD watch sector. The prices of 3.5 digit watch displays, one of the major sectors in LCD business, has dropped from \$0.70 in the spring of 1981 to the present value of \$0.20 in the Far

TABLE 2

(A) Display market in U. S. (in Million dollars)[16] total consumption in U. S. market as supplied by U. S. and foreign manufacturers

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1985
ACTIVE DISPLAYS											
Cathode ray tubes (CRTs) T. V.	709.7	611.7	496	569.4	633	710.5	792.5	833.4	874.1	929.6	1122
Non T. V.	22.4	31.3	29	34.9	40	45.5	47.3	49.3	52.1	56.8	72
Light emitting diodes multicharacter display	63.0	76.0	26	36.0	41	46.7	53.2	60.6	65.4	74.9	90
Lamp or single character display	23.0	27.5	23	28.2	35	38.2	42.0	46.2	45.0	47.0	48
Gas discharge	28.0	23.8	27	26.7	41.5	68.0	72.0	82.2	102.8	121.5	179
Vacuum fluorescent single character	1.2	1.3	1.5	1.6	2.0	2.1	2.3	5.2	5.6	6.2	8
multi character		1.8	2.0	2.4	2.2	3.7	6.1	7.1	8.0	8.5	11
Incandescent	10.0	12.5	14.3	4.7	5.2	4.5	4.8	5.0	5.3	5.6	7
Electroluminescent		2.5	3.0	1.9	2.3	3.1	4.2	5.2	5.2	5.5	6
PASSIVE DISPLAYS											
Liquid crystal displays	1.6	3.4	4.3	14.9	25.0	25.0	31.6	40.9	54.5	72.1	124
Electrochromic displays											
Electrophoretic displays											
Dispersed particles						In Developmental Stages					
Ferroelectric displays											
Magneto-optic displays											

(B) Display market in Japan[5] (in billion yen, approx 220 yen = $1.00 U. S.)

	1979	1980	1981	1982
Liquid crystal displays	30.4	35	44	55
Light emitting diode	23.4	32	40	45
Vacuum fluorescent	21.1	28	32	38
Plasma display	3.1	5	6	7

TABLE III

The worldwide market for LCDs (millions of constant US dollars 1982)

Applications	1981	1982	1983	1985	1990
Watches	115.9	110.6	111.7	113.9	117.4
Calculators	231.7	229.4	230.8	235.8	230.5
Clocks	36.7	38.1	28.7	32.1	33.2
Electronic games and toys	23.5	22.6	17.9	11.7	22.4
T. V. and video	2.3	2.5	3.0	6.1	20.0
Electronic data processing	4.2	7.4	10.0	34.4	107.8
Telecommunications	0.7	1.2	3.0	8.0	28.0
Automobiles	0.5	5.9	8.8	23.8	37.0
Test and measuring equipment	1.6	1.8	2.3	3.2	5.5
Aircraft cockpit	X	0.1	0.3	1.0	4.6
Petrol pump	4.2	4.5	4.7	5.2	5.6
Radio, camera etc.	1.9	2.2	2.4	2.7	4.4
Domestic appliances	1.9	1.7	2.5	6.7	14.8
Business systems	1.4	2.3	3.3	5.6	9.5
Marine instruments	1.6	1.6	1.6	2.0	2.8
Agriculture	0.1	0.1	0.2	0.5	1.1
Others	0.8	1.1	2.4	4.8	15.5
Total:	427.6	433.2	433.9	497.8	660.1

East market. The calculator sector has not been affected that much. The author hopes that after 1983 the watch sector would be stabilized and will increase with a moderate rate of 1% in terms of constant dollar value. The growth rate for calculators and clocks would be practially stagnant.

With the advent of electronic games in the late eighties, it was initially thought that LCDs would capture a major portion of this very fast growing sector. However, the portable electronic games could not become much popular being uncompetitive against CRTs in price, eye appeal, response, etc., and so is the case of LCDs in this sector. Besides this, because of more importance attached to eye appeal and response than cost and power consumption, LCDs will be behind vacuum fluorescent and other types of displays. The situation is expected to improve a little bit with the advent of colored displays and TFTs, but this LCD sector is going to be worse hit for a couple of years. However, in later years the popularity of hand-held games will increase, giving more market to LCDs.

Very recently a Japanese company (Seiko) has released a wrist watch T. V. (size 1.2″ × 1.2″). Casio has recently released E. L. panel back-lighted L. C. pocket T. V. This thin (26mm thick) pocket T. V. is having overall size 80 × 118 × 26mm^3 and display area 41 × 54mm^2 with 19200 picture elements. These types of portable T. V.'s will be useful not only for consumers use but also for business use to receive the special information broadcasts. Some other Japanese companies are also putting efforts for developing portable pocket LCD TV's. However, it is unlikely that future development of LCD T. V. would be able to replace CRTs. The other likely application of LCDs in consumer TV and Video would be for displaying time/channel or replacing some controls in terms of digital modification.

The portable personal microcomputer market is expanding tremendously according to the latest report (from 400 million dollars in 1981 to 1210 million dollars in 1985 in U. S. market only) as published in Electronics. These will be needing a low power consuming portable flat panel display to have interface with human element. LCDs are expected to get tremendous market in these types of computer terminals. Initially smectic and intrinsically multiplexed TN displays will be finding applications but will be replaced by TFTs in near future. This sector is expected to become almost equal to the watch and calculator sector in 1990 in terms of dollar value. We hope to see a truly portable minicomputer using LCDs sitting on everybody's desk by 1990.

Earlier it was thought that present TN LCDs would not be able to meet the high information content requirement of computer terminals and mini TVs and hence LCDs cannot get desired share of these two market sectors unless mass scale production technology of active matrix devices is perfected. However, the increasing capability and growing acceptability of multiplexed TN mode displays has started fetching the market in these sectors. Radio Shack has recently released portable personal microcomputers using 32 level intrinsically multiplexed TN displays, which is becoming very popular. The Casio pocket TV is also using intrinsically multiplexed TN displays.

The use of LCDs in telephone and other telecommunication industries will become a reality by the end of this year. Companies like Data Images have already developed such type of displays. This sector is expected to have tremendous growth rate, sales being multiplied two times each year to its preceding year up to 1985 and then having a growth rate of 150% up to 1990.

Experiments are being conducted for displaying various operational parameters like speed, gas, mileage, etc. and wind speed, temperature, etc., in automobiles by electro-optical displays. While some of the companies like Ford are going for active displays like CRTs and LEDs, most of the companies are concentrating their efforts toward LCDs. In my opinion LCDs will be the ultimate winner in this field because of their several superiorities. LCDs in automobiles will probably face the worse treatment such as temperature, shock, dust, humidity, etc., and will require high reliability, durability, wide temperature range and wide viewing angle. However, the recent developments in LCDs (specially in polarizer, alignment, hermatic sealing, extension of operational temperature range) make them very reliable and operative even up to −50°C without any heater.

Once the automobile industry accepts these displays, this sector is expected to have vertical growth rate. Both dye phase change effect displays and T. N. mode displays have promise. General Motors and Chrysler are putting LCDs in automobiles. GM has recently released Corvette models with an LCD dashboard. LCDs have also started appearing in motorbikes. A 25 million dollar market is predicted in 1985 for this application. However, present LCD manufacturers should not expect much business from this sector. After success of prototype LCDs in automobiles, most of the auto manufacturers will open their own LCD plants rather than purchasing it from LCD manufacturers. For some standard units like clocks, Far East companies will get market in automobiles.

The use of LCDs in portable, test, measuring and analytical instruments have become almost as established as in the case of watches and calculators. However, compared to stagnant watch and calculator sector, this sector has a growth rate of approximately 15% and the same growth rate is expected in the near future. More and more, the electronic equipment manufacturer will shift to LCDs due to its advantage over other types of displays.

A lot of interest is being shown by companies manufacturing instruments for aircraft cockpits toward LCDs. Though the pilots are very reluctant to switch over from familiar electro-mechanical displays to any other form of electro-optical displays, there is no choice left. The modern planes need a lot of information for flight, and the cockpit is becoming too conjested. Now there is not enough room for installation of bulky electro-mechanical devices and compact electro-optical devices, capable of displaying much more information, have to come. Liquid crystal displays are being preferred as they would not fail even in glaring sunlight during daytime flights unlike other active displays. Night viewing is, of course, a problem but it is being sorted out with proper backlighting. This market segment is expected to make very good progress in coming years. LCDs will find applications not only in commercial jet lines but also in fighter planes too. Both T. N. mode and dye phase change LCDs will find applications.

In petrol pumps, LCDs are gaining a strong hold. The growth rate of LCDs will be fast up to 1985 and then will become nearly flat. This market segment also requires highly reliable LCDs capable of working in stringent conditions. The growth rate of LCDs in this sector in the late eighties will depend on the growth rate of petrol pumps, which is declining at present.

LCDs have started finding applications in portable radios, cameras and two-in-one systems. The growth rate of these types of displays will be fair to moderate. The number of LCDs in this sector will increase rapidly, but however, as these applications will be using standard and cheap LCDs, whose prices are declining, the growth rate in terms of dollars will not be that much.

In the domestic appliances sector, too, LCDs are penetrating. They have found applications not only in washing machines, microwave ovens, temperature controlling systems for room heating etc., but also in sewing machines. This sector is expected to have good growth rate in future. However, the growth rate of this sector will be affected more by the economy.

Business systems such as cash registers, banking terminals, data collection systems and other specialized terminals will be using more and more LCDs. This sector is also expected to have excellent growth rate. Another application is expected in office systems equipped with electronic diary using LCD clocks and information exhibiting LCDs etc. People are thinking for more and more novel applications in office and business systems which has been made possible only with development of microprocessors and electro-optical displays.

Marine and agricultural instruments have been using LCDs extensively. The chief reason behind this is that it is the only commercial display technology that is visible in direct sunlight. In fact, agricultural instrumentation was one of the first instruments using LCDs. LCDs are finding applications not only in analytical field equipment but also on tractors. The market will grow with a slow pace.

A lot of interest is being shown by medical equipment manufacturing companies for LCDs. LCDs can display information and digital readings. They are portable and least power consuming. With fast LCDs, they are expected to find market in moving sign type business, outdoor as well as indoor information displaying devices. These two sectors may have a combined market of 10 million dollars by 1990.

CONCLUSION

LCD technology has now become mature, reliable and established technology. Its novelty and superiorities over other types of displays is increasing its use tremendously in electronic equipment and systems.

Recent research and developments in liquid crystal materials, glass, ITO coating, polarizers, thermoplastic sealing materials and mass scale production technique have not only improved the overall performance of LCDs but also cut their cost. Now LCDs are available operating from −55°C to +85°C with a life of 10 years. They can tolerate the harsh environment (high humidity and high temperature operation) and shocks. The switching speed has been improved by a factor of 5–10 compared to first generation LCDs. Tremendous improvements have been made in inherent multiplexibility of LCDs. Now 16-level multiplexed LCDs are commonly available in the market and 32 level multiplexed displays have started appearing on the sceen. Recently Sharp has released 64 level multiplexed TN display in the market. Research is being continuously made to improve the inherent multiplexing capability of LCDs. In laboratories 64–128 level multiplexed TN LCDs are being tested. These may generate 8–32 line alphanumeric LCDs. The use of nonlinear devices like MIM, TFTs etc. will enhance the multiplexing drastically. Once the production technology using TFT is perfected, it will provide the cheapest and least power consuming display for high information content. The developments in thermally addressed smectic A displays have resulted in a practical display for high information content. Within a couple of years thermally addressed S_A displays and TFT coupled LCDs will be available commercially. Dual frequency switching and multiple cell approach are also being tried for high information content.

The recent developments in synthesis of photochemically stable pleochroic dyes with high order parameter (the anthroquinone dyes) have resulted in improved dichroic displays. Developments in ferroelectric displays will result in very fast switching display (μs).

The dominence of TN mode display will continue in the near future. Dichroic displays will ultimately find some market.

As the market is concerned, the overall growth rate would be ~5–10% in terms of constant dollars of 1982. The number of units of watch, calculator and clock displays will increase, but because of static or declining unit prices, the market will grow moderately. LCDs will get tremendous market in telecommunications, industrial, domestic, military, automobile, etc., markets.

During the last couple of years, the world wide recession slowed down the pace of LCD growth. Now it seems the impact is over. There has started a tremendous demand in custom LCDs in North American and Europe even giving birth to some new companies in Europe.

The progress made by LCDs is very satisfactory. During the last one and a half decades LCDs have not only made spectacular growth but pushed aside older displays like LEDs, plasma, nixie tube, electroluminiscent, etc., to secure second position just behind CRTs. Today more and more industrial and consumer products are using LCDs more than ever. The realization that a low cost, low voltage, extremely low consuming display with good visibility, reliability, and compatibility with microprocessors, is available, has prompted many manufacturers of electronic devices, systems and consumer products to incorporate LCDs in their equipment. In the future we hope to see more and more applications of and market for liquid crystal displays.

The views expressed in this paper are personal.

Acknowledgments

Thanks are due to Mr. Alan G. Bruce, Data Images Inc., Canada and Dr. Joseph A. Castellano, Stanford Resources, U. S. A. for discussions and providing some useful information.

References

1. G. F. Weston, "Alphanumeric Displays" *Proc. IEE*, **125**, 1077 (1978).
2. G. W. Gray, "Molecular Structure and Properties of Liquid Crystals," Academic Press, New York (1962).
3. G. J. Sprokel, ed. "The Physics and Chemistry of Liquid Crystal Devices," Plenum Publishing Corp., N. Y. (1980).
4. B. Bahadur, "Nonsteriod Chiral Mesogens," Liquid Crystal Abstracts, 3212 (1978).
5. J. Imikata, "A Comparative Market Survey of Liquid Crystal Displays—The United States, Japan and Europe," Displays 2, 331 (1981).
6. L. Waller, "Watch Surge Generates LCD Shortage," *Electronics*, page 67, January 6, 1977.
7. E. K. Faulkner, R. K. Whitney and J. F. Zeman, Conference Record of (1982) International Display Research Conference, page 171 (1982).
8. T. Uemeda, T. Miyashita and F. Nakano, 1982 SID International Symposium, Digest of Technical papers, page 178 (1982).
9. Information sheet on polarizers from Nitto, Sanritsu, Hoechst, etc.
10. Information sheets from BDH, (England), E. Merck (Germany), Hoffman La Roche (Switzerland, Data Images (Canada), etc.
11. Information sheets from NEC, Motorola, Hitachi, Hughes, etc. on their LCD drivers.
12. T. Ishabashi, K. Toriyama and K. Suzuki, Conference Record of 1982, International Display Research Conference, page 115 (1982).
13. S. Lu, D. H. Davis, R. Albert, D. Chung, A. Hochbaum and C. Chung, 1982 SID International Symposium, Digest of Technical papers, page 238; L. Leberre, M. Harneg, R. Hehlen and J. N. Perbet., *ibid*, page 252.
14. A. I. Lakatos, Conference Record of 1982 International Display Research Conference, page 146 (1982).
15. J. A. Castellano, "Current U. S. and World Markets for Electronic Displays," paper presented at SID Symposium, San Diego, 1982, SID Digest, page 24 (1982).
16. *Electronics*, January issue containing market forecast from 1973 to 1983.